1. Baseline metalens design using a standard hyperbolic phase profile

For the sake of comparison with our work, a baseline metalens operating at 5.2 μm wavelength was designed with the same NA and input aperture size, as schematically illustrated in Figure S1a. As commonly configured, the baseline design uses a hyperbolic phase profile and position of the metasurface overlaps with that of the aperture stop. As shown in Figure S1b, such a design can effectively suppress spherical aberration with a Strehl ratio of unity at normal incidence. However, the Strehl ratio reduces below 0.8 as the AOI increases beyond ~ 7°, due to the exacerbated coma aberration.

![Figure S1.](image)

2. Design of the WFOV metalens

The commercial optical design software OpticStudio® (Zemax, LLC) was used to obtain the initial phase profile of the metasurface under ideal conditions. The rotationally symmetric phase profiles are expressed in a polynomial form:

\[
\phi(\rho) = \sum a_n \left(\frac{\rho}{R}\right)^{2n}
\]

where \(\phi(\rho)\) is the desired phase response of specific meta-atoms with \(\rho = \sqrt{x^2 + y^2}\), \(a_n\) are aspheric coefficients, and \(R\) is the normalization radius. During the design process, an initial phase profile and optical system structure were first laid out according to the targeted performance and optical system specifications. The phase profile is optimized using the damped least-squares method such that the Strehl ratios are larger than 0.8 across all field angles. The 2-D phase profile is then discretized spatially and into eight phase levels according to the meta-atom array arrangement and phase levels, respectively. Angular-dependent responses of each meta-atoms were subsequently incorporated to generate angular-dependent phase masks. Using these phase masks, the focusing performance of the metalens was re-evaluated under different AOIs using the Kirchhoff diffraction integral model, followed by iterative optimizations on the meta-optic system. The final phase profile (Figure S2) was optimized to achieve diffraction-limited focusing performance for continuously-varying incident angles up to ± 90°. Angular-dependent phase profiles (in the center 1-mm-diameter region) based on phase shifts of individual meta-atoms are shown in Figure S3.
Figure S2. Phase profile of the WFOV metalens at $y = 0$. The 2-D phase map is rotationally symmetric.

Figure S3. Angular-dependent phase profiles of the center 1-mm-diameter region of the WFOV metasurface.

Table S1. Dimensions of meta-atoms used in the meta-optical devices.

<table>
<thead>
<tr>
<th>Meta-atom number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_x$ ($L_{cd}$)</td>
<td>2.0 (0.6)</td>
<td>1.8 (0.6)</td>
<td>2.0 (0.7)</td>
<td>2</td>
<td>1.78</td>
<td>1.38</td>
<td>0.62</td>
<td>2</td>
</tr>
<tr>
<td>$L_y$ ($L_{yd}$)</td>
<td>1.7 (0.9)</td>
<td>1.9 (0.8)</td>
<td>1.6 (0.7)</td>
<td>0.78</td>
<td>0.7</td>
<td>0.66</td>
<td>0.52</td>
<td>1.26</td>
</tr>
</tbody>
</table>
Figure S4. Meta-atoms angular response for different linear polarization with oblique incidence at planes (a) y-z, (b) 45°-rotated between y-z and x-z, (c) x-z (TM-polarized). E-field y-component is equal to zero.

Figure S5. Modulation transfer functions (MTF) of the simulated focal spots under different angles of incidence.

3. Efficiency measurements

The power focused by a metalens $P_{\text{ms,foc}}(\theta)$ can be expressed in terms of $P_0$ total incident power transmitted through the frontside aperture (1 mm circular aperture), metalens focusing efficiency
\( f(\theta) \), and Fresnel transmittance factor \( T_p(\theta) \) accounting for reflection losses at the interface of air and CaF\(_2\):

\[
P_{ms,foc}(\theta) = P_0 \cdot T_p(\theta) \cdot f(\theta).
\]

The \( P_0 \) term can be further written as \( P_0 = P_{0i}(\theta) \cdot \cos(\theta) \), where \( P_{0i}(\theta) \) is the total incident power through the aperture at normal incidence (\( \theta = 0^\circ \)). The cosine factor comes in because when the same collimated laser beam (with a beam diameter much larger than the aperture size) incident obliquely on the sample, the power density drops by a factor of \( \cos(\theta) \) due to geometric projection.

In our experiments, we measured \( \eta(\theta) \) – the ratio of focused to total transmitted power by metalens, \( P_{ms,trans}(\theta) \) – power transmitted by metalens, and \( P_{ref}(\theta) \) – power transmitted through a reference sample (a CaF\(_2\) substrate with identical thickness and a 1 mm aperture but without the backside metasurface). By these definitions:

\[
\eta(\theta) = \frac{P_{ms,foc}(\theta)}{P_{ms,trans}(\theta)}
\]

\[
P_{ref}(\theta) = P_0 T_p^2(\theta) = P_0 (\theta) \cos(\theta) T_p^2(\theta)
\]

In Eq. 3, the \( T_p(\theta) \) factor is squared because there are two CaF\(_2\)-air interfaces with identical transmittance. Finally, the value of focusing efficiency \( f(\theta) \) is given by:

\[
f(\theta) = \frac{P_{ms,foc}(\theta)}{P_0 \cdot T_p(\theta)} = \frac{P_{ms,foc}(\theta) T_p(\theta)}{P_{ref}(\theta)}
\]

In the experiment, \( P_0, P_{ms,trans}(\theta) \), and \( P_{ref}(\theta) \) were straightforwardly measured using a large-area detector (S302, Thorlabs Inc.) to ensure that all transmitted power was captured. \( T_p(\theta) \) was then calculated from \( P_0 \) and \( P_{ref}(\theta) \) according to Eq. 3. To quantify \( P_{ms,foc}(\theta) \), we measured the transmitted power \( P_{hole}(\theta) \) incident upon a detector (PDA10PT, Thorlabs Inc.) integrated with a 200 \( \mu \)m diameter pin hole. We further used the InSb FPA camera to image the focal plane around the focal spot over a 200 \( \mu \)m diameter area. By integrating the optical intensity values pixel-by-pixel, we quantified the fraction of power concentrated at the focal spot over the total power transmitted through the pin hole, i.e. \( P_{ms,foc}(\theta)/P_{hole}(\theta) \). \( P_{ms,foc}(\theta) \) was extracted via \( P_{hole}(\theta) \times P_{ms,foc}(\theta)/P_{hole}(\theta) \). The reason we could not directly read out the focused power from the camera is that the FPA does not give optical power readings and instead only specifies relative optical intensity in counts.

![Figure S6. Experimental layout for measuring metalens focusing efficiency.](image-url)
4. NIR WFOV metalens design

The a-Si nano-posts have a uniform height of 750 nm, diameters ranging from 100 nm to 250 nm, and a fixed lattice constant of 450 nm. Full wave simulation results in Fig. S7a show that the design yields high transmittance for all eight meta-atoms, which together cover the full $2\pi$ phase space with a step of $\pi/4$ under normal incidence. The metasurface has an overall dimension of $6.4 \times 6.4 \text{ mm}^2$, containing $14,222 \times 14,222$ meta-atoms on a 3.9-mm-thick sapphire substrate. The metasurface is designed to have a constant focal length of 2.5 mm and an image plane dimension of approximately $5 \times 5 \text{ mm}^2$. A circular input aperture with a diameter of 1 mm is positioned on the front side of the substrate, corresponding to an effective NA of 0.2.

Figures S7b-d plot simulated transmittance and phase responses of the eight meta-atoms at different AOIs inside the substrate (corresponding to $0^\circ$ to $90^\circ$ AOIs in air). The results indicate that the phase responses of such high-index-contrast waveguide-type metatoms are almost completely independent of AOIs. The full-wave simulated meta-atom responses are incorporated in the metalens design presented in Fig. 6 in the main text.
Figures S7b-d further suggest minimal polarization dependence of the meta-atom design. Polarization diversity of the NIR WFOV metalens design is validated by evaluating the focal spot intensity distribution, Strehl ratio, and focusing efficiency for both TE and TM polarizations at oblique incidence (Fig. S8). Differences in optical responses for the two polarizations are negligible for all AOIs over the full 180° FOV.

Figure S8. Simulated metalens performance at different AOIs (in air): normalized optical intensity at the focal plane for (a) TE and (b) TM polarized light; Strehl ratio and focusing efficiency for (c) TE and (d) TM polarized light.

5. NIR WFOV metalens image simulation

The imaging performance of the NIR WFOV metalens operating at a wavelength of 940nm is evaluated using OpticStudio’s Image Simulation tool that evaluates diffraction, aberration and distortion effects, etc. of an imaging system. The object is mapped to the angular space (covering a horizontal FOV of 180° and a vertical FOV of 78°), equivalent to positioning the scene at an infinite distance away from the metalens. The source image contains 7,000 × 3,033 pixels, corresponding to a horizontal angular resolution of approximately 0.03°. This value is smaller than the diffraction-limited angular resolution of the WFOV metalens (~ 0.1°), and thus using the image as the scene offers adequate resolution to identify image blurring due to aberration or diffraction. During the simulation, the source image is convolved with a 2-D field-dependent point spread function (PSF) grid to generate the image at the image plane. Since our WFOV metalens readily provides diffraction-limited PSFs across the entire 180° FOV, it enables a high-quality image with minimum aberrations.