

Single atom trapping in a metasurface lens optical tweezer

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Optical metasurfaces of sub-wavelength pillars have provided new capabilities for the versatile definition of the amplitude, phase, and polarization of light. In this work we demonstrate that an efficient dielectric metasurface lens can be used to trap and image single neutral atoms. We characterize the high numerical aperture optical tweezers using the trapped atoms and compare to numerical computations of the metasurface lens performance. We predict future metasurfaces for atom trapping can leverage multiple ongoing developments in metasurface design and enable multifunctional control in complex experiments with neutral-atoms arrays.

Single neutral atoms in optical tweezers are an important platform for quantum simulation, computing, and metrology [1–3]. With ground-up control similar to trapped ions, individual atoms can be prepared and entangled [2, 4, 5]. Control of single neutral atoms relies heavily on optical potentials for trapping, either in lattices or arrays of tightly-focused laser beams, termed optical tweezers. In optical tweezers, high numerical aperture (NA) optics are key for both creating trapping potentials and imaging fluorescence of single atoms [6, 7]. The requisite high-NA optics must have wide field-of-view (FoV), high focusing efficiency, large chromatic range, and long working distance. Yet the large conventional objective lenses that best approach these requirements are difficult to incorporate into increasingly complex vacuum chambers and multi-functional photonic systems. Recent advances in patterned low-loss dielectric metasurfaces have defined a new paradigm for optical design [8, 9] and offer an intriguing solution to atom-trapping challenges. Here, we introduce the use of a high-NA dielectric metasurface lens to trap and image single atoms and obtain tight trap confinement. We form an atom array by combining the metasurface lens with tunable acousto-optic deflectors, and characterize the tweezer foci using the trapped atoms. We predict future optimized photonic metasurfaces that leverage ongoing advances in element design libraries and multi-layer design will be an important frontier for advancing quantum information with neutral atoms.

Metasurfaces are planar photonic elements composed of a periodic array of subwavelength dielectric or metallic nanostructures. Contrary to traditional optical elements that rely on refraction for phase shift, the nanostructures constituting a metasurface couple, resonantly or off-resonantly, and re-radiate the incoming light with a transformed phase, polarization, or amplitude determined by the nanostructure shape, size, and material composition [8]. Electromagnetic modeling, device optimization and fabrication of nanostructures with unprecedented complexity and resolution have enabled multi-

functional control of the optical wavefront [8, 9]. For example, by spatially varying the nanopillar width in a pattern similar to a Fresnel lens the re-radiated light will converge at the far field to form a focal point, *i.e.* create a metasurface lens (Fig. 1b). An important performance metric for metasurface optics is transmission efficiency, which is governed by multiple factors, including choice of low-loss and high-index dielectric thin films and the ability to pattern high-aspect ratio nanostructures with high-fidelity. Recently, metasurface lenses have been reported with efficiencies ranging from 60% to 92% [10–12], utilizing a range of materials such as TiO₂, HfO₂, Si and GaN, and operating from the deep-ultraviolet to the near-infrared. Further, utilizing inverse design, machine learning, and multilayers can improve the performance and expand the versatility of metasurface optics [13, 14].

In atomic physics, metasurface optics are intriguing to explore given their combination of high performance, multifunctional response, and low form-factor. Initial explorations in metasurfaces for atomic experiments have been used to create beamshaping and splitting elements in magneto-optical traps [15, 16]. In this work, we open the use of metasurfaces to optical dipole traps, in the form of tightly-focused optical tweezers, which will be important for deployable atomic systems, as well as in increasingly complex quantum information experiments with neutral atoms. For example, in experiments that harness neutral atoms as quantum bits arbitrary polarization and chromatic control is increasingly desired, and stability of the optics is crucial, for example, in registration of optical tweezers and lattices or for in-vacuum applications.

Typically in optical tweezer experiments multi-element objective lenses are required to achieve requisite performance [6, 7, 17], although experiments with targeted requirements can make use of single aspheric lenses [18]. Optical tweezer experiments require both low aberrations to achieve tight confinement and high focusing efficiency to achieve sufficient trap depth for a given trapping power and to efficiently image single atoms. Achromatic prop-

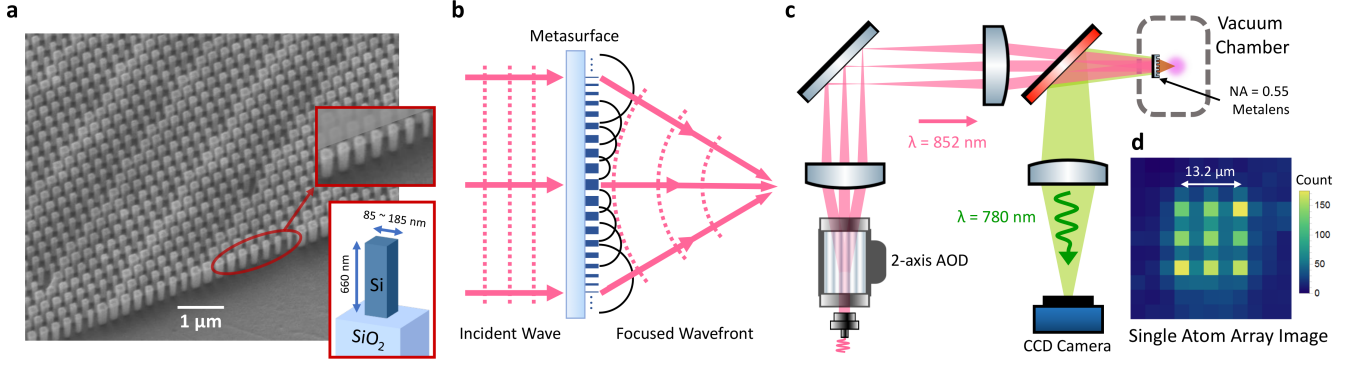


FIG. 1. Metasurface optics for optical tweezer trapping (a) Scanning electron micrograph of the fabricated metasurface lens containing a periodic array (lattice constant = 280 nm) of amorphous-Si nanopillars (height 660 nm) of width ranging from 85 nm to 185 nm (dark blue) on top of a 500 μm thick fused-silica substrate (light blue). Inset shows the varying nanopillar width to achieve the desired phase shift (see Appendix Fig. A1a). (b) Notional illustration of metasurface lens operation showing light propagation (pink), wavefronts (dashed lines), and secondary wavelets (black semicircles) re-emitted by the nanopillars that interfere to create the focusing wavefront. (c) Optical setup for trapping (pink) and fluorescence imaging (green) of single atoms in an array created with multiple input beams generated using a 2-axis acousto-optic deflectors. (d) Image of a trapped ^{87}Rb array created by averaging over multiple experiment iterations (100 in this case) with $\sim 52\%$ probability of a single atom in each trap per image. The variation in the averaged intensity is caused by trap depth and shape variations that affect relative loading probability and imaging signal in the array.

erties are needed for conservative trapping in a far off-resonance trap, collecting atom fluorescence detuned by 100's of nanometers through the same lens, and often also delivering excitation light that controls the atomic spin in individual tweezers [4]. Perturbations to the trap focus due to multi-beam interference or scattered light can be detrimental, especially if they are not static, as these fluctuations can drive atom motion. A long working distance (WD) is required to allow access for laser cooling beams, to maintain sufficient distance between the lens substrate and atoms in high-energy Rydberg states that are sensitive to surface electric dipoles, and to focus light into a complex vacuum chamber or cryogenic environments [19].

For the demonstration presented in this work, we use a high-contrast transmission-mode metasurface lens (metalens) with NA of 0.55, a measured focusing efficiency of 58%, and a focal length 3 mm (equivalently a WD of 3 mm for the thin lens) (Fig. 1). Using the trapped atoms we measure the Gaussian waist of the focused tweezer spot to be $(0.80 \pm 0.04) \mu\text{m}$, which is consistent with the designed lens NA. Further, we create an array of traps with our focusing metasurface lens by introducing multiple beams with tunable angle derived from an acousto-optic deflector pair, and demonstrate a field-of-view (FoV) of $\pm 11 \mu\text{m}$ ($\pm 0.2^\circ$) (Fig. 1d), which is consistent with a full theoretical model of the metalens. Our successful trapping is an indication that potential deleterious effects of metalenses, for example, scattered light, the presence of undeflected zero-order light, or deformations due to absorption and heating of the lens, has negligible contributions to the trapping performance of large-

spacing tweezers.

The design wavelength of the lens is the trapping wavelength of $\lambda = 852$ nm, which is sufficiently far off resonance for ^{87}Rb atoms to avoid recoil heating. The 4 mm $\times$ 4 mm square lens is illuminated with a circular Gaussian beam with a $1/e^2$ waist of 2 mm. The lens is also used to collect fluorescence on the ^{87}Rb D2 line at 780 nm, but given the singlet properties of the lens and design space offered by the square-shaped nanopillars used in this work, it is not optimized to be diffraction limited at 780 nm. The metalens is comprised of a thin-film of amorphous-Si (refractive index, $n = 3.62 + i0.004$ at $\lambda = 852$ nm) deposited and patterned on a fused-silica substrate ($n = 1.45$) (Fig. 1a) (see Appendix for fabrication details). The materials used for the metalens are fully UHV compatible and can resist UHV baking temperatures without change of properties. The lens is mounted on a sample holder inside AR-coated glass cell (see Appendix for sample mounting and vacuum chamber).

We have carried out a full numerical simulation of the expected metalens properties using the finite-difference-time-domain (FDTD) method (see Appendix). The theoretical focusing efficiency, estimated as the fraction of the incident light that is diffracted towards the focal spot, is 78%; the loss is expected to be from a combination of reflection (14%), light remaining in the 0-th order (6%), and light scattered into higher orders (2%). The amount of 0-th order undiffracted light can potentially be an issue if it is large enough to alter the trapping potential by interfering with the focused light; however, for our tightly focused optical tweezers, the intensity at the focal spot is

expected to be more than six orders of magnitude larger than the 0-th order intensity.

To optically characterize the fabricated metalens we perform a number of optical tests of the device used in the atom trapping experiment. First, to characterize the focal spot, we image a pair of 300 nm diameter pinholes separated by $6.86\text{ }\mu\text{m}$ using the metalens; we find that the lens is diffraction limited at 852 nm (Fig. 2f) by measuring the imaged point spread function (PSF). Because the metalens images the 780 nm atom fluorescence out of focus, we use the pinholes to also analyze and predict the divergence of the imaging system (see Appendix). Second, to characterize the efficiency, we measure both the 0-th order light directly, and also assess the combined loss from all factors by measuring the optical tweezer power transmitted through a 300 μm diameter spatial filter (see Appendix). We find 0-th order light transmitted through the lens (which is conveniently used for system alignment) to be 13%, somewhat larger than the theoretical estimation. The measured focusing efficiency, defined as the ratio of power that passes through the 300 μm spatial filter placed at the lens focus to the total power incident on the substrate, is determined to be 58% at 852 nm and 56% for 780 nm. The efficiency of the lens is somewhat smaller than the theoretical value, likely due to fabrication imperfections resulting in non-ideal nanopillar cross-sections and sidewall tapering that can increase the scattered and 0-th order light above predicted values.

Atoms are captured into the optical tweezers by overlapping the focus of the metalens with a magneto-optical trap (MOT) and applying polarization-gradient cooling (PGC) for 15 ms while the optical tweezer traps are on (see Appendix) [20]. Light assisted collisions are used to ensure only one atom remains in the trap [6]. To image the atoms, we use a 1 mm diameter probe beam that avoids scattering off of the metasurface by propagating parallel to the substrate (see Appendix Fig. A2e). This beam, in PGC configuration (see Appendix for imaging details), illuminates the atoms for 25 ms, the fluorescence is collected by the metalens, and the slightly diverging fluorescence is reflected by a dichroic mirror, passed through an imaging lens system and focused onto a charge-coupled device (CCD) camera (see Fig. 1c and Appendix Fig. A2). Figure 1d shows an example single-atom array averaged over 100 loading iterations.

We first analyze in detail one trap that is at the center of the metalens FoV. We plot a histogram of the fluorescence counts collected through the metalens and registered on the camera (CCD counts) versus occurrence from a single pixel at the atom location (Fig. 2a,b). The lower count histogram peak corresponds to background signal with no atom and the second higher CCD count peak corresponds to the fluorescence of the single atom. Collisional blockade prevents loading of more than one atom into the tweezer, as reflected in the absence of

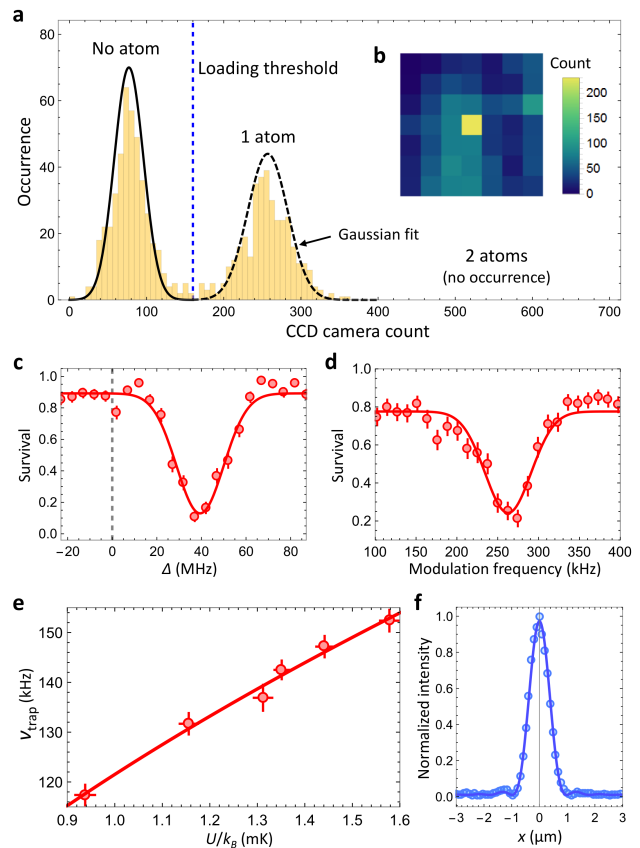


FIG. 2. Single atom trapping in a metalens optical tweezer (a) Camera count histogram indicating presence of either 0 or 1 atoms in a tweezer trap. A threshold is chosen to determine if an atom is trapped and to calculate the loading efficiency. (b) Typical single shot fluorescence image of a single atom imaged through the metalens with PGC imaging. (c) Typical light-shift measurement with a Gaussian fit (red line) to the shifted atomic resonance. Dashed line corresponds to free-space ^{87}Rb $D2$ $F = 2$ to $F' = 3$ transition (d) Typical parametric heating measurement with a Gaussian fit (red line) to extract the trap frequency (ν_{trap}) from the modulation resonance ($2\nu_{\text{trap}}$). Each point is an average of 100 trap loading sequences. (e) Measured trap frequency versus trap depth (light shift) obtained from multiple measurements similar to (c) and (d). The solid red line is a model fit (see main text) to extract the effective Gaussian tweezer waist seen by the trapped atom. (f) Peak-normalized cross-section of intensity transmission through a 300 nm diameter pinhole imaged at the 852 nm trapping wavelength by the metalens. Solid blue line is an Airy function fitted to the data to extract the spot size and effective NA. (Error bars in (c,d) represent the standard deviation and error bars in (e) are standard error of the fitted Gaussian centers.)

a two-atom peak [6]. We find a loading probability of $(47 \pm 5)\%$. However, due to the limited imaging beam geometry (see Appendix Fig. A2e), the atom loss during imaging is $(10 \pm 2)\%$. Taking this into account, a loading probability of $(52 \pm 5)\%$ is comparable to typical load-

ing efficiency from other optical tweezer experiments [21]. We determined the length of time a single atom remains trapped in the optical tweezer focus, with no cooling light present, by holding the atom with variable time between two consecutive images. The measurement gives a lower bound of exponential decay lifetime of 10 sec; atom lifetime assessment in a metalens trap beyond this scale will require additional investigation of background gas collision rates due to finite vacuum level and potential atom loss contributions due to inelastic light scattering from residual trapping light.

Next, we characterize the effective tweezer focus size by measuring both the trap depth and the trap frequency (harmonic oscillator strength of atom moving in the optical tweezer light). The measurements are made by determining atom survival following perturbations that depend upon a parameter of interest. For measuring the trap depth U , we make use of the fact that the trap light induces an AC-Stark effect that shifts the atomic resonance by 28.8 MHz/mK compared to that in free-space, and we determine the frequency at which resonant light heats the atom out of the trap. For trap frequency measurements, we modulate the trap between 5% and 10% of its depth around the nominal value to parametrically heat at twice the trap frequency (ν_{trap}) and subsequently lower the trap depth to eject hot atoms. Figure 2c,d show the typical light shift and trap frequency measurements. The trap waist can be deduced from the slope of a graph that plots the trap frequency versus depth as per $\nu_{\text{trap}}(U, w_0) = \frac{1}{2\pi} \sqrt{\frac{4U}{w_0 m_{\text{RB}}}}$ (Fig. 2e). We extract a gaussian waist of $w_0 = (0.80 \pm 0.04) \mu\text{m}$ at 852 nm, which is consistent with the value determined from the optical lens characterization (Fig. 2f). With the clipped Gaussian beam illumination used for the optical tweezer trapping (versus uniform illumination during characterization) we expect the tweezer to have a waist of $0.78 \mu\text{m}$, consistent with the measured value.

An important metric for creating and imaging large atom arrays is the lens FoV. Figure 3 illustrates a study of the metalens tweezer off axis. For this, we create four traps with the lower left tweezer at the center of the field of view (optical axis), and characterize the traps (with various spacing) in analogy to Fig. 2c,d. In the presence of aberrations the traps become asymmetric, resulting in non-degenerate frequencies in the radial dimensions of the trap. This will manifest as a double-peak structure in the trap frequency measurement (Fig. 3b). We characterize the FoV by plotting the waist determined from the trap frequency and depth measurements as a function of the distance from the optical axis (Fig. 3c) and find the aberrations are consistent with FDTD calculations of tweezer intensity from our metalens optical field distribution (blue lines, Fig. 3c). Here FoV is defined as the distance to a point where the average waist is 10% larger (Strehl ratio > 0.8) than at the center, and we find

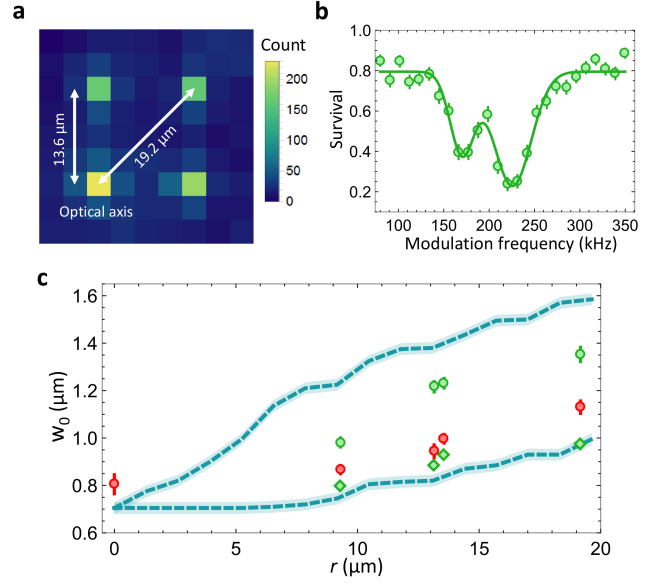


FIG. 3. Atom array and metalens field of view (a) PGC fluorescence image of atom array trapped with metasurface optical tweezers. Image is averaged over 100 experimental cycles. Bottom left tweezer is on optical axis of the metalens. The off-axis tweezer site typically have a lower loading probability and non-optimal PGC imaging detuning resulting in a dimmer single atom signal. (b) Example of typical trap frequency measurement data at $\approx 13.6 \mu\text{m}$ from FoV center where asymmetric aberrations in the trap are present, along with a double Gaussian (green line) fit. (c) Extracted Gaussian waist as determined from the atom trapping as a function of distance (r) to the metalens optical axis (center of FoV). Shown is both the average waist extracted from a single Gaussian fit to the trap frequency data (red), and (for larger offsets) the major waist (green circle) and minor waist (green diamond) extracted from data similar to (b) when the two trap frequencies start to become distinguishable. We compare to theory by plotting the major and minor Gaussian waist fitted from FDTD simulation (see Appendix Fig. A1c). (Error bars in (b) represent the standard deviation and error bars in (c) are standard error.)

a FoV of $\pm 11 \mu\text{m}$ ($\pm 0.2^\circ$).

As one comparison, we discuss the aberration and FoV performance of a typical commercial asphere that has been used in optical tweezer experiments. Reference [18] uses an aspheric lens with $\text{NA} = 0.5$, a working distance of 5.7 mm, and a focal length of 8 mm. This aspheric lens has a transverse field of view of $\pm 25 \mu\text{m}$ ($\pm 0.18^\circ$) and an inferred beam waist of $1 \mu\text{m}$ for the trapping wavelength, and a $0.9 \mu\text{m}$ waist for the imaging wavelength. The metasurface lens presented here achieves similar trapping performance, but with a zero-thickness lens. In comparison, a complex objective lenses can have field of view of a few $100 \mu\text{m}$ ($\approx \pm 3^\circ$) combined with achromatic operation over a wide range of wavelengths [3, 7]. While the singlet metalens described in this work does not yet achieve these metrics, opportunities for future metasur-

face optical designs have the potential to replace bulky objectives with monolithic optical assemblies.

We expect future metasurface designs for atom trapping will leverage multiple ongoing developments. An enhanced FoV can be achieved by patterning both sides of the substrate to create a double-layer metasurface [22]. Further design improvements can be achieved through the use of an expanded unit-cell library to include cross, donut and other exotic nanopillar shapes [23] or via inverse design [24]. Choosing optimal materials and designs that are robust to nanofabrication variation is expected to offer higher efficiencies that exceed that achieved in the experiments presented here [9]. Further, a hybrid lens design consisting of a curved refractive surface and a metasurface patterned on the same substrate will offer additional prospects for enhanced design space [25, 26]. We also note that it is possible to achieve a focusing response that is either polarization selective [27] or one that transforms the polarization [28], which are functions not offered by traditional optical lenses. For example, polarization multiplexing provides a method to trap and collect fluorescence at the diffraction limit for two different wavelengths using a singlet metasurface lens, and may find utility in combining additional multifunctional beams in complex trapping experiments.

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During the preparation of this manuscript we learned of a recent experiment using high-NA metasurface lenses for nanoparticle trapping [29].

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APPENDIX

Metasurface design

The metalens used in this study consists of a square lattice (lattice constant $a = 280$ nm) of a-Si nanopillars on a fused-silica substrate. Each nanopillar unit cell, of square cross-section (side length L) and height $H = 660$ nm, acts as a phase-delay waveguide (Fig. 1a). The in-plane side lengths L of the nanopillars vary between 85 nm to 185 nm, forming a library of metasurface unit-cell designs offering transmittance close to unity and relative phase shift ϕ covering the full 0 to 2π span (Fig. A1a). This design library is then used to implement the phase profile of an ideal lens [30], given by:

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

where λ is the design wavelength (here, $\lambda = 852$ nm), f is the focal length (here, $f = 3$ mm), and x, y are the coordinates of sampled phase position relative to the lens center.

Metasurface theoretical estimation of efficiencies

We use the grating averaging technique [31] to estimate the focusing efficiency, the fraction of incident light

remaining as undeflected 0th-order light, and the total reflectance of the mm-scale diameter metalens. Following this technique, we approximate the metalens as a combination of aperiodic beam deflectors. For an aperiodic beam deflector with a deflection angle θ_D ($\theta_D = \sin^{-1}(\lambda/Na)$, where N was chosen to calculate θ_D between 0° to 50°), the deflection efficiency η_1 , the fraction of light in the 0th-order η_0 , and the reflectance η_{refl} , for unpolarized input light, are calculated (circles in Fig. A1b) using rigorous coupled wave analysis (RCWA), and fitted with parabolic functions (solid lines in Fig. A1b). Finally, the focusing efficiency of the metalens T_1 , the total fraction in the undeflected 0th-order T_0 , and the total reflectance T_{refl} , are estimated as the area average of η_1 , η_0 , and η_{refl} , respectively, using:

$$T_i = 1/(\pi R^2) \iint_S \eta_i ds = 2/R^2 \int_0^R \eta_i(r) r dr, \quad (2)$$

where $i = 1, 0$, or refl ; $r = f \tan \theta_D$; and R is the radius of the metalens.

Metasurface theoretical estimation of FoV

The beam waist at the focal spot as a function of distance from the metalens optical axis, or equivalently the incident angle of the input beam, is calculated using FDTD technique, with a minimum mesh size of 4 nm. Due to the millimeter scale size of the metalens, a cylindrical metalens is simulated instead, implemented by using one unit-cell along the y -axis with periodic boundary condition. All the unit cells along the x -axis are included in the simulation, and the oblique incidence angle is only applied along the x -direction. For a given incident angle, a near-field monitor records the electric and magnetic fields of the output beam at a distance of 50 nm from exit surface of the metasurface. A near-field to far-field projection is then used to calculate the focal spot intensity profile at the focal plane (Fig. A1c). The major and minor waists of the focal spot are obtained as the distance from the intensity peak to the $1/e^2$ of peak intensity along the x -axis.

Metasurface fabrication

The metasurface optics is fabricated by depositing a layer of 660 nm thick a-Si on a 500 μm thick fused silica wafer using plasma enhanced chemical vapor deposition (PECVD). A 300 nm thick layer of electron beam resist (ZEP 520A) followed by a 20 nm thick layer of anti-charging conductive polymer (ESpacer 300Z) are spin-coated onto the a-Si film. A 100 keV electron beam lithography system is used to expose the nanopillar pattern, followed by ESpacer removal with deionized water at room temperature, and resist development with hexyl

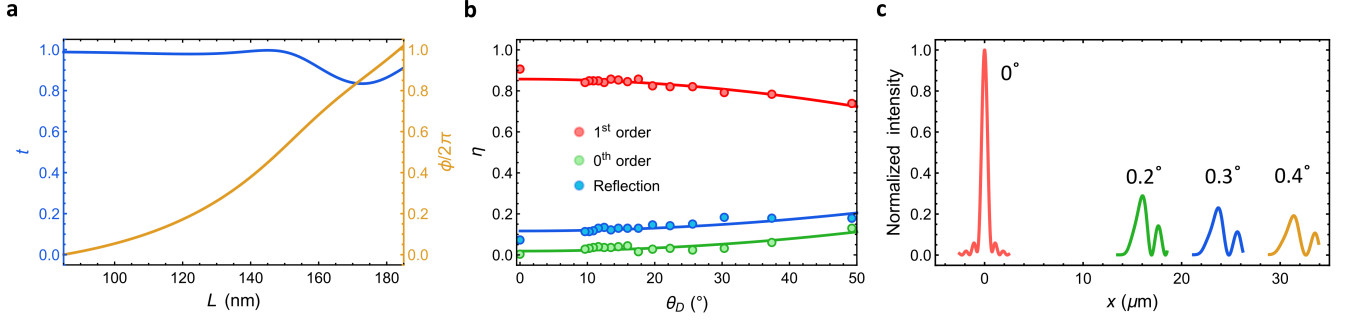


FIG. A1. **Metalens design and simulations** (a) Transmittance t and phase shift ϕ as a function of nanopillar side length L . (b) Calculated deflection efficiency η_1 , the fraction of light in the undeflected 0th-order η_0 , and the reflectance η_{refl} of aperiodic metasurface beam deflectors as a function of deflection angle θ_D . Circles are data from RCWA simulations and solid lines are parabolic fit. (c) FDTD simulated beam profiles of the focal spots as a function of the angle of incident light.

acetate at 4 °C. The developed pattern in the resist layer is transferred to an electron-beam-evaporated 70 nm thick Al_2O_3 layer using the lift-off technique. By using the patterned Al_2O_3 layer as an etch mask, inductively-coupled-plasma reactive ion etching (ICP-RIE, gas mixture: SF_6 and C_4F_8 ; ICP power: 1750 W; radio frequency (RF) power: 15 W) is performed to etch the underlying a-Si layer at 15 °C, to create high-aspect-ratio a-Si nanopillars. The metasurface optics fabrication is finalized by soaking the wafer in a mixture of hydroperoxide and ammonia hydroxide solutions (80 °C for 30 min) to remove the Al_2O_3 etch mask and any etch residue.

Metasurface characterization

To verify the lens is diffraction limited at 852 nm, we image a pair of pinholes spaced by $6.86 \mu\text{m}$ and 300 nm in diameter with the metalens. The pinholes are sufficiently small to be treated as point sources. The magnification of the system is calibrated by using the known separation of the pinholes. Fitting an Airy function to the imaged PSF, a Gaussian waist of $(0.72 \pm 0.02) \mu\text{m}$ and an effective NA of 0.55 ± 0.01 is extracted (Fig. 2f), which is consistent with the diffraction limit.

To measure the focusing efficiency, a spatial filter is used to exclude the 0-th order transmission from the focused light. A collimated 852 nm laser beam of 4 mm in diameter illuminates the metalens. A pinhole of dimensions that allow the focused light to be transmitted ($300 \mu\text{m}$ pinhole of $300 \mu\text{m}$ thickness) is then placed at the metalens focus. A power meter is placed 7 mm away from the metalens (4 mm from the metalens focus), and the pinhole is translated in x , y and z to maximize the power transmitted. The input power and transmitted power are compared to extract the focusing efficiency. The procedure is then repeated for 780 nm and for other input polarizations. The focusing efficiency is found to be 58% at 852 nm and 56% for 780 nm and insensitive

to polarization rotation for both wavelengths.

Sample mounting and vacuum Chamber

The metasurface sample is mounted in a Pyrex cell (science cell) with anti-reflection coating on the outside (Fig. A2a). A sample holder machined from a fused-silica wedge (0.5°) with faces polished to better than $\lambda/8$ is epoxied to the inside of the cell with ultra-low outgassing high-temperature epoxy (Epotek-353ND). The epoxy absorbs any minor thermal expansion mismatch between the Pyrex and the fused-silica substrated. The metalens sample (Fig. A2b) is then optically contacted to the sample holder (Fig. A2a). The optical contact bonding ensures the metalens substrate remains optically flat after ultra high vacuum (UHV) bake (up to 220 °C). The adhesive-free optical contact also allows the cell to be reused indefinitely. The materials used for the metalens (a-Si and fused-silica) are UHV compatible and can be baked to high temperature (>200 °C).

The atomic source is a magneto-optical trap (MOT) glass cell that is located 40 mm from the science cell and connected through a differential pumping orifice with vacuum conductance of 0.05 L/s. The science cell connects to an ion pump with pumping speed of 25 L/s resulting in a vacuum environment of $< 10^{-10}$ hPa measured at the ion pump. A valve between the source MOT cell and the rest of the system isolates the source MOT while the system is vented for sample exchange. The compact construction of the vacuum chamber allows the chamber to be moved elsewhere for sample mounting and UHV baking.

Acousto-Optic deflectors

To generate an array of optical tweezers a $1/e^2$ waist = 2 mm collimated beam at 852 nm (pink shaded beams in

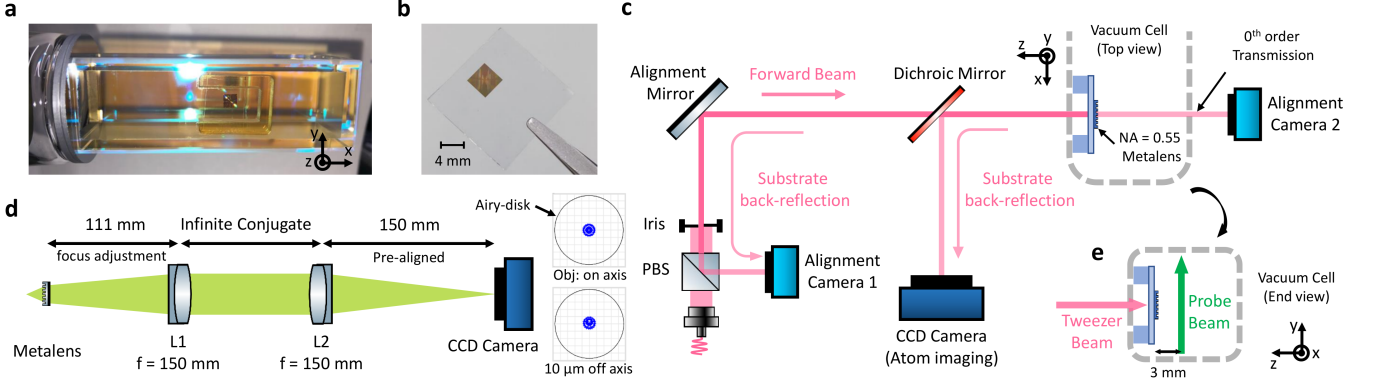


FIG. A2. **Metalens in-vacuum mounting and tweezer alignment** (a) Photo of the metalens sample optically contacted onto the wedged fused silica sample holder that is epoxied onto the AR coated glass cell. (b) Fabricated NA of 0.55 metalens sample designed for 852 nm tweezer light. (c) Schematic illustrating how the tweezer light and science CCD camera are aligned to the metalens sample via substrate back-reflection. (d) Schematic illustration of optical tweezer imaging path with lenses that compensate for out-of-focus imaging due to chromatic focal shift introduced by the metalens. Insets are the ray-tracing simulation of the imaging system (object on-axis and $10\ \mu\text{m}$ off axis) assuming metalens only has chromatic focal shift and no other aberration. The result shows L1 and L2 does not introduce additional aberrations. Black circle is the diffraction limited Airy-disk. (e) End view of the vacuum cell, showing the probe beam (also resonant heating beam) orientation in relation to metalens sample and tweezer beam. Probe beam is 1 mm in diameter, shines vertically up and is 3 mm away from the metalens overlapping with the optical tweezer focus.

Fig. 1c) is launched into a two-axis acousto-optic deflector (AOD) (AA Opto-electronics Model: DTSXY-400-850.930-002). This produces a series of deflected beams with variable angle controlled by the AOD input RF frequencies. This array of angled collimated light is then imaged with a 1:1 relay lens onto the back aperture of the metalens substrate. The relay lens ensures all the deflected beams coincide on the metalens to minimize asymmetric beam clipping.

Metalens tweezer and CCD camera alignment

To ensure optimal tweezer performance from the high NA metalens the input light is aligned perpendicular to and centered on to the metalens (Fig. A2c). The back-reflection of the substrate is used to align the tweezer input light. The tweezer light ($1/e^2$ waist of 2 mm) is passed through a polarizing beam splitter (PBS) and an iris apertures the beam down to 0.5 mm diameter. Alignment camera 1 (Fig A2c) is placed on the reflection port of the PBS to monitor the back-reflection from the metalens substrate. This iris allows <0.25 mrad angular alignment resolution between the input beam and substrate. Alignment camera 2 (Fig. A2c) is placed behind the glass cell to monitor the 0-th order metalens transmission. The shadow cast by the structure on the metalens allows the input beam to be centered on the metalens. The input beam is walked while monitoring the image on both alignment cameras until the input is both perpendicular and centered. The residual reflection

of the back-reflected tweezer beam from the dichroic mirror (Fig. A2c light pink) is used to align the position of the science camera and the imaging system. Finally a bandpass filter centered at 780 nm (Semrock LL01-780-12.5) is placed in the imaging path to block any residual tweezer light.

Imaging path compensation

Because the metalens is only designed to be diffraction limited at 852 nm, it is important to characterize the imaging performance of the lens at the atomic fluorescence wavelength of 780 nm. To measure the chromatic focal shift, the metalens is illuminated with a collimated tunable laser source and the focused spot is imaged with an apochromatic microscope objective with NA of 0.9. By changing the microscope focus we determine the chromatic focal shift to be $+300\ \mu\text{m}$ between 852 nm to 780 nm. We then calculate the signal of an atom trapped at 852 nm focus and emitting 780 nm fluorescence diverges with EFL of $-39\ \text{mm}$ after passing through the metalens (Fig. A2d). To compensate, a lens of EFL=150 mm (L1 in Fig. A2d, Thorlabs AC254-150-B) is placed 111 mm from the metalens. The combined optical system (metalens + L1) becomes infinitely conjugate so the tube lens (L2 in Fig. A2d, Thorlabs AC254-150-B) is decoupled from the compensated imaging system. L2 is pre-aligned to the camera, and L1 is translated to focus the imaging system by only adjusting one optical element. The inset of Fig. A2d shows the ray-tracing simulation of the

imaging system for both on-axis and 10 μm off-axis on the tweezer plane verifying that the compensation lens and tube lens does not introduce aberrations. The ray-tracing simulation does not include aberration inherent to the metalens design.

To characterize the compensated imaging system, the same 300 nm diameter double pinhole is imaged again with the pinhole positioned at metalens' 852 nm focus and illuminated with 780 nm light. The resulting PSF has a waist of (1.1 ± 0.07) μm which is not diffraction limited (due to metalens has spherical aberration at 780 nm) but sufficient for single atom detection, and the effective solid angle for light collection is equivalent to metalens NA of 0.55.

Loading and detection

The single atom loading starts with the three-dimensional (3D) science MOT. The atoms from the dispenser in the source cell are cooled in the transverse direction with MOT laser red detuned from ^{87}Rb $D2$ $F = 2$ to $F' = 3$ transition (free-space atomic resonance) by 14 MHz and transported to the science cell via a push laser beam. The collimated atom beam has a flux up to 10^8 s^{-1} . The science MOT loading lasts 500 ms with a typical MOT size of (3×10^7) atoms and a density of 10^9 cm^{-3} . After loading, the source MOT lasers are shut off and the magnetic field gradient is turned off and the MOT lasers are changed to 144 MHz red detuned from free-space atomic resonance to perform PGC with $\sigma_+ - \sigma_-$ configuration for 15 ms. During the PGC the optical tweezer is turned on to load atoms into the tweezer. The typical free-space PGC temperature is between 30 μK to 50 μK , and the tweezer trap depth is typically at 1.3 mK during loading. During the PGC loading the laser is red detuned from the atomic resonance resulting in light assisted collision that assures only a single atom is trapped [6].

To image a single atom in the tweezer, we utilize PGC imaging. The PGC configuration with less detuning cools the atom while scattering photons. The trapped atom is

illuminated with a 500 μm waist and 150 μW PGC/probe beam (beam geometry shown in Fig. A2e, $\approx 10I_{\text{sat}}$, 47 MHz red detuned from free-space atomic resonance) for 25 ms and the fluorescence is collected by the metalens (I_{sat} is the saturation intensity of ^{87}Rb $D2$ $F = 2$ to $F' = 3$ transition). After passing through the metalens, the slightly diverging fluorescence is reflected by a dichroic mirror and passed through the compensation and imaging lens (L1 and L2 in Fig. A2d) and focused onto a Princeton Instruments PIXIS 1024B CCD camera. The imaging loss rate is higher than typical PGC imaging due to the probe beam being perpendicular to the metalens substrate so no axial cooling is present during PGC imaging. The data presented are in CCD counts and are not converted to photon count. The intensity variation in the averaged atom array image presented in Fig. 1d and Fig. 3a stems from varying trap depths and aberrations that affect both loading and imaging. In the array trapping experiment, the optical power of the traps are equalized to within 5% relative difference at the Fourier plane in between the relay lens, but due to aberrations the actual trap depth deviates from the on-axis trap.

Trap depth and trap frequency measurement:

To measure the tweezer trap depth a resonant heating beam is used. Between the two consecutive PGC imaging sequences the heating beam intensity is set to 100 μW ($\approx 6I_{\text{sat}}$) and is pulsed on for 60 μs . The pulse time and intensity of the resonant heating beam is carefully chosen such that the atom only heats out near the atomic resonance. The atom survival versus heating beam detuning is recorded by measuring the atom survival between the two PGC images (Fig. 2c).

To measure the trap frequency, the tweezer trap depth is modulated around the nominal value between the consecutive PGC imaging and the atom survival is recorded as a function of modulation frequency (Fig. 2d). The modulation depth ranges between 5% to 10% of the trap depth and modulation time ranges from 30 ms to 50 ms.