Single-shot three-dimensional imaging with a metasurface depth camera

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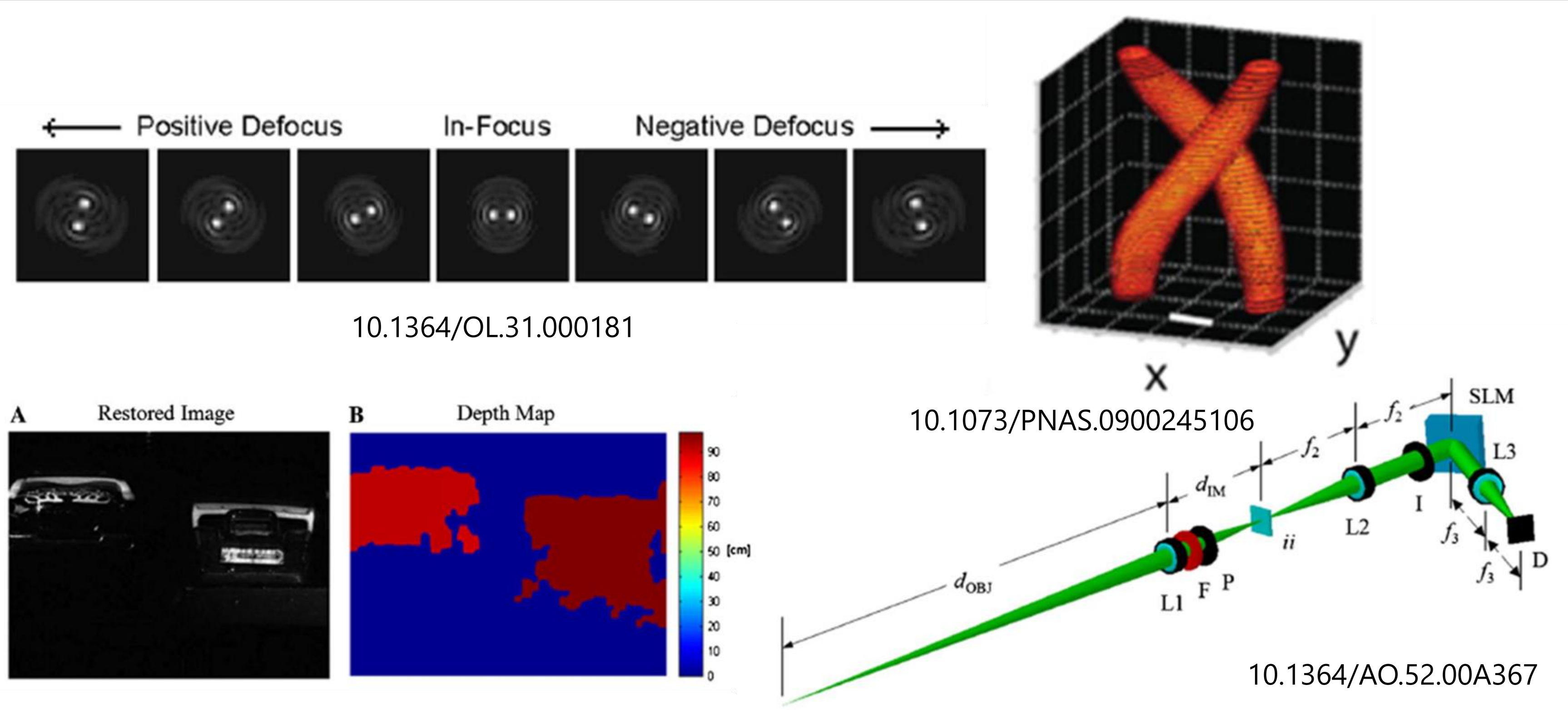
Abstract

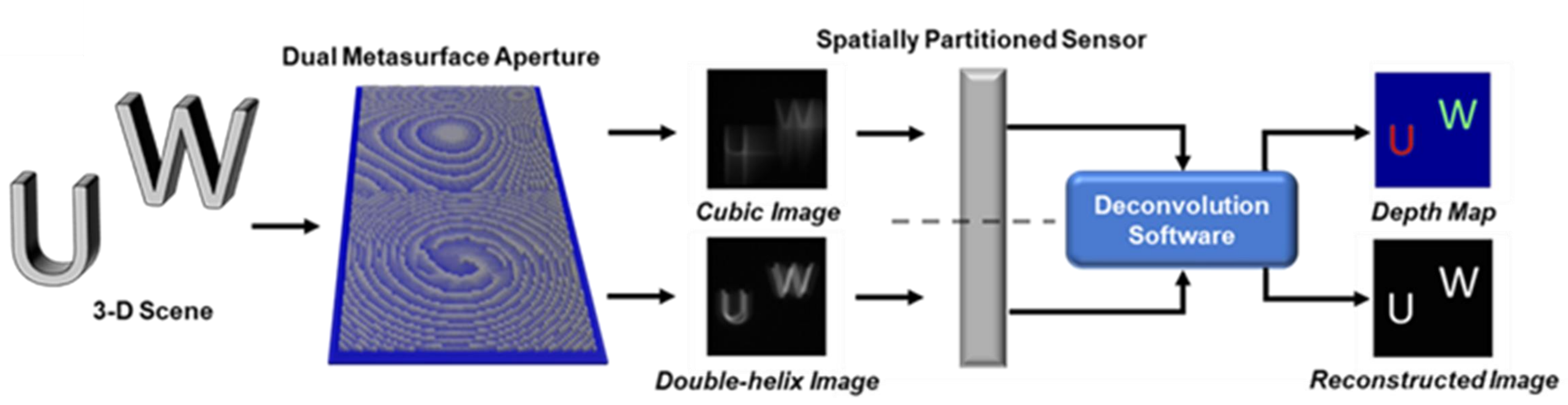
Imaging in three dimensions is vital for many emerging technologies with applications that demand compact and low-power systems beyond the capabilities of state-of-the-art depth cameras. Here, we exploit a single spatially multiplexed aperture of nano-scatterers to demonstrate a passive and compact solution that replicates the functionality of a high-performance depth camera typically comprising a spatial light modulator, polarizer, and multiple lenses. Our visible wavelength and polarization-insensitive metasurface simultaneously generates focused accelerating and rotating beams that utilize propagation-invariance to produce paired images with a single snapshot. We computationally recover a focused image coupled with a depth map achieving a fractional ranging error of 1.7% after accounting for the change in Gouy phase over the field of view.

Background



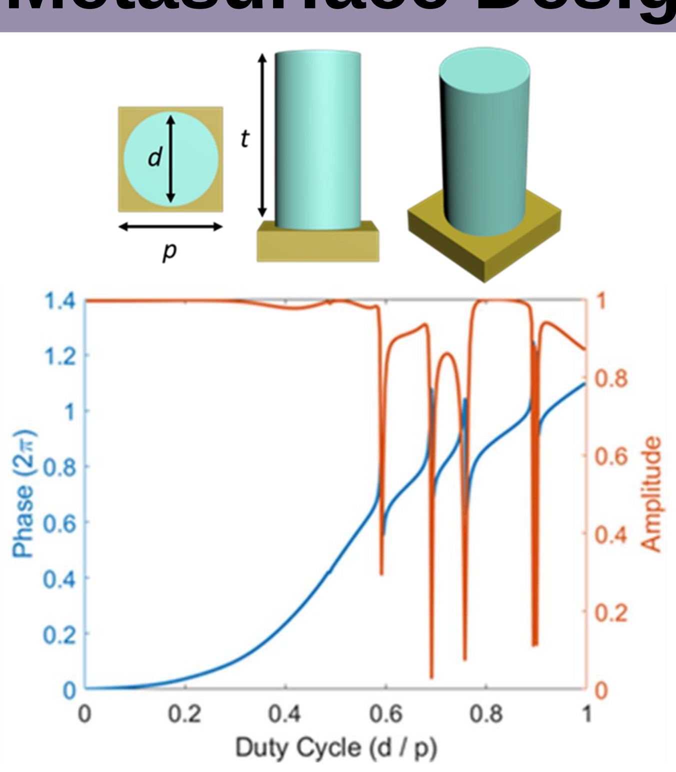
Double-helix optics are elements that instead of focusing to one point like a lens, they focus to two points that rotate continuously, tracing a double-helix pattern in space that enables very precise depth discrimination. These elements were recently used in a high precision depth imaging system; however, this system required numerous lenses and a bulky spatial light modulator to achieve its behavior.

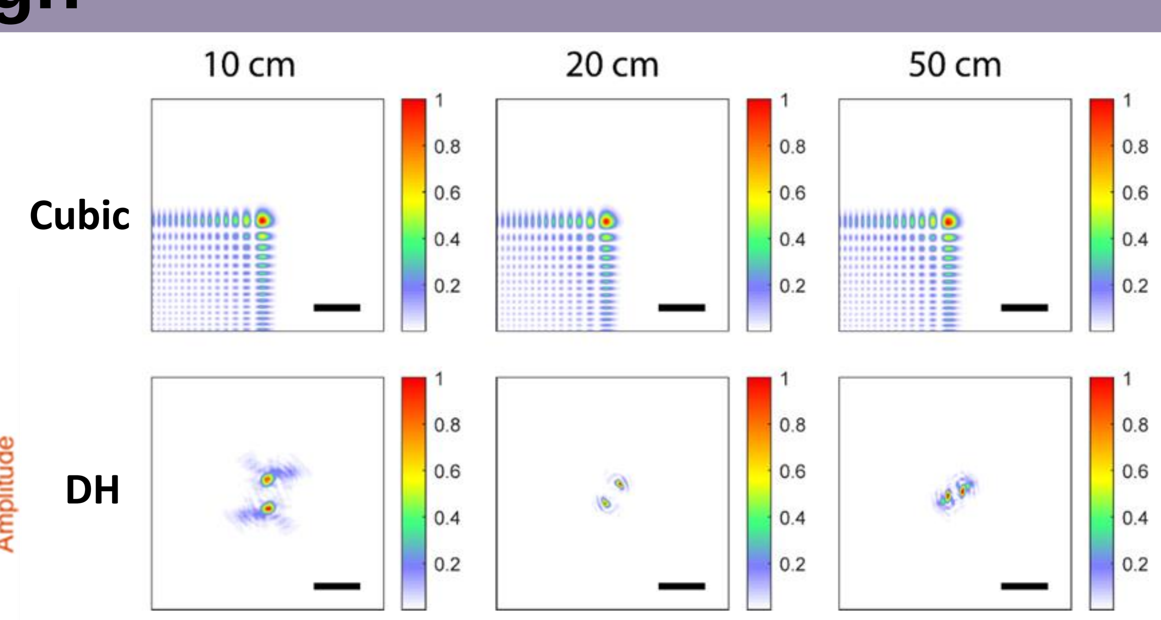
System Overview



We propose a system comprising a pair of complementary metasurfaces. The double-helix (DH) metasurface discriminates depths while the cubic metasurface enables capture of image data for reconstructing the scene over a wide depth of field. With a single snapshot, we use deconvolution software to reconstruct both the scene and corresponding depth map.

Metasurface Design





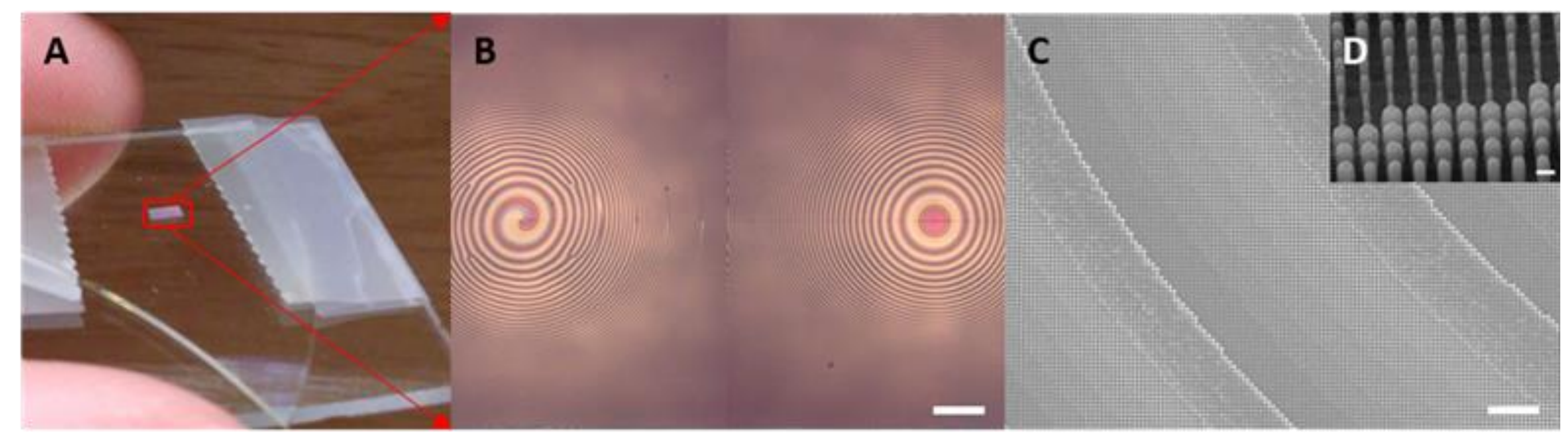
$\Phi = \Phi_{lens} + \Phi_{WC}$

$\Phi_{cubic} = \frac{\alpha}{L^3}(x^3 + y^3)$

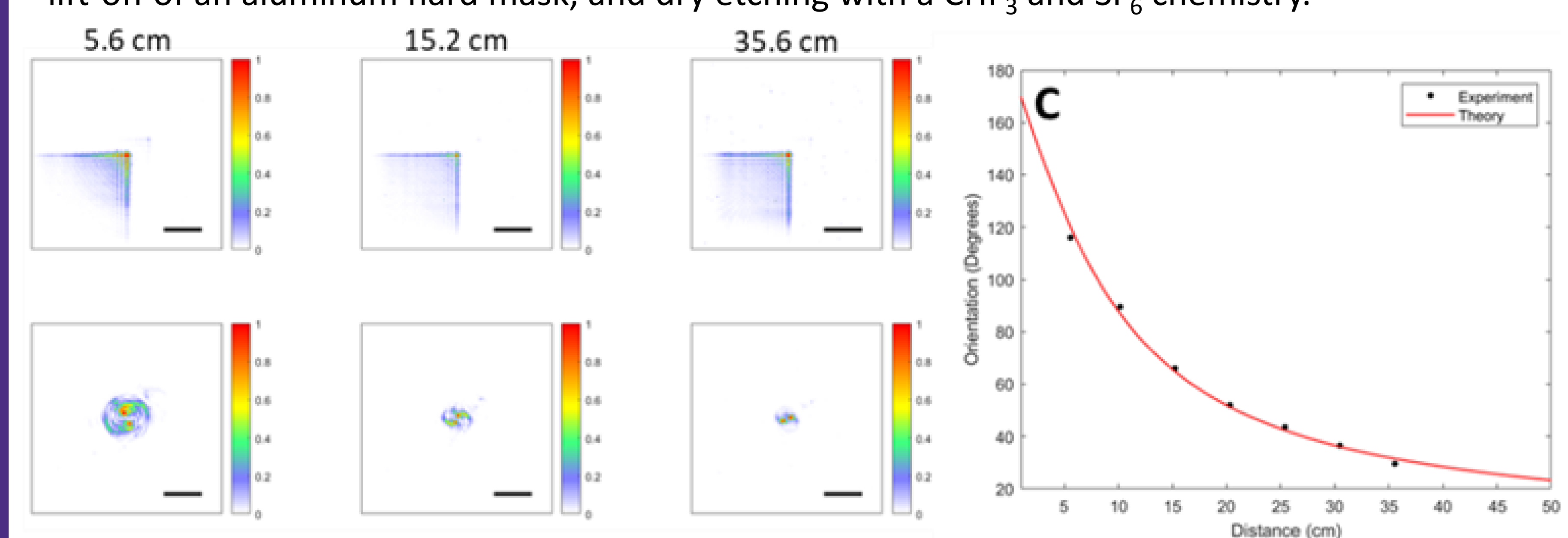
$\Phi_{lens} = \frac{2\pi}{\lambda}\left(f - \sqrt{x^2 + y^2 + f^2}\right)$

We simulate the phase and amplitude of the transmission coefficient of silicon nitride cylindrical nanoposts. We use this data as a lookup table to map desired phase shifts to diameters. With the known transmission coefficients and the desired phase functions, we simulate the point spread functions of the metasurfaces, demonstrating depth-invariance for the case of the cubic element and a strong depth sensitivity in terms of orientation angle for the DH metalens.

Fabrication and Experimental Validation

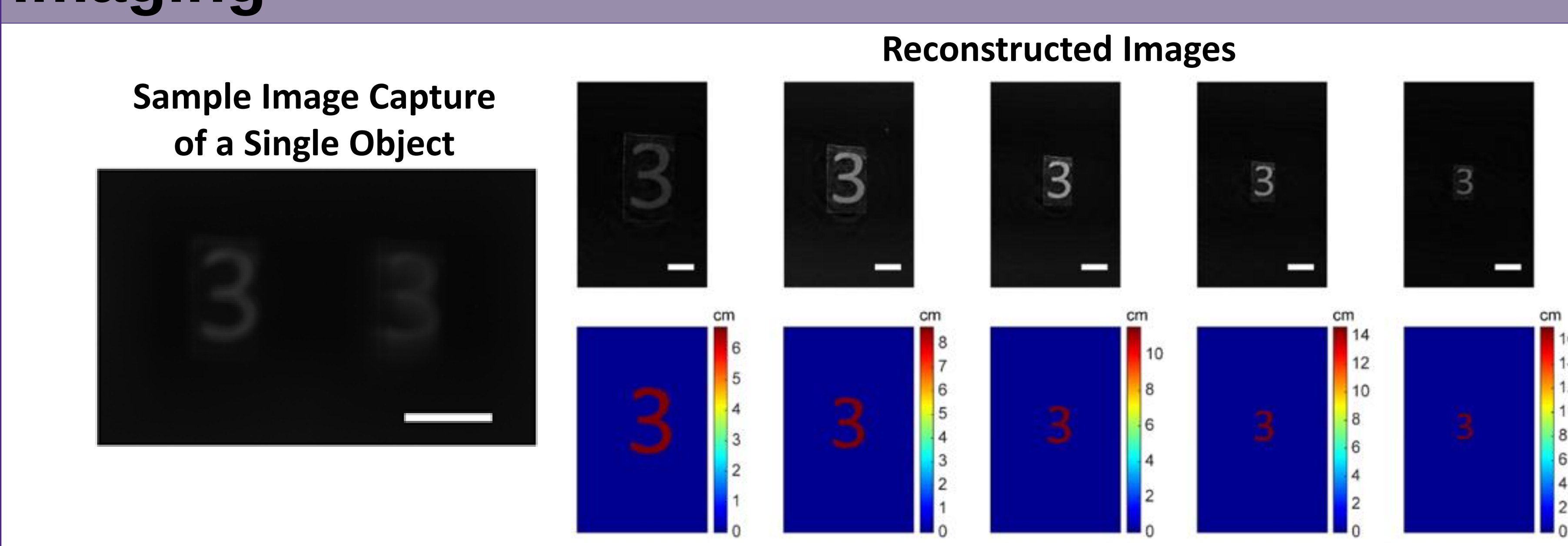


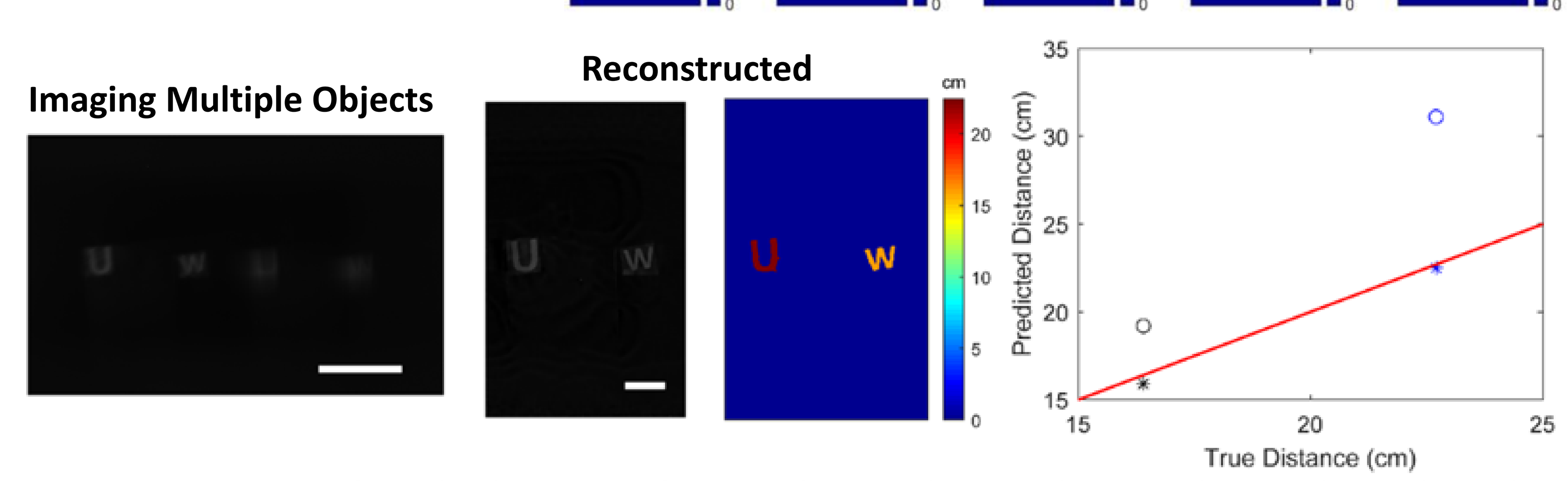
The metasurfaces were made using semiconductor microfabrication techniques at the Washington Nanofabrication Facility (WNF). The process consisted of electron-beam lithography, lift-off of an aluminum hard mask, and dry etching with a CHF_3 and SF_6 chemistry.



The experimental orientation angle of the DH metalens PSF agrees well with the theory.

Imaging





We capture images from both metasurfaces with a single snapshot. By deconvolving the cubic sub-image, we retrieve a focused scene image that paired with the double-helix sub-image enables calculation of a depth map. By accounting for the metalens' field curvature, we achieve a fractional ranging error of 1.7% and our predicted distances agree well with the true values.

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