A monolithic immersion metalens for imaging solid-state quantum emitters

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Quantum emitters such as the diamond nitrogen-vacancy (NV) center are the basis for a wide range of quantum technologies. However, refraction and reflections at material interfaces impede photon collection, and the emitters’ atomic scale necessitates the use of free space optical measurement setups that prevent packaging of quantum devices. To overcome these limitations, we design and fabricate a metasurface composed of nanoscale diamond pillars that acts as an immersion lens to collect and collimate the emission of an individual NV center. The metalens exhibits a numerical aperture greater than 1.0, enabling efficient fiber-coupling of quantum emitters. This flexible design will lead to the miniaturization of quantum devices in a wide range of host materials and the development of metasurfaces that shape single-photon emission for coupling to optical cavities or route photons based on their quantum state.
Solid-state quantum emitters have emerged as robust single-photon sources\textsuperscript{1} and addressable spins\textsuperscript{2}—key components in rapidly developing quantum technologies for nanoscale magnetochemistry\textsuperscript{3}, biological sensing\textsuperscript{4}, and quantum-information science\textsuperscript{5}. Performance in these applications, be it magnetometer sensitivity\textsuperscript{6} or quantum key generation rate\textsuperscript{7}, is limited by photon-collection efficiency. However, efficient collection of a quantum emitter’s photoluminescence (PL) is challenging as its atomic scale necessitates diffraction-limited imaging with nanometer-precision alignment, oftentimes at cryogenic temperatures or in other situations incompatible with free-space bulk optics. Beyond their atomic scale, the challenges associated with coupling to solid-state quantum emitters are exacerbated by the high refractive index of their host substrates. Diamond, for example, has a refractive index of $n_D \approx 2.4$ at visible wavelengths, which traps photons in the material by the total internal reflection for propagation vectors oriented beyond $\theta_c \approx 25^\circ$ from the surface normal of a planar air interface. Furthermore, imaging through more than a few microns of diamond with a high-numerical-aperture objective results in spherical aberrations that severely limit collection efficiency. While a number of nanophotonic structures have been investigated for increasing emission from diamond nitrogen-vacancy (NV) centers through Purcell enhancement\textsuperscript{8}, these devices require NV centers positioned close to diamond surfaces, which degrades their spin\textsuperscript{13} and optical properties\textsuperscript{14}.

For this reason, a common approach to minimizing optical losses when addressing single NV centers in bulk diamond is to mill or etch a hemispherical surface, known as a solid immersion lens (SIL), around the NV center of interest\textsuperscript{15}. By ensuring uniform optical path length and reflectance for rays emanating to all angles, SILs remove the losses caused by the total internal reflection and spherical aberration. SILs have enabled numerous advances in quantum optics using NV centers, including all-optical quantum control\textsuperscript{16} and loophole-free violations of Bell’s inequality\textsuperscript{17}. However, a high-NA objective lens is still required to image a quantum emitter through a SIL. For quantum-optics experiments, a cryostat that can accommodate a vacuum-compatible objective and associated optomechanics must be used, or the optical losses associated with imaging through a cryostat window must be accepted. Neither option provides a clear route for packaging quantum emitters in a scalable fashion.

Since quantum emitters are point sources with relatively narrow emission spectra, the compound optical system of a microscope objective, designed for broadband imaging with a flat field-of-view, is not actually necessary for efficient photon collection. Flat optics, such as phase Fresnel lenses used to image trapped ions in ultra-high-vacuum cryostats\textsuperscript{18}, are an attractive alternative; however, a flat optic on its own cannot compensate for the high refractive index of a solid-state quantum emitter’s host material. The ideal solution is a flat optic fabricated at the air/diamond interface to form a planar immersion lens; such a design can be realized using the concept of a metasurface.

Metasurfaces have recently gained attention as they offer design flexibility for optical components with arbitrary phase responses\textsuperscript{19, 20}. In particular, diffractive optics\textsuperscript{21, 22}, high-contrast gratings\textsuperscript{23, 24}, and more recently, dielectric metalenses\textsuperscript{21, 25–28} comprised of high-refractive-index dielectric elements such as TiO$_2$ and amorphous silicon have been demonstrated with high transmission efficiency and diffraction-limited focusing. While spherical and chromatic aberrations limit the field-of-view of single-element dielectric metalenses as compared with aberration-corrected multi-lens objectives\textsuperscript{21}, they are ideally suited for collimating emission from point sources\textsuperscript{27}. When fabricated at a material interface, a metasurface can be designed to use the underlying substrate as an immersion medium\textsuperscript{25, 28, 30} to overcome the total internal reflection losses in a similar manner to a SIL; see Supplementary Note 1, Supplementary Fig. 1, and Supplementary Table 1.

Building on these advances, we leverage diamond’s high refractive index to design and fabricate a 27.9-μm-diameter (19.3 μm effective aperture) metalens composed of subwavelength pillars etched into the surface of a single-crystal substrate that collimates the emission of an individual NV center located ~20 μm beneath the surface (Fig. 1a). The metalens eliminates the need for a collection objective by operating as an immersion lens with a numerical aperture (NA) greater than 1.0. This marks the first step in designing and fabricating metasurfaces for controlling photons from quantum emitters using only top-down fabrication techniques and provides a clear pathway to packaging quantum devices by eliminating the need for an objective.

**Results**

**Immersion metalens design and fabrication.** The metalens is fabricated using standard, top-down, electron-beam lithography and O$_2$-based dry etching. Its pillars approximate a desired continuous
phase profile, $\phi(x, y)$, on a square grid by mapping the pillar diameter, $d$, to the effective refractive index, $n_{\text{eff}}$, of the lowest-order Bloch mode supported by the pillar (Fig. 1b). We use a Fresnel lens phase profile in conjunction with Fig. 1b to assign a pillar diameter to each grid point. The discretized phase profile for a focal length $f = 20 \mu m$ at $\lambda = 700$ nm is shown in Fig. 2a, with a corresponding SEM image of the fabricated structure shown in Fig. 2b. Since the effective refractive index of each pillar is between the refractive index of air and the refractive index of diamond, the metalens is inherently anti-reflective, as evidenced by the bright-field reflection microscope image shown in Fig. 2c; see also the simulation and measured lower-bound on the metalens reflectance in Supplementary Fig. 13a. To demonstrate that the structure operates as a lens, in Fig. 2d we use a transmission microscope to form an image through the metalens of a chromium shadow mask illuminated from below the diamond; see Supplementary Note 4 and Supplementary Fig. 6 for details.

**Metalens performance and characterization.** We characterize the metalens using a combination of three-dimensional full-field electromagnetic simulations and confocal-scanning optical microscopy. Placing an NV center at the metalens focus in diamond results in collimation of the emitter’s PL in air, as illustrated by the simulations in Fig. 3a. The PL can then be coupled directly into low-NA collection optics with high efficiency, as shown by the simulations in Fig. 3c. The solid black line corresponds to the NA = 0.19 achromatic collection lens. Simulations of a plane wave launched from air and focused through the metalens were also performed; the simulated values of NA and focal length, $f$, shown as open squares in Fig. 3c and 3d, respectively, are extracted from the simulated electric field profile at each wavelength. The simulation for $\lambda = 700$ nm is shown in Fig. 3e. We use confocal-scanning optical microscopy in a double-pass geometry to produce high-resolution scans of the metalens focal spot and its position inside the diamond (see the Methods section). These measurements are analyzed to obtain the experimental values of NA and $f$ shown in Fig. 3c, d (black points), demonstrating that the metalens has NA $> 0.9$ across wavelengths spanning the NV center’s full emission spectrum, with NA $= 1.10^{+0.12}_{-0.09}$ at $\lambda = 700$ nm. To enable this accurate comparison of simulation and measurement, we have numerically modeled the microscope’s point-spread function using confocal measurements of isolated NV centers and deconvolved it from the focal-spot measurements to reveal the metalens’s transverse and axial field profiles. Even with no free parameters, the deconvolved field profiles in Fig. 3f show excellent agreement with the simulations in Fig. 3e, as evident by the transverse and axial cross sections shown in Fig. 3g. Details regarding the characterization measurements, deconvolution analysis, and calculations of the transmission, collection, and focusing efficiency are available in the Methods, Supplementary Notes 5–6, and Supplementary Figs. 7–14.

**Imaging an NV center with the immersion metalens.** To image an NV center with the metalens, we focus a 532-nm pump beam through the backside of the substrate using an oil immersion objective (Fig. 4a). The confocal collection/excitation volume of the objective is axially positioned in the plane of the metalens focus and is rastered using a fast-steering mirror (FSM). NV-center PL at each scan position is simultaneously measured by two fiber-coupled single-photon counting modules (SPCMs): one is aligned to the metalens, and the other is aligned to the confocal path through the objective. The counts collected by the SPCMs at each point of the FSM raster scan form the images shown in Fig. 4b, c. The lenses in the metalens path (L1, L2 in Fig. 4a) collimate the diverging metalens output beam so that a 568-nm long-pass filter (LPF) can be inserted to block the pump beam. Figure 4b and c both exhibit a bright spot at the same lateral position, denoted by the black dashed circles. We fix the FSM position at the center of this spot and measure the PL signals (S$_{\text{ML}}$, S$_{\text{obj}}$) through the metalens and objective paths, respectively. Background signals are separated recorded from a position off the spot but within the metalens field of view. The background-subtracted spectra of both paths (Fig. 4d) clearly exhibit the NV center’s zero-phonon line at 637 nm and characteristic phonon side band. Background-subtracted PL saturation curves (Fig. 4e) display saturation count rates of 87.3 ± 2.8 photons/ms and 24.9 ± 0.4 photons/ms when measured through the metalens and objective, respectively. The objective NA is limited to 0.75 in order to mitigate spherical aberrations. Finally, we measure the second-order cross-correlation function, $g^{(2)}(\tau)$, between both paths. The background-corrected $g^{(2)}$ measurements (Fig. 4f) exhibit the characteristic antibunching dip and short-delay bunching of a single NV center with $g^{(2)}(0) = 0.175 \pm 0.031$, clearly demonstrating that the spots in Fig. 4b, c are indeed the same single-photon emitter. Details regarding the background-correction analysis are available in the Methods, Supplementary Note 7, and Supplementary Figs. 15, 16.

**Discussion**

The immersion metalens lays the foundation for future advances in controlling light-matter interactions for quantum emitters in high-refractive-index substrates. By integrating the typical objective/SIL combination onto the quantum emitter’s host substrate, the metalens has the potential to enable direct fiber coupling of quantum emitters. In our experiment, two relay lenses and a free-space long-pass filter were used to prevent the pump beam from entering the collection fiber (L1, L2, and LPF in Fig. 4a). However, the metalens output can be coupled directly
into a fiber using a different excitation geometry or a commercially available multilayer-dielectric-coated fiber tip (available from Omega Optical, Inc., for example). Another limitation of our current demonstration is the inability to co-focus the pump beam and collection volume through the metalens due to chromatic aberration inherent to the Fresnel lens phase profile. Going forward, achromatic metalens designs can enable co-focusing of multiple wavelengths, or a second metalens can be incorporated on the backside of the diamond to focus the pump beam, replacing the objective in our experiment.

Unlike previous high-NA metalens demonstrations that relied on diffraction to focus wide angles far from the optical axis, the high NA of our metalens is achieved by using diamond as an immersion medium. This implies that optimized design strategies could yield a diamond metalens with a substantially larger NA, potentially with a value approaching the maximum, $NA_{max} = n_D = 2.4$. Beyond lenses, the expanding body of research on metasurface design can be leveraged to explore phase profiles that shape emission from quantum emitter ensembles, compensate for an emitter’s dipole orientation, control coupling to orbital–angular–momentum modes, and enable chiral quantum photonics. An immersion metasurface can also be incorporated with nanophotonic structures for Purcell enhancement, for example to collimate the output of a chirped grating structure or parabolic mirror through the backside of the diamond, or to extend the cavity length of a fiber-based resonator cavity.

The immersion metalens promises major advances in performance and scalability of quantum devices. Its top-down fabrication processes are readily compatible with those used to fabricate on-chip microwave antennas and electric-field gates required for dynamic spin control and Stark shifting in quantum optics applications. Furthermore, the metalens design can be applied directly to other quantum-emitter systems, including spin defects in silicon carbide, quantum dots in III–V compound semiconductors, and rare-earth ions in laser crystals. More generalized metasurface designs can mediate quantum entanglement and interference of quantum emitters. Ultimately, this demonstration has broad implications for nanophotonics, quantum optics, and quantum nanotechnology, as dielectric metasurface design will lead to compact, fiber-coupled single-photon sources, sensors, and quantum memories, with further potential applicability to designing diffractive optics for space and Raman lasers.
The symmetry of this structure ensures polarization-independent performance. Design details. Prior to spin-coating HSQ, a 7-nm adhesion layer of SiO₂ was deposited on the substrates. The SiO₂ adhesion layer was removed using buffered oxide etch (RIE, Oxford Instruments, Plasma lab 80) to create a clean surface for the HSQ layer. The HSQ was then patterned using e-beam lithography to define the metalens structure. The metalens was fabricated on 3.0 × 3.0 × 0.15 mm double-side polished silicon substrates.

Methods Design. The metalens was designed using the procedure devised by Lalanne et al. for TiO₂ deposited on glass. The procedure was carried out as follows: first, the Bloch-mode effective index, n_{eff}, was calculated as a function of pillar diameter (Fig. 1b) on a subwavelength grid. The grid-pitch, λ, was chosen to be just below the onset of first order diffraction, λ ≤ \frac{2π}{d} ≈ 291 nm at λ = 700 nm, which was rounded up to λ = 500 nm. The pillar height was chosen to be h = 1.0 μm and the minimum pillar diameter was set to d_{min} = 100 nm to ensure compatibility with our fabrication process. The maximum pillar diameter, d_{max}, was then found by determining the n_{eff} required to achieve an optical pathlength increase of 2n relative to the minimum pillar diameter:

n_{eff}(d_{max}) = \frac{λ}{2π} + n_{eff}(d_{min}).

The corresponding d_{max} is found from the dispersion curve in Fig. 1b. The minimum and maximum pillar diameters are indicated in Fig. 1b (black dashed lines) along with the corresponding relative optical pathlengths (red dashed lines).

The Fresnel phase profile in Fig. 2a was calculated by

ϕ = n_{eff}(d_{max}) (\sqrt{x^2 + y^2} − x),

with 93 grid points for a diameter of 27.9 μm measured by the grid edges at the maximum widths along the Cartesian design dimensions. The symmetry of this structure ensures polarization-independent focusing, which has been shown for similar designs using TiO₂ deposited on glass.

Fabrication. The metalens was fabricated on 3.0 × 3.0 × 0.15 mm double-side polished silicon wafer using a 50 keV electron beam lithography tool (Elionix, ELS-7500EX; see Supplementary Note 3, Supplementary Figs. 3-5, and Supplementary Table 2 for details). Prior to spin-coating HSQ, a 7-nm adhesion layer of SiO₂ was deposited on the silicon wafer by electron beam evaporation to promote adhesion. After exposure, the pattern was developed in a mixture of 200 mL of deionized water with 8 g of sodium chloride and 2 g of sodium hydroxide. Our e-beam lithography process for HSQ on diamond can be found in ref. 30. A reactive ion etch (RIE, Oxford Instruments, Plasma lab 80) was used to remove the SiO₂ adhesion layer and to transfer the HSQ pattern into the diamond surface. The SiO₂ adhesion layer was removed by a 1 Min CF₃ reactive ion etch, followed by a 23 Min O₂ RIE etch with a flow rate of 40 sccm, a chamber pressure of 75 mTorr, and an RF power of 200 W to form the diamond pillars. Finally, the HSQ hardmask was removed using buffered oxide etch.

Simulations. Calculations of n_{eff} and ϕ (Fig. 1b, left and right axes, respectively), and pillar transmission efficiency (see Supplementary Note 2 and Supplementary Fig. 2) were performed using 3D rigorous coupled-wave analysis (RCWA) based on the method developed by Rumpf et al. The effective index of the pillars was calculated by solving for the eigenvalues of Maxwell’s equations with the z-invariant refractive index profile of the pillar cross-section in a 300 × 300 nm square unit cell at λ = 700 nm. The eigenproblem was defined in a truncated planewave basis using 25 × 25 plane waves, with implicit periodic boundary conditions. Following these calculations, the pillar height was set to 1.0 μm with air above and homogeneous diamond below, and the complex amplitude transmission coefficient, t, of a normal incidence plane wave from air is calculated as a function of pillar diameter. The right axis of Fig. 1b was found by φ(λ) = ϕ(λ).

The focused spot in Fig. 3d was calculated using 3D finite-difference time-domain simulations (FDTD, Lumerical Solutions, Inc.). The 27.9-μm-diameter metalens is contained in a 28.1 × 28.1 × 22.25 μm total-field/scattered-field (TFSF) excitation source to reduce artifacts caused by launching a plane wave into a finite structure. Perfectly matched layers (PMLs) were used as boundary conditions 0.5 μm away from the TFSF source. The simulation mesh in the pillars was set to 10 × 10 × 10 μm, increasing gradually to 50 nm along the propagation (z)-direction into the diamond. The metalens was modeled with a non-dispersive refractive index, n_{eff} = 2.4. An x-polarized plane wave (ω₀ = 2π × 440, Δω = 2π × 125 THz) is launched from air toward the metalens surface. Steady-state spatial electric-field distributions, E( r), at five wavelengths ranging from 600 nm to 800 nm were stored, and the spatial fields at λ = 700 nm was plotted as an intensity distribution (Fig. 3e). The focal length, f, at each wavelength (Fig. 3d) was determined by finding the grid point in the simulation cell where |E|^2 is maximum. The spatial distribution of the steady-state field amplitude, E( r), in Fig. 1a was simulated by removing the TFSF source and placing an x-oriented dipole current source at the metalens focus position with a wavelength of 700 nm, −18 μm below the metalens in diamond.

The electric-field intensity distribution in Fig. 3a was simulated in a similar manner by adding the intensity distributions resulting from two independent simulations of current sources with orientations corresponding to the two optical dipoles of the NV center. This simulation was run using a 30.0 × 30.0 × 34.0 μm cell with PML boundaries. The simulation mesh in the pillars was set to 30 × 30 × 25 nm, increasing gradually to 50 nm along the z-direction into the diamond. The temporal pulse distribution used in the TFSF simulations was applied to the dipole sources, and steady-state spatial electric-field distributions, E( r), and dipole source power, P₀, were stored at five wavelengths ranging from 600 nm to 800 nm. These quantities were used to calculate the coupling efficiency plotted in Fig. 3b as described below.

Given a fixed acceptance angle of the collection optics following the metalens, η_{collection} = sin^{-1}(NA_{collection}), the metalens coupling efficiency as a function of wavelength is defined as follows:

\eta_{collection}(λ) = \frac{\int_{θ_{min}}^{θ_{max}} P_{eff}(θ_{collection}, λ) dθ_{collection}}{P_{0}(λ)},

where P_{eff}(θ, λ) and P_{0}(λ) are, respectively, the time-averaged powers transmitted through the metalens and emitted by a dipole current source located at the position of the metalens focal spot in the solid angle defined by the metalens NA. A 2D spatial
Fourier transform is performed at each wavelength on the FDTD-calculated transverse electric-field amplitudes in air 215 nm above the top surface of the metalens, using the MATLAB function FFT with zero padding to increase the simulation cell size to 4097 × 30 × 4097 nm to calculate \( P_{\text{nl}}(\lambda, l) \), which is then integrated from normal incidence up to \( \theta_{\text{electron}} \) using the geometrical efficiency68 of the metalens, \( \eta_{\text{geom}} \) (see Supplementary Note 6), and the total time-averaged power emitted by the dipole, \( P(\lambda, l) \). \( \eta_{\text{geom}}(\lambda, l) \) = \( \eta_{\text{geom}}(\lambda_{\text{ML}}, l) \). The spreading efficiency \( \eta_{\text{spreading}} \) is calculated using a weighted sum over the NV center’s spectrum as \( (\eta_{\text{spreading}}) = \int W(\lambda) \cdot \eta_{\text{spreading}}(\lambda, l) \, d\lambda \), where \( W(\lambda) \) is the spectrum measured through the oil immersion objective shown in Fig. 4d normalized such that \( \int W(\lambda) \, d\lambda = 1 \).

**Experimental.** Measurements of the metalens were carried out with a custom-built confocal microscope, comprised of an oil immersion objective with adjustable iris (Nikon Plan Fluor x100.05:1.30) and an inverted optical microscope (Nikon Eclipse TE2000) with a 2×-z piezo stage (Thorlabs MZS5000-E) as well as a scanning stage for the \( x \) and \( y \) axes (Thorlabs ML5203-I). The diamond host substrate was fixed to a microscope coverslip (Fisher Scientific 12-548-C) using immersion oil (Nikon type N) with the patterned surface facing upwards. A 30 mm cage system and SM1-thread components (Thorlabs) were used to create a fiber-coupled optical path above the stage of the inverted microscope. This configuration allowed for simultaneous excitation and measurement of the metalens from (fiber-coupled path) or through the diamond (objective path). The objective path was routed outside the microscope body by a beam-splitter and laser-scanning confocal excitation and collection optics could be added. A 4f-relay-lens system consisting of two achromatic doublet lenses (Newport, 25.4 mm × 150 mm focal length, PAC050AR.14) was used to align the back aperture of the objective to a fast-steering mirror (FSM, Optics in motion, OM1010), which was used to raster the diffraction-limited confocal volume in the transverse \( x \)–\( y \) plane of the objective space. A 560-nm long-pass dichroic mirror (Semrock, Brightline FF560-650i) placed after the FSM was used to couple a 532-nm excitation laser (Coherent, Compass 315M-150) into the objective, while wavelengths above 560 nm pass through the dichroic mirror and are focused into a 25-μm core, 0.1 NA, multimode fiber (Thorlabs M67L01) that can be connected to a single-photon counting module (Excelitas, SPCM-AQRH-14 FC) or a spectrometer (Princeton Instruments iPlane-160, 750-nm blaze wavelength with 1200 G/mm) with a thermoelectrically cooled CCD (Princeton Instruments Pixis 1008X). Computer control of the FSM and counting the electrical output of the SPCM was achieved using a data acquisition card (DAQ, National Instruments PCIe-6323).

For the measurements presented in Fig. 3, a broadband supercontinuum source (Fianium WhiteLase SC-400) was coupled through a single-mode fiber (Thorlabs P1-630AR-2), collimated, and brought into the collection path of our microscope via a beam-splitter (Thorlabs BS014). A \( f = 2.0 \) mm collimating lens (Thorlabs CFC-2X-2-A) and \( f = 15 \) mm achromatic lens (Thorlabs AC064-015-B) were used to couple the metalens to a single-mode fiber (Thorlabs P1-630-FC-1) and a fiber retroreflector (Thorlabs P1-630-FC-1) which, upon reflection, creates a 28-μm-diameter Gaussian beam that emulates the plane-wave source used in our FDTD simulations. The excitation wavelength is limited to the planewave source used in our FDTD simulations. The excitation wavelength is set by passing the supercontinuum beam through a set of linearly variable short-pass filters (Delta Optical Thin Filters using the point-spread function of the microscope objective. The point-spread function is numerically calculated from confocal measurements of a single emitter; see Supplementary Note 5 and Supplementary Fig. 8. The deconvolution of the measured transverse focus spots used for the fits is obtained by an iterative deconvolution of the experimental profiles using the point-spread function of the microscope objective. The point-spread function is numerically calculated from confocal measurements of a single emitter; see Supplementary Note 5 and Supplementary Fig. 8. The deconvolution operations are performed using the Lucy-Richardson method (MATLAB function deconvlucy) with the number of iterations selected by minimizing the mean-squared-error (MSE) of the deconvolution algorithm. The MSE is calculated between the measured data and the re-deconvolution of deconvolved measured data with the objective point-spread function (MATLAB function imsmm and convnfft, respectively). The fit uncertainty is calculated by bootstrapping the objective’s NA, which was verified to be 0.76 ± 0.03. The confidence intervals plotted as error bars in Fig. 3c reflect this range of objective NA values used as input for the deconvolution and fitting analysis.

The entrance pupil, \( D \), of the metalens can be calculated by geometry using \( N_{\text{AML}} \) and \( n_{\text{air}} \):

\[
D = \frac{n_{\text{air}}}{n_{\text{D}}} \left( \frac{\sin^{-1} \left( \frac{N_{\text{AML}}}{n_{\text{D}}} \right)}{\lambda} \right)^{1/2} \tag{4}
\]

Using Eq. 3 alongside with Eq. (4), we find that \( D = 19.3 \) μm, which is smaller than the physical 27.9-μm diameter of the metalens. This indicates a maximum collection angle inside of the diamond \( \theta_{\text{max}} = \sin^{-1} \left( \frac{n_{\text{air}}}{n_{\text{D}}} \right) = 27.8^\circ \). Despite this limited collection angle, Fig. 3c clearly illustrates \( N_{\text{AML}} = 1.0, \) which can be increased by using diffraction designs for larger angles.

The focal length of the metalens in Fig. 3d was determined by measuring the distance between the metalens surface and the focused spot formed below the metalens using the piezo stage of the microscope. The distance traversed by the piezo stage is then scaled by a factor of \( n_{\text{air}} / n_{\text{D}} \) to compensate for distortions caused by imaging through diamond96. Further details are given in Supplementary Fig. 9. Corrections for the PL background in Fig. 3d–f were performed by recording background levels near the NV center of interest. The NV center’s PL saturation curve is nonmonotonic due to ionization and recombination, together with shelving in the spin-singlet manifold. At high powers approaching saturation, saturation curves cannot be fit with the typical two-level saturation model109. For the measurements in Fig. 4e, the PL has clearly saturated for \( P_{\text{pump}} > 12 \) mW; therefore, we calculate the saturated count rate and corresponding uncertainty from the average and standard deviation of the data recorded above this power level. Background curves are shown in Supplementary Fig. 15.

**Background correction of the cross-correlation data in Fig. 4f was performed using the following relationship109:**

\[
g_0(t) = g_1(t) - \left( 1 - \rho^2 \right) \frac{g_2(t)}{\rho^2} \tag{5}
\]

where \( g_2(t) \) is the measured second-order correlation function and \( \rho = 0.26 \pm 0.01 \) is the ratio of background-corrected signal to total signal determined by 40 repeated measurements. After background correction, \( g_0(t) \) is fit with the following analytical function:

\[
g_0(t) = 1 - Ae^{-t/\tau_1} + Be^{-t/\tau_2} \tag{6}
\]

which corresponds to the approaching of the NV center as a 3-level emitter110. The fit coefficients are as follows: \( A = 1.31 \pm 0.03, \quad R = 0.48 \pm 0.01, \quad \tau_1 = 2.2 \pm 0.2 \) ns, \( \tau_2 = 8.8 \pm 0.3 \) ns, \( \tau_{21} = 22 \pm 6 \) ns. The best-fit value of \( g_0(t=0) = 0.17 \pm 0.03 \). Background-uncorrected data and additional details are given in Supplementary Note 7 and Supplementary Fig. 16.

**Data availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Code availability**

Coded used for the calculation of effective refractive index as a function of pillar diameter, the mapping to a discretized phase profile, and the generation of GDS layout files are available at https://github.com/pen-qml/metalens-fresnel. 

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Author contributions
T.-Y.H, R.R.G., S.A.M., A.R.K., and E.C.G. performed the design and simulations; R.R.G. and G.G.L. fabricated the metalenses; T.-Y.H., R.R.G., D.A.H., A.I.E., and L.C.B. performed the measurements and analysis. All authors contributed to writing the paper.

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