Large-aperture Metasurfaces for Broadband, Incoherent Optical Edge Detection

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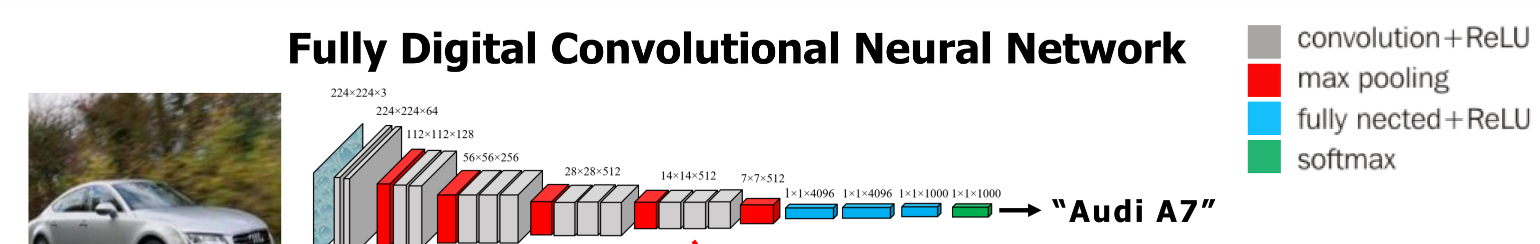
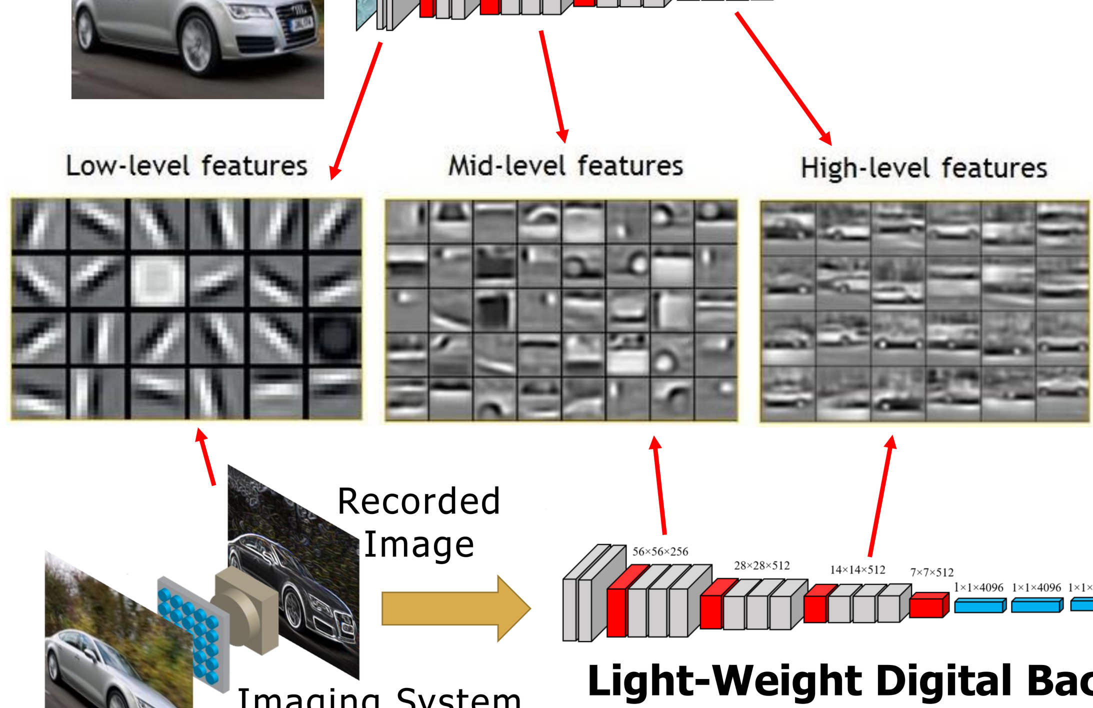
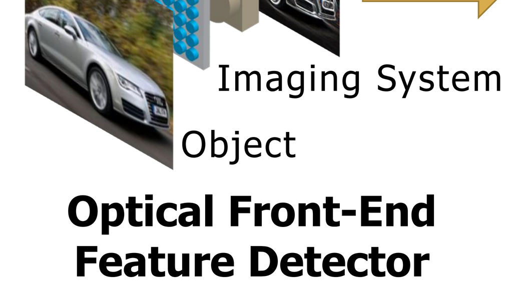
Motivation







Feature detection is a vital component in computer vision systems designed to interpret information in images.

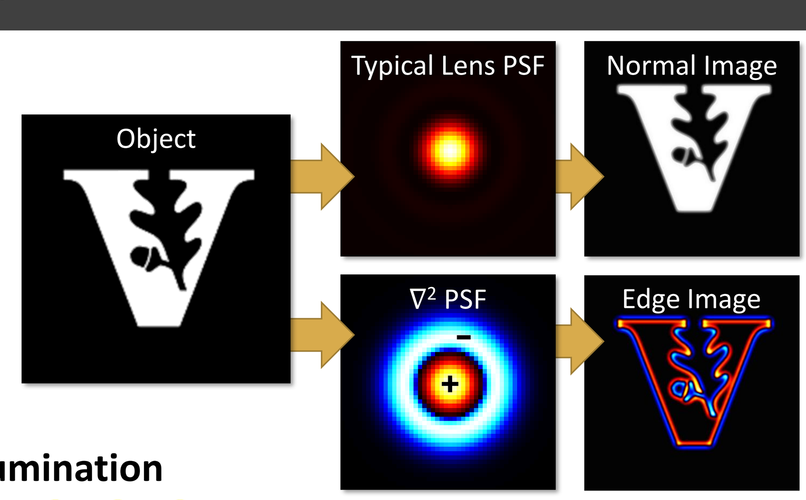
Digital computer vision systems typically require billions of floating-point operations per inference.

An analog optical feature detector could offload some computations from the digital backend, reducing the latency and power consumption of the computer vision system.[1]

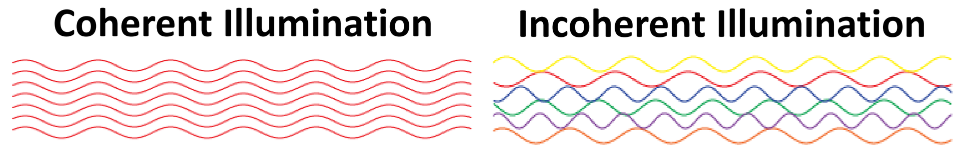
Optical Edge Detection

We demonstrate edge detection as an example of optical feature detection.

Optical edge detection is achieved by engineering the point spread function (PSF) of an optical system.



Coherent Illumination | **Incoherent Illumination**



Linear with respect to light fields

$E_{out} = E_{in} * PSF$

Coherent Point Spread Function

Linear with respect to light intensity

$I_{out} = I_{in} * PSF_{ic}$

$PSF_{ic} = |PSF|^2$

Incoherent Point Spread Function (Always positive)

Point spread functions for edge detection, such as the Laplacian PSF (above), always have positive and negative values.[2]

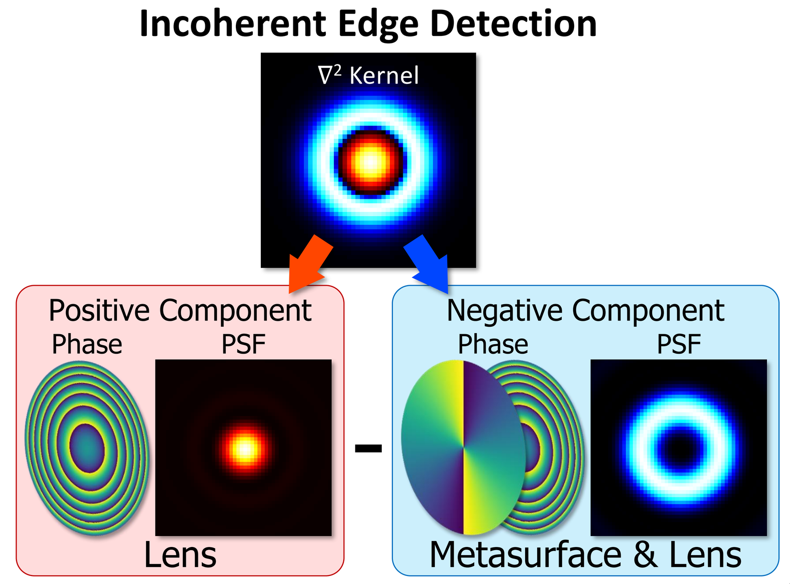
Most previous demonstrations of optical edge detection have only worked for coherent illumination[3]; however, most real-world light sources are incoherent.

Incoherent optical edge detection is less straightforward, because incoherent PSFs are always positive.[4]

To achieve a bipolar PSF for edge detection, the PSF must be decomposed into positive and negative components, which can be imaged separately and digitally subtracted.

The positive component of a Laplacian PSF can be formed with a refractive lens, while the negative component can be shaped by adding a specially designed metasurface.

Two PSF, Optoelectronic Solution for Incoherent Edge Detection

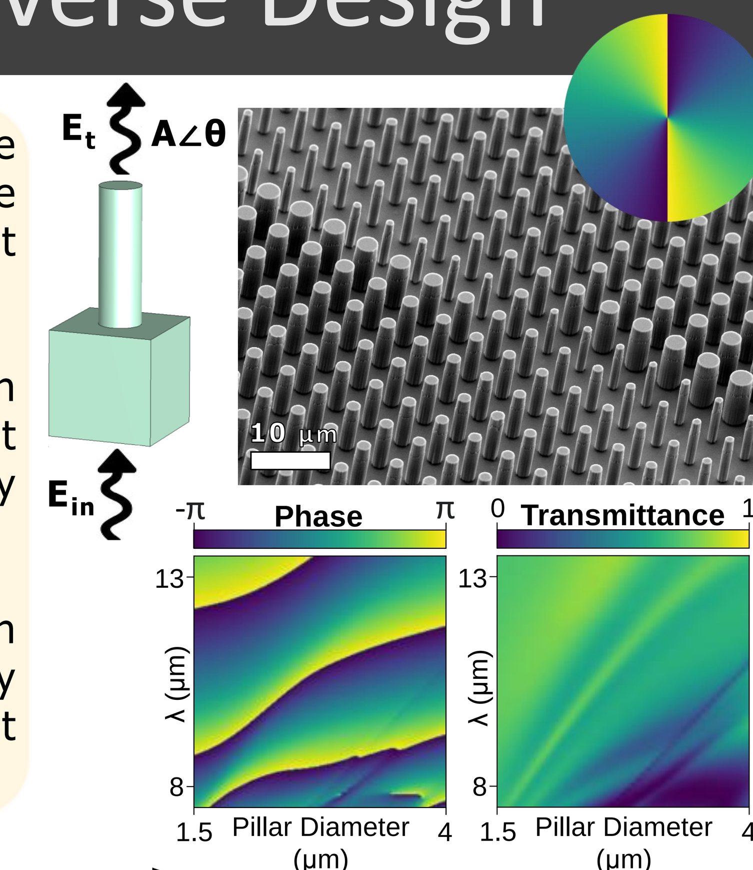


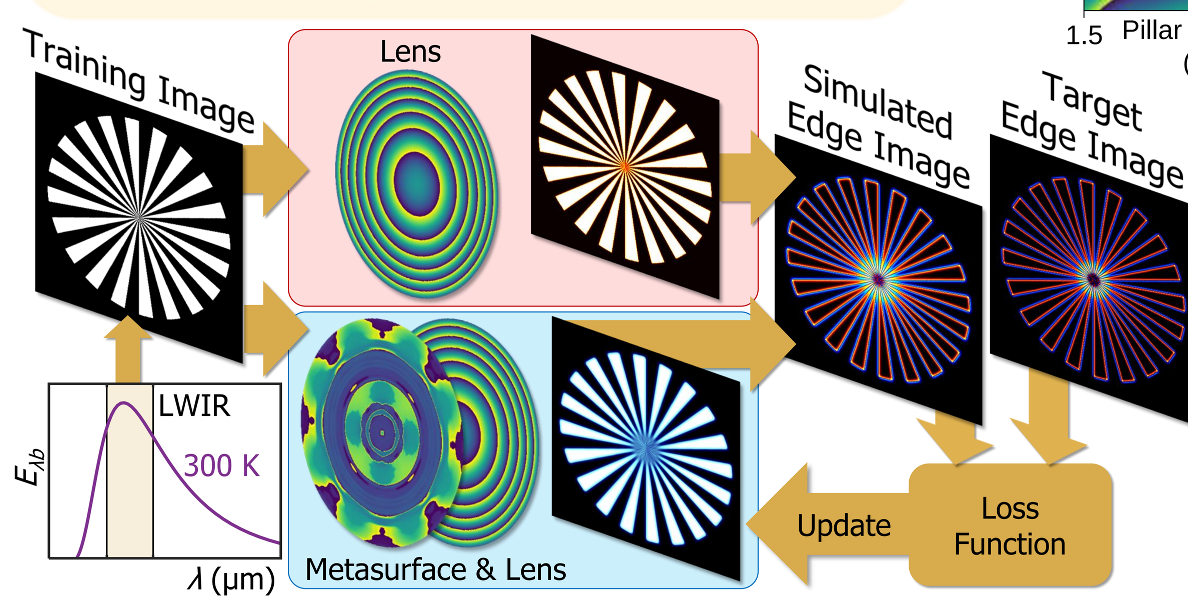
Metasurface Inverse Design

Metasurfaces are flat optics that use subwavelength scatterers to modulate the phase, amplitude, and/or polarization of light waves.

We designed metasurfaces for edge detection in the long-wave infrared using non-resonant phase propagation meta-atoms, with spatially varying geometry.

The geometry of 17.6 million meta-atoms within a 23.7 mm aperture was simultaneously designed using an efficient, gradient-descent based inverse design algorithm.

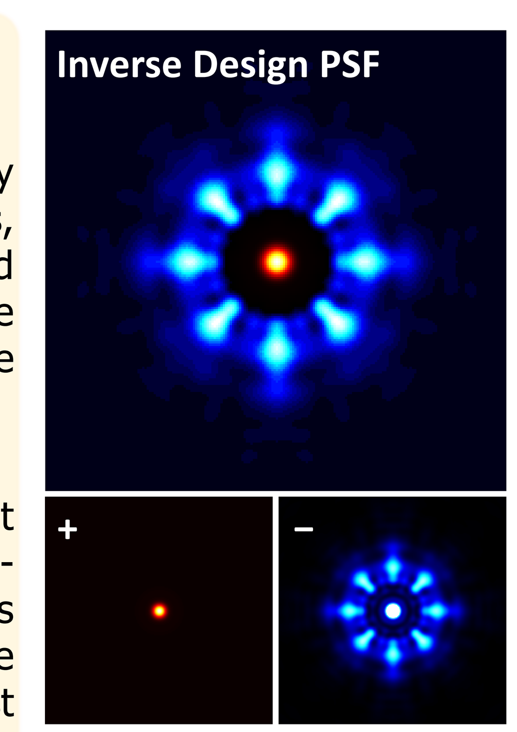




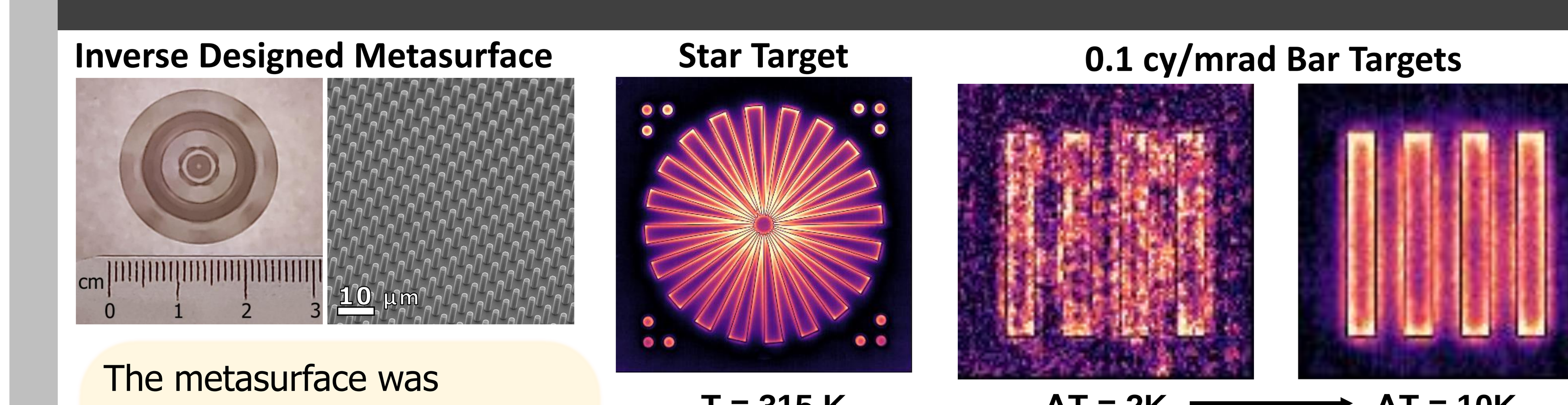
The inverse design involved iteratively updating the meta-atom geometries to decrease the error between a simulated and target edge image and maximum the simulated edge signal.

Design Features

- Broadband
  The refractive lens in the optical system enables naturally broadband focusing. Using non-resonant meta-atoms, simulating broadband illumination during inverse design, and rewarding solutions with more gradual metasurface phase changes facilitated a design that works across the entire LWIR imaging band (7.5 – 13.5 μm).
- High Signal-to-Noise Ratio
  Digital subtraction of similar images normally reduces net signal while magnifying noise. Our approach prioritizes signal-to-noise ratio during inverse design, which results in solutions with maximum separation between positive and negative component PSFs, which minimizes unnecessary signal lost during digital subtraction.



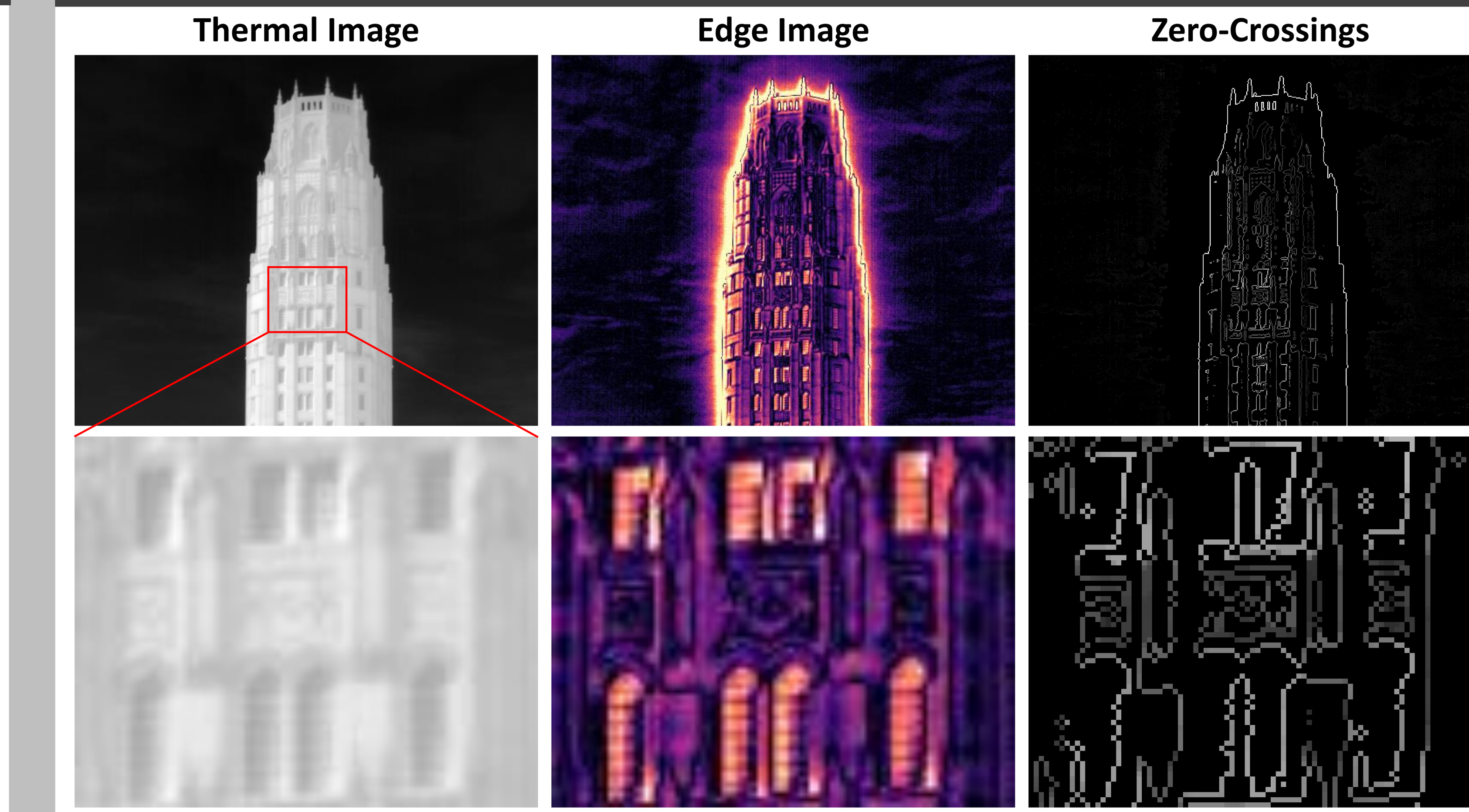
Lab Characterization



The metasurface was fabricated in VINSE by first using photolithography and liftoff to pattern an Al_2O_3 etch mask, then using reactive ion etching to etch pillars directly into a silicon substrate.

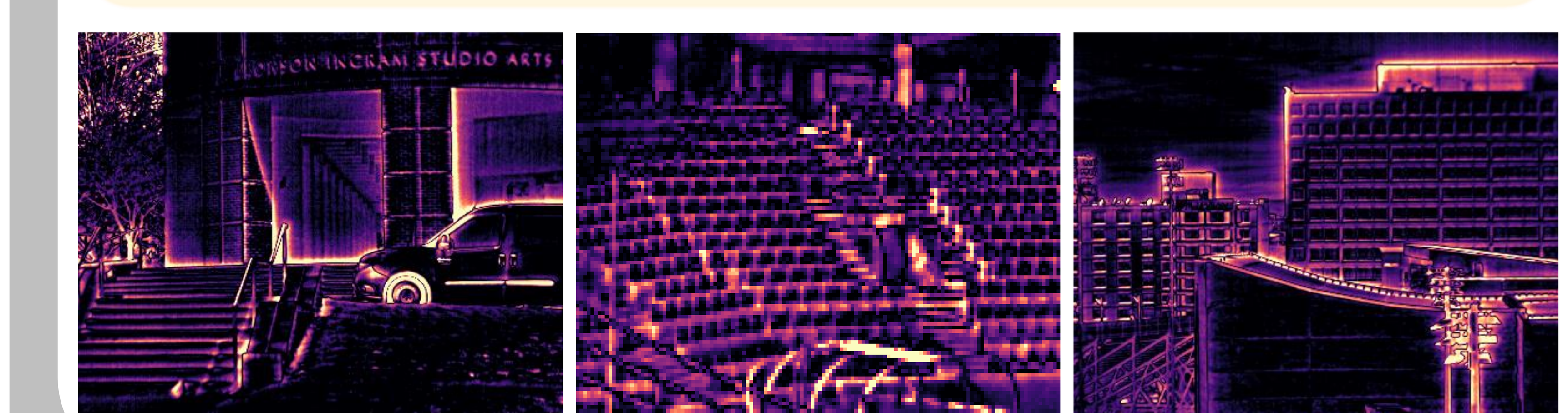
Edge detection was characterized by imaging blackbody star targets and bar targets. Edge detection is shown for spatial frequencies up to 0.1 cy/mrad, and temperature differences as low at 2 K.

Real World Imaging

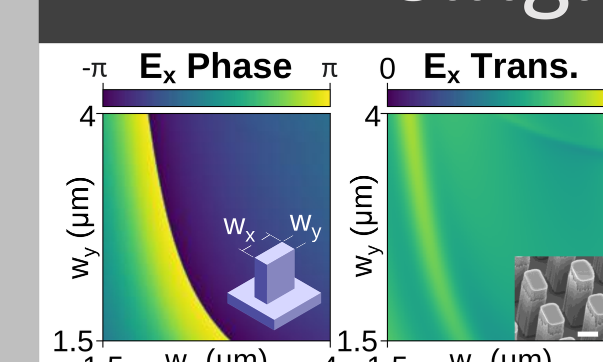


We demonstrated practical edge detection in real world conditions by imaging buildings around the Vanderbilt campus. The above edge image of the West End Tower shows a prominently highlighted outline of the tower.

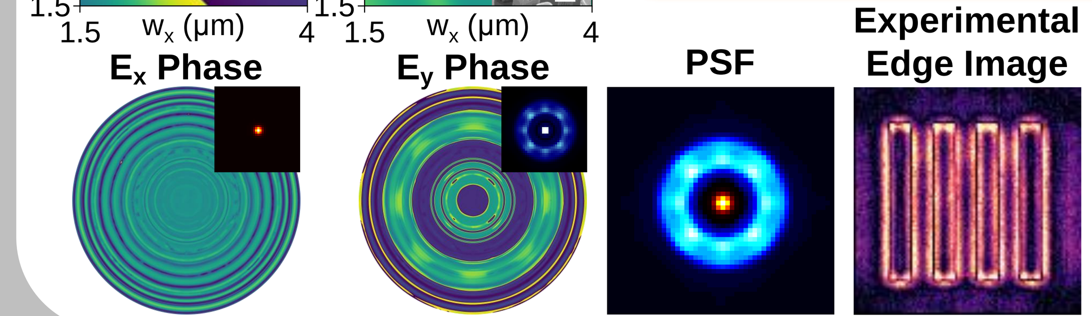
For very small features below the limit for edge detection, our system acts as a high-pass filter, increasing contrast by removing low-frequency background.



Single Aperture Design



We have also designed and fabricated a single aperture optical edge detector, capable of simultaneously capturing both positive and negative component images using birefringent metasurfaces for polarization multiplexing.



With a commercially available polarimetric camera, this could allow for optical edge detection in real time, without the need for complex alignment.

References & Acknowledgements

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