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Design and Characterization of Multifunctional Thermal Meta-Optics

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Abstract

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Miniaturization of optical components, namely, lenses for high-quality cameras are ubiquitous in today's world. The phone cameras which we carry around in our pocket consist of a series of lenses that are governed by the same principles of optics that were known centuries ago. The capability to shrink optical components for integration in larger, complex assemblies is of great importance for size, weight and power (SWaP)-constrained applications. The oldest category of optical lenses, refractive lenses, can be limiting in modern technology due to their volume. On the other hand, diffractive optics have found great success particularly with added control and tunability for light propagation. The micro- or nanostructure array that comprise a recently established type of diffractive optical element are known as meta-optics. In particular, for applications where reduced bulk is important, metasurfaces are a promising solution given their ultrathin form-factor and fabrication process flows which may be compatible with semiconductor

foundry techniques. The individual meta-atoms that comprise a metasurface have sub-wavelength periodicity. Through designing the optical response of each meta-atom unit, a metasurface can be designed with a specific phase, amplitude, and polarization which is not constrained by the aperture size. For the infrared wavelength bands, SWaP considerations become more stringent as the optics scale with the wavelength.¹ In this dissertation, we examine the effects of broadband imaging in a computational imaging system across the MWIR band and show the performance by a single-wavelength hyperboloid metalens. We also demonstrate the fabrication capabilities of centimeter-scale meta-optics with metasurfaces designed with unique approaches including synthetic apertures and Fresnel zone phases. The effect of photolithography fabrication for polarization-dependent meta-optics is also demonstrated towards the end of depth estimation imaging. These applications present the unique potential of metasurfaces to replace traditional lens counterparts in applications focused in the infrared bandwidths including imaging, sensing, and spectroscopy.

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DEDICATION

To my family, near and far

Chapter 1. Introduction

1.1 Motivation

The study of optics is split into fields of successive rings by operating assumptions that generally trend with the size of the optical component. Geometrical optics follows principles of ray-tracing and Snell's law of reflection and refraction.² An example of refractive optics is a plano-convex lens. The lens perimeter is defined by a radius of curvature and incident light passes through the optical lens in straight lines (rays) determined by the relative effective indices of the system.

The material library, manufacture and production, and implementation of refractive optics is an ubiquitous area for technology. In the 18th century, Augustin-Jean Fresnel invented the Fresnel lens. This ultra-large refractive optic was put into lighthouses to guide ships at far distances and his invention was enabled by modifying the radius of curvature into discrete zones. Through a concentric lens profile with curved grooves that refract light in combination, Fresnel removed bulk material from the lens alleviating the physical weight required for optics on the order of meters in size.

When an optical component is very small, or the wavelength of operation is comparable to the aperture size, scalar refractive theory becomes insufficient. As early as the 1600's Francesco Grimaldi described the principle of diffraction to be any deviation from the rectilinear propagation of light rays. In contrast to geometrical rays, diffraction models light as a complex wave where each point on the wavefront is treated as an origin for secondary waves. The Huygen-Fresnel theory demonstrates how a propagating wave shows similar characteristics to interference, particularly when apertures are small or boundaries are sharp and diffraction becomes apparent. In this dissertation, the devices considered are diffractive optics which are comprised with sub-wavelength-spaced elements known as meta-atoms or scatterers.

1.2 Meta-Optics

What happens when periodic structures are placed in distances on the order of wavelength of light? For a normally incident plane wave, diffraction theory predicts that all light is propagated to the 0th mode. In reality, a perfectly normal wave is impossible to achieve, but such structures end up being highly efficient. Meta-optics are a type of diffractive optic where the structural periodicity is smaller than the operating wavelength.³ The structures, known as meta-atoms, function as the discrete zones to modulate light. By changing the individual meta-atom geometry, the effective index can be engineered to control the phase delay. The global arrangement of the metasurface causes a global transformation that can be engineered in amplitude, phase, and polarization.

In refractive optics, phase is based solely on material index and the radius of curvature. The optics are bulky and can be difficult to manufacture, particularly with curved grooves like in blazed and surface-relief gratings. However, refractive lenses can be completely aberration-free. Diffraction has a theoretical resolution limit that is always limited by aberrations and extent of phase diversity expressed through group delay and group delay dispersion.⁴ There is a level of engineered control available to metasurfaces, however, that is amenable for optical design. Methods of metasurface design allow for solutions in dispersion and phase engineering, and computational imaging techniques. In particular, PSF engineering, multifunctional encoders, and passive polarization control to name a few.⁵⁻⁷ Aberration-free refractive optics can stack into achromats with high visual acuity, yet are constrained by physical limitations in speed and volume of the refractive media.^{8,9}

1.3 Thesis Outline

In my time in Arka's group, I've had the privilege to work on many different projects related to meta-optics and other photonic devices. In particular, I focused the bulk of my work for devices designed in the MWIR and LWIR bandwidths. Following the meta-optics research community across the past 5 years or so, the majority of the work has been applied to the visible range. However, there is an increasing interest to investigate ultra-thin optics for free-space optical communication (MWIR) and long-range chemical sensing (LWIR). I believe one of my main contributions to the meta-optics community is a detailed investigation in the design process for the IR bandwidths, as the established research methods were first developed for visible applications. I hope that this dissertation may be useful for those who are entering the maturing field of meta-optics towards the advancement of higher efficiency and robust metasurface systems. The structure of my dissertation is as follows. In Chapter 1, I present an introduction to meta-optics as a category of diffractive optics. In Chapter 2, I provide a general overview to metasurfaces specifically designed for infrared bandwidths before moving onto specific applications. In Chapter 3, I provide a detailed comparison for an inverse-designed meta-optic against a hyperboloid lens to understand the imaging performance achievable in the MWIR for broadband imaging. In Chapters 4 and 5, I showcase two interesting applications that capitalize on the design tunability of the metasurface phase profile. In particular, I focus on the meta-optic fabrication and characterization from the techniques outlined in the Introduction, discussing the unique fabrication challenges that exist for polarization sensitive optics in the infrared bandwidths. Finally, in Chapter 6, I close with a summary and concluding remarks on possible directions for thermal metasurfaces in the future.

Chapter 2. Metasurface Background

2.1 MWIR and LWIR Metasurfaces

For over the past fifteen years or so, meta-optics have been researched under the scope of transmitarrays, flat lenses, and diffractive optics.^{10–12} Community understanding of light propagation with optical components on the length scale near the order of design wavelength showed how abrupt phase discontinuities, from meta-atom to meta-atom, can be described through the derivative of phase along the optical path.¹³ Because of the periodic structure from an array of meta-atom scatterers, there is a constant phase gradient that can still be approximated through Snell’s generalized law of refraction, $\sin(\theta_t) n_t - \sin(\theta_i) n_i = \frac{\lambda_o}{2\pi} \frac{d\Phi}{dx}$. However, because the phase gradient brought on by the meta-atom array is not continuous, the discrete periodicity can be engineered through adjusting the scatterer geometry, thus changing the phase discontinuity brought about by the boundary of each meta-atom in full $0 - 2\pi$ phase shift of an incident wavefront through anomalous refraction that gives rise to a spatially varying wavefront, or diffraction orders. For meta-optics in particular, these optics are defined when the periodicity of meta-atoms is smaller than the operating wavelength. While metasurfaces were first investigated with radio-wave frequencies, meta-optics that perform operations of lensing and focusing light quickly followed in the visible wavelength range.^{14,15} Correspondingly, because of the considerable size and weight reduction in a single metalens, the community investigated how to design meta-optics for full-color imaging across the entire visible bandwidth. Colburn et al. demonstrated one of the first full-color imaging techniques with a single meta-optic, by adjusting the phase profile to have an elongated focal line, as opposed to a single focal spot along the optical axis.¹⁶ This approach is paired with inverse-design, where the desired metalens is optimized through computational algorithms by a figure of merit at the outset, and the designer iterately compares the metalens performance of the optimized result.^{17–19} The inverse-design

technique was expanded to include an end-to-end approach to further increase the quality of metasurface imaging, where the image produced by a metasurface acts as an intermediary for an enhanced, reconstructed final image through a co-optimized metasurface and computational backend optical system.^{20–22} While community research has been primarily in the visible band, there is great interest in thermal imaging in the MWIR and LWIR atmospheric windows, particularly in applications of night vision, remote sensing, and atmospheric long-range imaging.^{22–24}

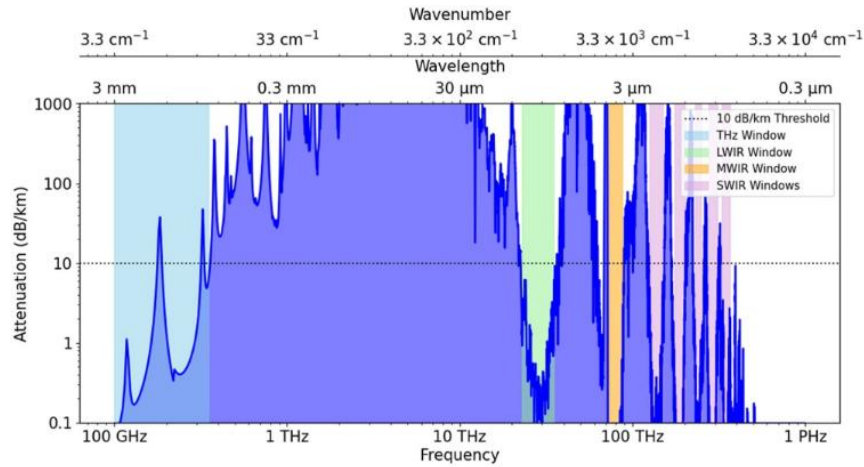


Figure 2.1 Transmission windows in the infrared wavelength regions. MWIR and LWIR are known as atmospheric windows.²⁵

In some sense, the operating bandwidth guides metasurface design. Recent demonstrations in meta-optics show diffraction-limited single wavelength lenses, polychromatic lenses with extended depth of focus, and broadband lenses across the visible band jointly designed with computational enhancement. In the infrared region, there are three bands of interest: short-wave infrared (SWIR), mid-wave infrared (MWIR), and long-wave infrared (LWIR). In the MWIR and LWIR ranges specifically, application interests include night vision, remote sensing, and long-range and multi-modal imaging.^{26–28} One reason for the interest in these bandwidths is

because they are known as atmospheric windows, where the light transmission is very high and thus signals can be propagated with high efficiency.^{29,30}

2.2 Design and Simulation

Towards the challenge of broadband imaging in thermal wavelengths, an optics designer must consider the nuances across wavelength bands and where the material, resolution, and size constraints can have the largest impact. The MWIR sits between the visible, with ubiquitous resolution and application interest, and the LWIR where pixel sizes and resolution targets are even larger.^{31,32} Limits between bandwidth and resolution have been established in the literature.^{21,33,34} For instance, a large, 1 cm aperture has been summarily investigated by our group's previous work in the visible, where a trade-off between numerical aperture and resolution was investigated through inverse-design methods.²¹ In the topic space of full-color imaging (visible) or analogous broadband imaging (infrared), there are two main solution methods that are routinely adopted in the meta-optics community. The first approach looks to engineer and modify the meta-atom geometry in both position and orientation through an approach known as dispersion engineering that focuses on tuning the group delay parameter. Developed by the Faraon group at Caltech, this method showed how the focusing operations of metasurfaces that are dispersion engineered with specific group delay parameters can yield different values of chromaticity beyond the traditional $1/F$ limit as described in their text.³

The second approach, pioneered by the Majumdar group at the University of Washington for imaging meta-optics uses an approach that seeks to modify the optical response of the metasurface into a computationally interpretable intermediary that is co-optimized with a software backend for image post-processing across a wide field of input parameters, namely

wavelengths for broadband imaging.²⁰ First demonstrated by Colburn et al. investigated a PSF-engineering approach with an extended depth of focus (EDOF) lens, an insight to the inverse-design method shows that the PSF that is slowly varying across the bandwidth of interest tends to perform best with the subsequent learned reconstruction.³⁵ This type of approach with gradient-descent optimization or adjoint method schemes have been widely used in the meta-optics community for achromatic metasurfaces in the visible. Additionally, Huang et al. showcased a MTF-engineered approach that selected the Strehl ratio parameter as a figure of merit for the optimization process of a broadband metasurface across the LWIR band.³¹ In this study, the MTF-engineered (inverse design) metasurface achieved a higher theoretical Strehl ratio over a hyperboloid counterpart with equal NA, a lens profile that is known to be the diffraction-limited solution for forward design diffractive optical elements. In experiment, the comparison of wavelength-averaged Strehl ratio across a considered bandwidth correlated with the broadband imaging performance quantified by experimental MTF contrast. This approach used a custom, Python-based module for the RCWA and optimization method powered by a deep neural network to efficiently model effective aperture sizes in the millimeter and centimeter scale.

What is the best method for designing broadband imaging optics? Another statement can be worded as, is there an efficient method towards designing a broadband imaging system that involves a forward design solution? One potential disadvantage towards inverse design methods is that the optimized solution is a blackbox insofar as the physical reasoning towards the converged result is not known or guaranteed. On the flip side, optical designers prior to AI-integrated design relied on heuristic, numerical, or analytic solutions developed from intuition or the assumptions in the limits of optics and physical theory. The project that follows considers the application of broadband imaging in the MWIR ($3 - 5 \mu\text{m}$), directly compares the inverse and

forward design solutions with matched NA through established optimization schemes previously reported in the literature, and presents a new approach for broadband imaging with a paired software reconstruction model that relies on minimal training data. A signature feature of meta-optics is chromatic aberration that arises from phase wrapping discontinuities. Because of the $1/\lambda$ dependence with focus for a traditional meta-optic, in some ways one process that an inverse-design method seeks to address is an effective way to redistribute spatial frequency content across a wavelength region. Through MTF-engineering, this can be clearly seen as the number of discrete wavelengths for optimization are increased. An analysis of an optimized phase profile shows the relationship between amplitude intensity at the focal plane and bandwidth. For an ideal broadband optic, the focal intensity across the bandwidth of interest shows a step function response with high, constant amplitude. In our study, we directly compare this relationship between a forward design (hyperboloid) and inverse design (MTF-engineered), in the future referred as “forward design” and “inverse design”. The key figure of merit for comparison is the volumetric MTF, that is the integrated MTF area calculated across a wavelength bandwidth.

In either case, a few parameters need to be selected from the outset for the meta-optic design including the focal length, diameter, and operating wavelength. The hyperboloid metalens is an example of the global phase profile which determines the shape of the modulated wavefront and thus the focusing by the equation,

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

Where λ is the operating wavelength and f is the focal length. Forward design also includes other types of phase mask profiles including cubic, aspheric, or quadratic functions.

By engineering the individual meta-atoms themselves with a specific phase, amplitude or polarization delay, a metalens can be designed directly by its phase mask. This simulation is typically run with an rigorous coupled wave analysis (RCWA) method or with the gold standard finite-difference time domain method. In our group, we typically use the S4 Python package for RCWA and Lumerical FDTD or Tidy3D.³⁶

Additionally, there are other methods to optimize the metasurface phase profile such as with Zemax. There are several application examples now for metasurfaces and other diffractive optics that are available directly on the Ansys website. A metasurface in Zemax is modelled by a Binary 2 surface which represents the phase change of incident light across the lens surface. This phase change follows the formula,

$$\Phi = M \sum_{i=1}^N A_i \rho^{2i}$$

Where A_i are the even phase coefficients and ρ is the coordinate position term.³⁷

First, an phase mask from Zemax can be optimized based on the formula above based on a figure of merit such as the RMS spot radius.

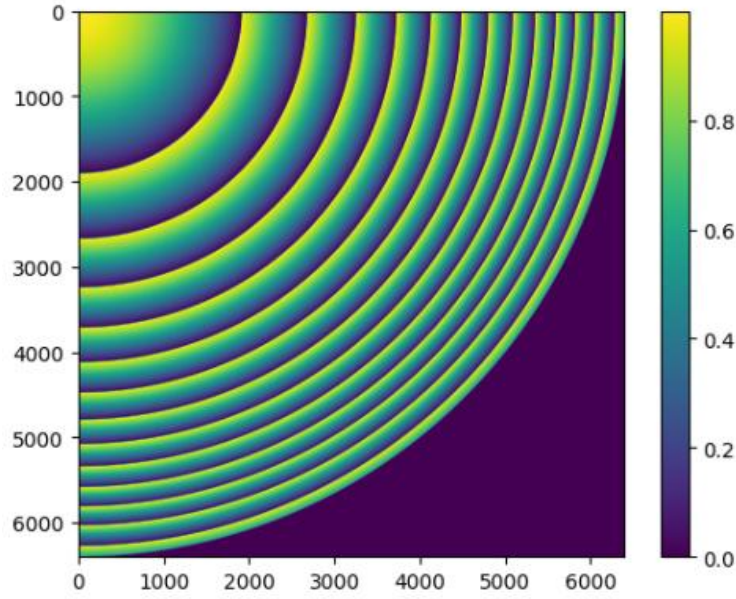


Figure 2.2 Zemax-optimized phase mask of a metalens. Shown is a quarter slice of the phase profile for a 12 mm diameter lens. Due to circular symmetry, the profile can be repeated to model the complete aperture.

To comprise the metasurface, a set of scatterers is determined with rigorous coupled wave analysis (RCWA) that considers a device stack of all-Silicon square pillars with a $2.5\ \mu\text{m}$ periodicity, $6.6\ \mu\text{m}$ height at a $10\ \mu\text{m}$ operating wavelength. The transmission response of the scatterers is also shown in blue.

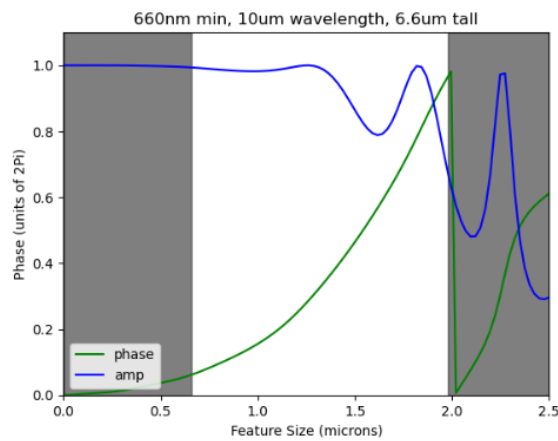


Figure 2.3 Transmission and phase response of scatterers designed for the LWIR at $\lambda = 10.0\ \mu\text{m}$ with a constant $2.5\ \mu\text{m}$ periodicity and $6.6\ \mu\text{m}$ pillar height.

From the calculated transmission response, a set of discrete scatterers are determined to streamline the fabrication process. The minimum feature size in the design is 660 nm, and the scatterers are selected to achieve a full $0-2\pi$ phase shift.

Typically, to evaluate inverse-designed or optimized metalens profiles, a hyperboloid metalens is designed to match the wavelength, focal length, and NA of the optimized meta-optic. From the generated phase masks, these profiles are converted into arrays of subwavelength scatterers to generate GDS files for fabrication. The GDS files are generated by the GDSII Tool Kit (Gdstk), a Python-based module. Then, the metasurface patterns are fabricated with direct laser writing as discussed in the next section.

2.3 Fabrication

There are two main methods for metasurface fabrication at the Washington Nanofabrication Facility (WNF). The first method is with electron-beam lithography (EBL) which offers the highest resolution quality. While it is expensive and it demands a slow writing speed, the exposure quality can achieve down to 10's of nm resolution. One detail to keep in note, however, is that this effectively limits the maximum aperture size that is feasible to write in a shared user facility. The maximum write area for our metasurfaces is typically around $1 - 2 \text{ cm}^2$. In order to fabricate larger apertures, laser-based photolithography is used at the expense of a maximum resolution quality in the several hundreds of nanometers. Our method for fabricating MWIR and LWIR metasurfaces is through direct laser writing. In this introduction example, the smallest spacing between pillars is 520 nm, with an aspect ratio of 1:10 (6.6 μm height and 660 nm minimum feature size). The design wavelength is 10 μm and the unit cell periodicity is 2.5 μm . The square pillar features range between 660 nm to 2 μm in width.

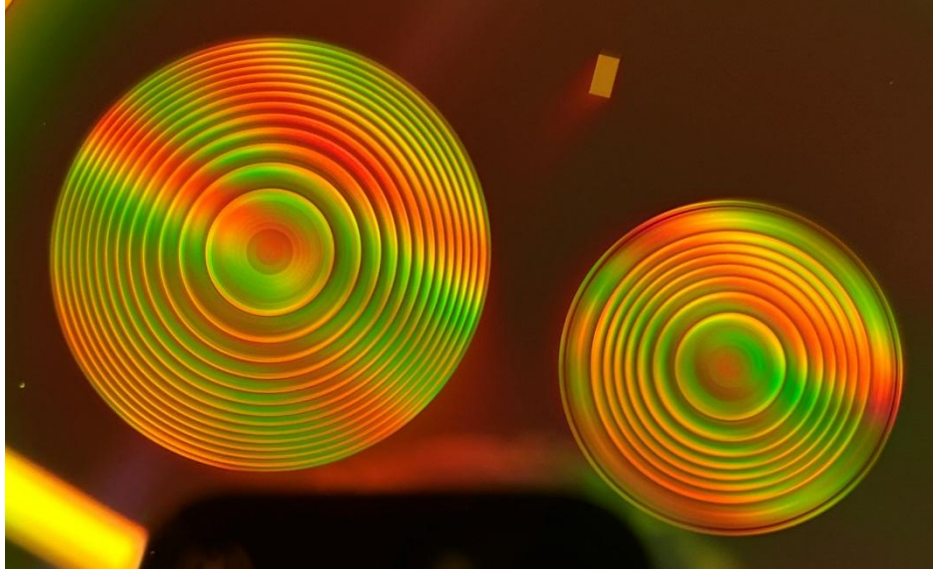


Figure 2.4 Camera image of two fabricated metalenses. The lens diameters are 12 mm and 32 mm.

There are also other methods to fabricate metasurfaces. For instance, our group has collaborated in the past with UCSB to fabricate centimeter-scale metasurfaces with their deep ultraviolet stepper (DUV) lithography equipment.³⁸ Furthermore, novel methods such as nanoimprint lithography (NIL) and two-photon polymerization has been investigated in our group to fabricate three-dimensional device volumes. These methods are based with UV illumination, which of course sets a large constraint in the resolution limits.

2.1.3 Metasurface Fabrication with Direct Laser Writing

As previously mentioned, the meta-optics designed for MWIR and LWIR applications are fabricated in house with direct laser writing. The WNF currently owns two tools for this, the Heidelberg DWL 66+ and the Heidelberg MLA which they just recently purchased. Most of the process development our group has achieved is with the DWL 66+, however myself and a couple of other students have looked into the MLA which is intended to have a slightly faster write time and lowered resolution quality. Unless otherwise stated, I will be referring to the process

parameters with the DWL 66+ tool, however the processes are very similar between tools. There are a few main parameters to consider when developing or optimizing a new photolithography process. The first is the minimum feature size which is the smallest gap (or pillar) for the design. When smallest feature size that we have been able to reliably pattern is 500 nm (this is closer to 650 nm on the MLA) with a 500 nm spacing for meta-atom pillars. Although it increases the write time, the HiRes (2 mm) write mode is used for this operation. When the smallest feature size is 1000 nm or greater, the 4 mm write mode can be used. For a typical MWIR lens, I found that a 1 cm meta-optic write took about 40 minutes – 1 hour to complete, not including the file conversion time. As myself and previous group members have found, spending a few extra moments in the GDS preparation can expedite the Heidelberg tool time, either by inverting GDS patterns beforehand based on photoresist tone, combined lens layouts in a single GDS file, or organizing a GDS file into separate layers such as for metasurface and aperture patterns.

In general, the standard AZ1512 photoresist recipes made available by WNF staff worked well for the 4 mm exposures, and the AZ 1505 recipes worked well for the HiRes exposures. More recently, I have developed new process recipes with the AZ 701 (11 cps) photoresist for the HiRes write mode, since this is made available with the RiteTrack equipment and allows for higher wafer-to-wafer consistency. I recommend periodically measuring the deposited photoresist thickness from time to time and always running a test wafer before an actual design write.

On the tool itself, there are exposure parameters that can be user-calibrated for the individual process run. While the WNF staff also routinely determine optimal exposure parameters, I've found that there is an inconsistency when choosing to use these values directly which I believe is a result from inevitable process drift (either from previous user writes or tool instability) and

differences which arise due to pushing the tool's resolution limits (300~500 nm). The four values to calibrate include the laser power, transmission, intensity, and focus offset. With an exposure test pattern that covers the scatterer sizes that match the metasurface design, we perform an intensity/focus matrix exposure test which sweeps any or all of these parameters. In general, the laser power and transmission remain relatively consistent and are determined by the type and thickness of the photoresist. The intensity and focus settings can be swept across the full range of values to create a 2D matrix. After inspection of the developed features, we expect to see a parameter set that most closely matches the GDS, where increasing or decreasing these values worsens the exposure quality. There is one other parameter that can be selected during the GDS conversion step which is a critical dimension (CD) bias. As a heuristic, we have applied a -100 CD bias to the HiRes writes.

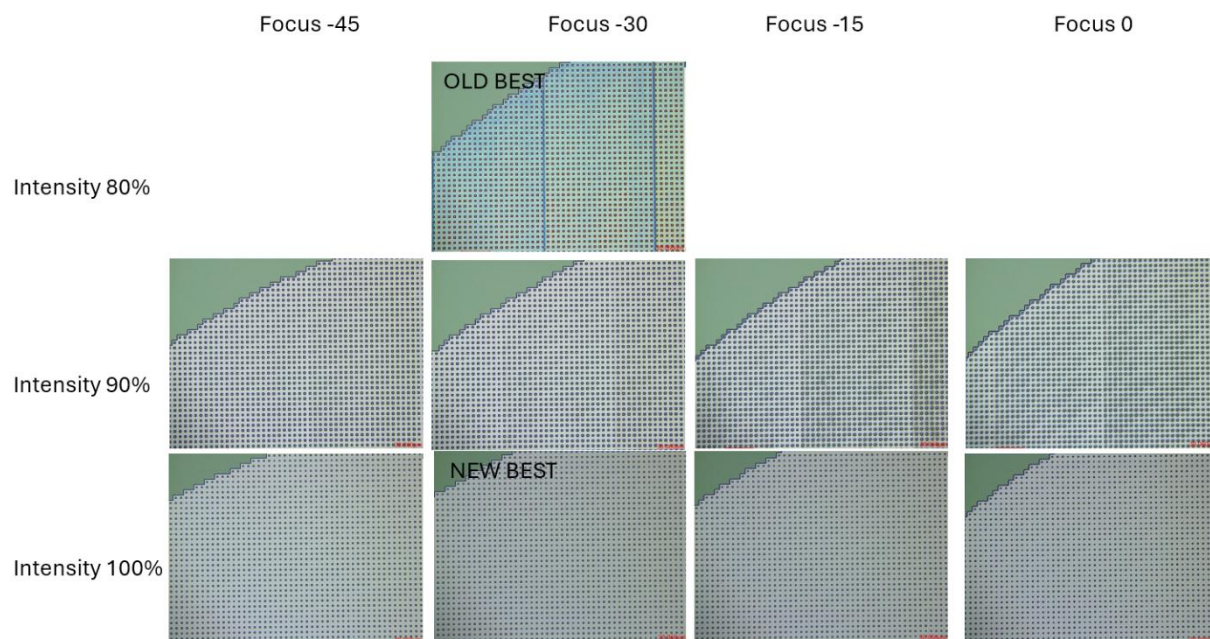


Figure 2.5 An example of a intensity/focus matrix exposure test. When the focus offset is misaligned, we sometimes see a striping artifact which occurs when the laser is shifted to the next write position. Here the optimal parameters are determined to be a focus offset of -30 and 100% intensity.

With the AZ photoresist series, the subsequent development is straightforward with commercial developers available at the wet benches (AZ 726 MiF / AD-10). The provided WNF recipes work well for the all-Silicon metasurfaces.

There are two etching options that are available post development. The first method is deep reactive ion etching (DRIE) which uses a technique known as the Bosch process that achieves very deep aspect ratio trenches. With this process, we can use the patterned photoresist layer directly as the etch mask and transfer the pattern directly into the bulk silicon. The other method uses inductively-coupled plasma with Fluorine gas chemistry (ICP-F). The available selectivity is much worse with ICP-F which leads us to additionally fabricate a hardmask from evaporated alumina to achieve etch depths of several microns.

2.4 Experimental Characterization

One of the key characterization parameters for imaging-based metasurfaces is the point spread function (PSF). The PSF quantifies how well the lens focuses incident light back into a point source. For an ideal, diffraction-limited lens without aberrations, the lens produces an identical point source. Another key parameters is the modulation transfer function (MTF). The MTF describes how well a lens resolves contrast from an object, typically with a resolution target of alternating bright and dark lines. For an ideal, diffraction-limited lens without aberrations, the lens resolves details as small as the cut-off frequency, which for the MWIR range is around 250 lp/mm.¹⁶ While refractive optics exhibit low to zero aberrations, meta-optics pose possible advantages owing to their size and high phase tunability, particularly in SWaP-constrained applications.

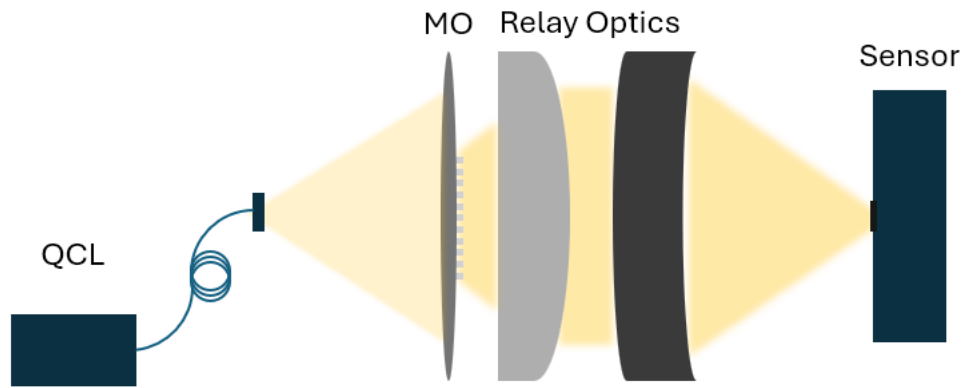
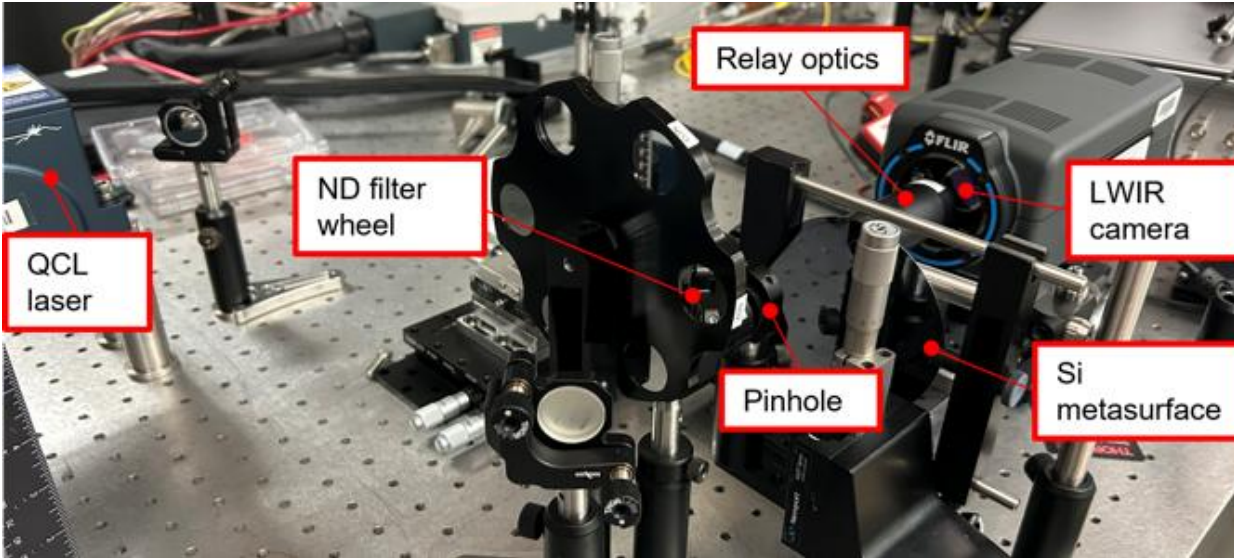


Figure 2.6 PSF Experimental Characterization Set-up (top) and schematic of the full layout (bottom).

An experimental PSF characterization is shown in Figure 2.6. A tunable QCL laser is aligned to a $30\text{ }\mu\text{m}$ pinhole to illuminate a Si metasurface with a point source intensity. The response is transferred through a relay optics system and is re-imaged onto the LWIR camera sensor. The purpose of the relay optics is to extend the imaging distance to reach the sensor plane as the physical camera housing is longer in distance the metasurface focal length. A set of 8 ND filters are used to control the QCL laser power.

In our group, the MWIR experiments are imaged with a FLIR MWIR A6751 camera with 15 μm pixel pitch and 512 $\times$ 640 resolution. The QCL laser is a Daylight Solutions MiRcat tunable across the full MWIR range.

In the LWIR, we typically use a FLIR Boson camera for measurements, however we do not own a tunable laser source in this range. These measurements were completed when I visited at the AFRL, where I had the opportunity to run a few individual experiments with the courtesy of their LWIR equipment.

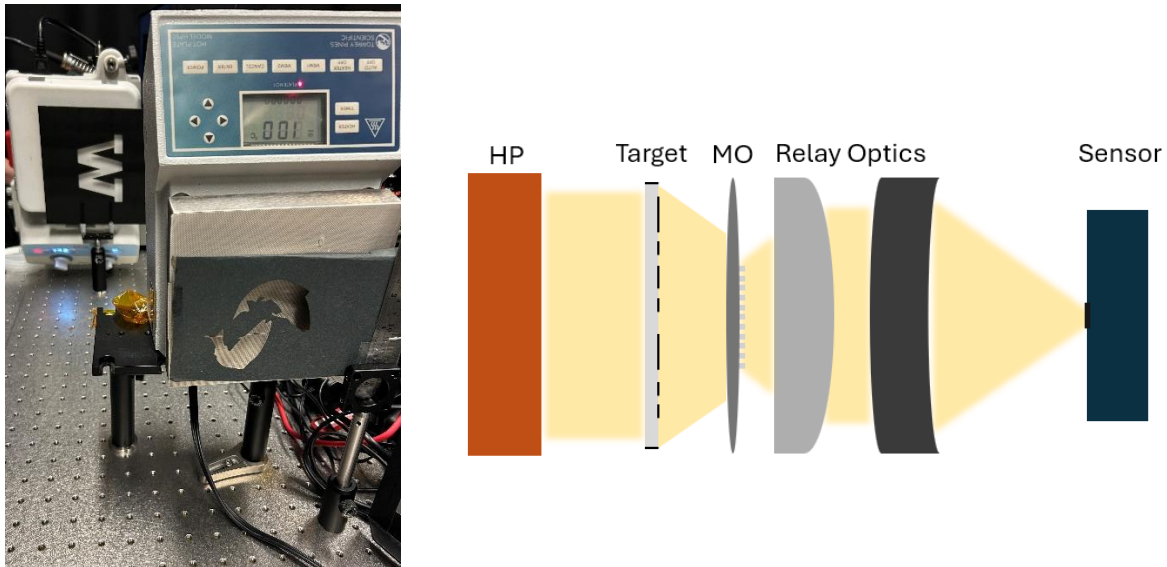


Figure 2.7 Target set-up for a broadband imaging measurement (left). Schematic of the full measurement set-up. Relay optics are used to extend the imaging distance from the meta-optic to camera sensor.

To provide a patterned contrast for broadband imaging, our group typically uses a hot-plate with laser cut aluminum stencils. For specific MTF characterization, standard resolution test charts, such as the USAF 1951 resolution target or the Siemens star target can be used to generate the experimental MTF curve.

Chapter 3. Broadband Imaging

3.1 Introduction

Devices that perform remote sensing and high resolution imaging are persistent across domains of agriculture, defense/military, and consumer electronics. Practical devices must consider size, weight, and power (SWaP) with advancing application demands of which maintain or enhance imaging quality in smaller and smaller form-factors. It follows that optical components with thin, lightweight, and straightforward fabrication are considered for device with near-term and scalable platform integration. Optical metasurfaces directly address such physical demands in systems where traditional bulky optics are infeasible. Although, metasurface imaging quality does not exceed refractive optics due to aberrations. In specific use cases, metasurfaces nonetheless show commensurate ability when designed for simultaneous and multimodal operation; particularly when a single operation, say lensing, is not the sole requirement in an optical system.^{24,39} While conventional, off-the-shelf optics are combined to achieve integrated tasks like parfocal zoom and achromatic imaging, these assemblies are often not practical for “in-the-wild” applications. Metasurfaces, on the other hand, may be intentionally engineered with all degrees of freedom of light (intensity, phase, polarization) by design. The subsequent optical systems are much smaller and lighter because of the fundamental difference in the way metasurfaces work from refractive lenses. In the present literature, metasurfaces operating in the infrared are hindered by the environmental noise, material availability, and size of sensor pixels.⁴⁰ In particular, with longer wavelengths, the requirements for pixel and therefore sensor size are larger. Determining efficient ways to miniaturize the optical component in integrated systems is one potential benefit for metasurfaces.

Full-color imaging is an application space that is of sustaining interest for display, vision and integrated electronics. In a simplified view, full-color imaging cameras use a focusing lens to take a passive scene (trees, sky, grass) and record the spectral intensities incident onto a detector plane and converts the photon intensity to an electronic signal that is interpreted by a combination of red, green, and blue signal values. Full-color imaging can therefore be achieved with a simultaneous read-out of three color channels combined with a sufficient level of resolution to represent the real-world scenes that we have come to expect for commercial displays and recorded images. With the extension to the thermal and infrared bandwidths, the concept of full-color imaging is described as broadband imaging, where the wavelength range in the visible (400 – 700 nm) is equivalent to common bandwidths of interest in the IR. For the mid-wave infrared (MWIR), the wavelength range is 3 – 5 μm , and for the long-wave infrared (LWIR), the wavelength range is 8 – 12 μm . Here, camera detectors in the infrared are monochromatic, where a single intensity channel records spectral intensity often across the complete MWIR or LWIR band. These detectors, such as cooled microbolometers or SLS focal plane arrays, often possess a lower resolution quality owing to the larger pixel size and quantum efficiency values that scale with the wavelength and detector material, respectively.

3.2 Design

3.1.2 MTF-Engineered Metalenses

The inverse-designed end-to-end optimization approach for MWIR broadband imaging consists of a single-layer meta-optic with an aspheric phase initial condition and a computational backend. While our group led this study, the optimization approach was done by our collaborators at UNC. I would like to thank Debrabrata Mandal and Zihao Zou for their help with the computational algorithm and MTF-engineered lens profiles, respectively. I also want to

thank their advisor, Praneeth Chakravarthula for his support with this project. In general, such optimization methods use a gradient descent approach and requires requires that the geometric parameters of the meta-optic to be designed in such a way so that it is differentiable.^{20,41,42}

Therefore, our group developed a proxy model for the metasurface that is used to generate imaging parameters and quantify the optimization result. First, a central wavelength is chosen at $4.5\ \mu\text{m}$ and an inverse, structure-to-phase mapping simulates the phases from a discrete set of meta-atoms of varying widths. The widths are normalized over the periodicity of the metasurface into a “duty-cycle”. Then, a forward, phase-to-structure mapping calculates from each duty-cycle value the corresponding phase at a series of wavelengths between the MWIR band.

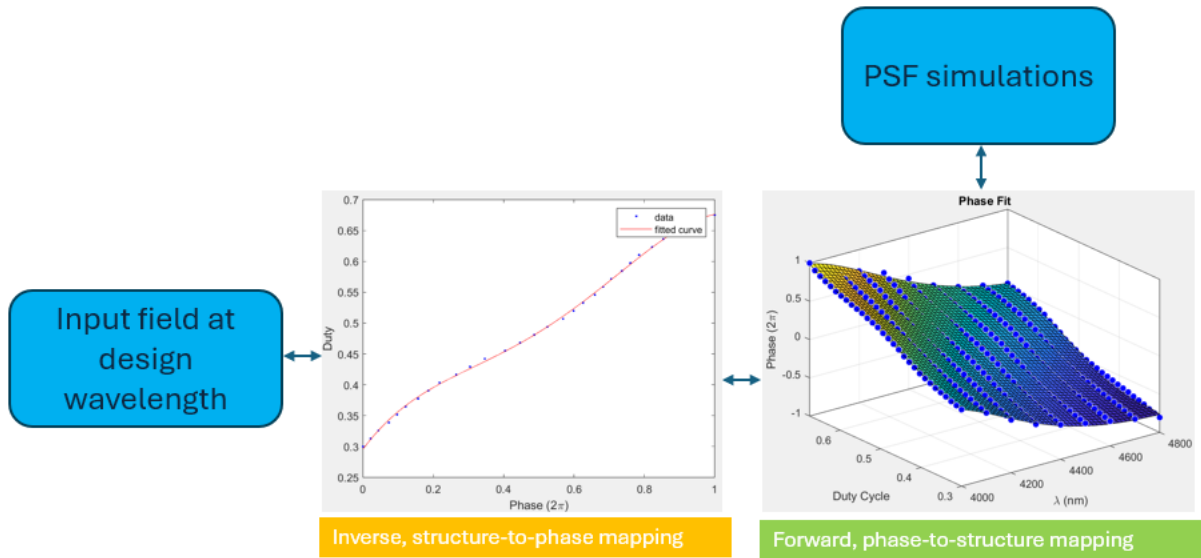


Figure 3.1 Schematic of the proxy model generation to model the metasurface for optimization.

This effectively creates an 1D polynomial for structure-to-phase and a 2D polynomial for phase-to-structure mapping, that can be used for subsequent simulations of PSFs and images. This method is required because the duty-cycles which are adjusted with each optimization iteration must be differentiable, and this approach enables the scatterers to be designed with a polynomial

proxy. The RCWA simulations to generate the proxy polynomial functions were truncated to the 9th harmonic orders and the broadband design considers a full MWIR bandwidth, 1.2 cm diameter aperture, and 2.5 cm focal length meta-optic.

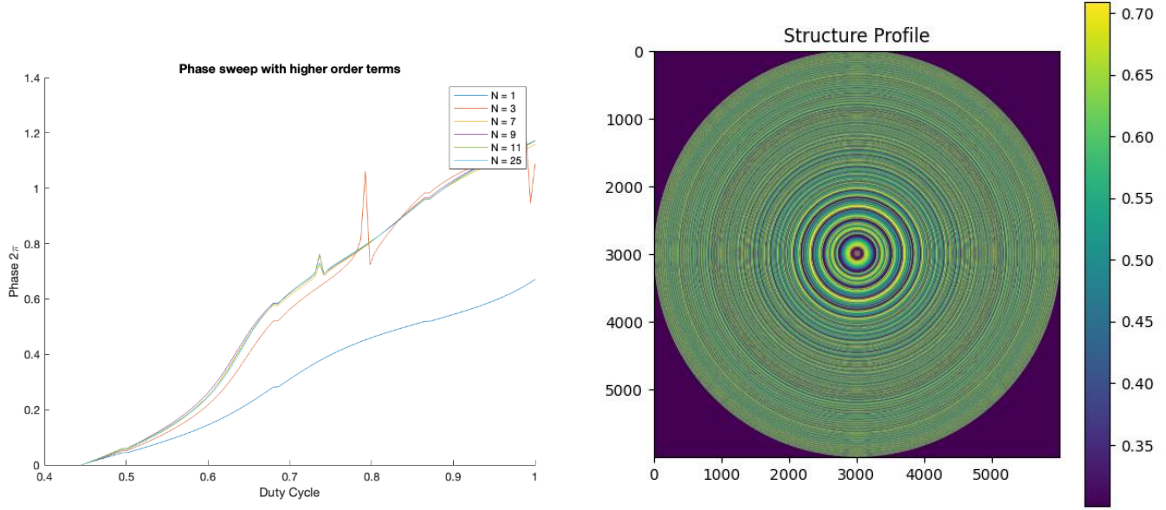


Figure 3.2 RCWA phase simulation with increasing harmonic orders (left). The proxy model considers up to 9 Fourier orders where no new resonances appear in the phase. Simulated phase mask of the MTF-engineered broadband metalens (right).

While employing a very similar approach to the past work done in the visible, we discovered that the optimization did not improve over the initial condition with this direct wavelength scaling approach.²¹ While increasing the number of discrete wavelengths to achieve a broadband focusing phase profile, we noticed a trade-off between the bandwidth and focal intensity. However, even approaching 100 wavelengths for optimization, a fraction of the total wavelengths optimized over in the visible case, the simulated focal intensity drops below the initial condition. From this result, we expect that the metasurface would function worse than the unoptimized lens, because the loss function is typically specified in terms of maximizing the center focal intensity.

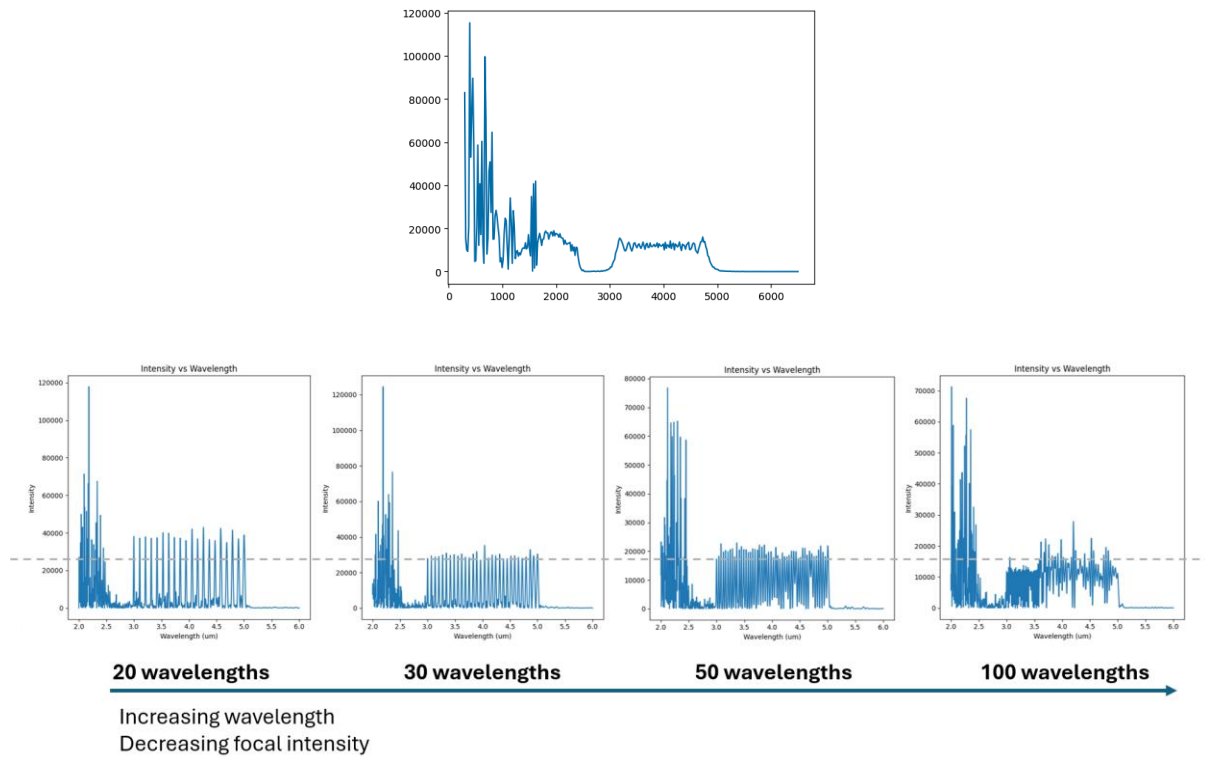


Figure 3.3 Comparison of the unoptimized initial focal intensity and optimized case over 100 discrete wavelengths. The initial, unoptimized focal intensity (top) results compared to the optimized cases (bottom). The trade-off between focal intensity and bandwidth causes the focal intensity of the optimized case to decrease below the focal intensity of the original phase profile, therefore it is hypothesized that the optimization does not improve over the initial condition.

3.2.2 Fractional Bandwidth

One hypothesis our group considers is that the MWIR band has a much larger relative fractional bandwidth to work over than the visible band. Though the fractional bandwidth is the same in both cases, because the visible color sensors include a tri-color filter, the sensor effectively filters out only three colors and our eye perceives the color discrimination of various red, green, and blue intensities. This allows the visible metalens to operate with a smaller fractional bandwidth between three colors in a total band between 400 – 700 nm. The fractional bandwidth is the bandwidth range over the central wavelength, is equal, but the effect from the color filter can be considered to produce a relative fractional bandwidth between the color filter wavelengths. On

the other hand, the thermal band is invisible to our eye, and the sensors are monochromatic. In this case, the image quality appears completely to our eye as brightness, and in comparison to the visible, there is a larger relative fractional bandwidth to capture all colors to pick up this brightness non-discriminately. Ultimately, the trade-off between reduced bandwidth and color filters at the present is ambiguous. In comparison to the visible case which accounts for the presence of color filters incorporated with a camera sensor, we find that in the MWIR, the large fractional bandwidth does not outcompete a simple hyperboloid metalens when comparing their MTF directly.

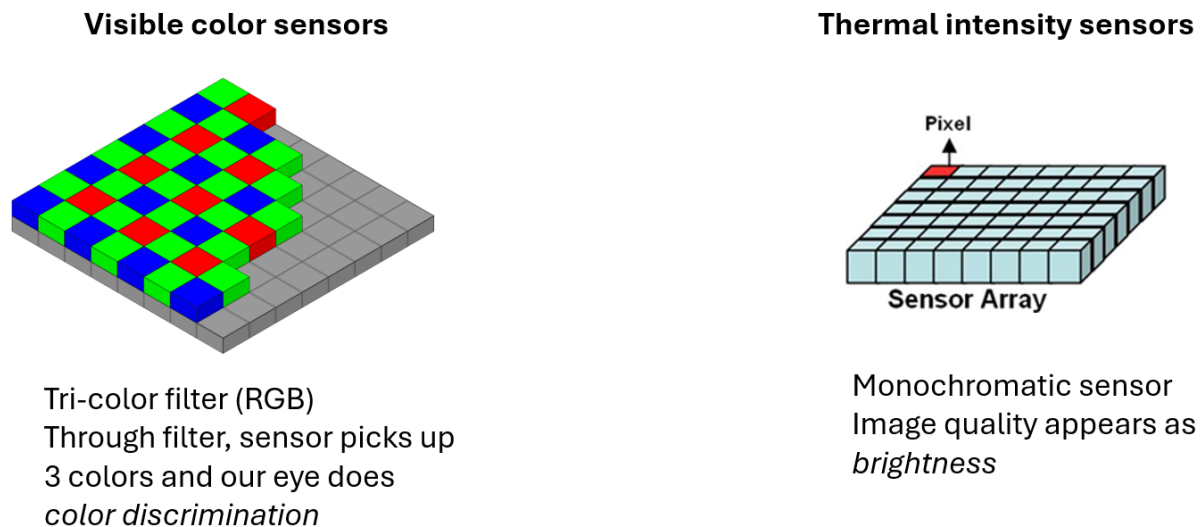


Figure 3.4 Comparison of sensors between the visible and thermal wavelength regions. The color sensors are typically paired with a tri-color filter, thus creating a relative fractional bandwidth of red, green, and blue compared to the equally scaled fractional bandwidth between the visible and thermal. Thermal sensors are monochromatic, and thus all image quality and aberrations appear to the eye as brightness.^{43,44}

The fractional bandwidth calculation includes an evaluation of imaging performance based on the simulated MTF area as function of spectral bandwidth. For a select number of bandwidths up to the full MWIR range, the wavelength range is centered around $4.5 \mu\text{m}$ and sampled every 10 nm.

The fractional bandwidth considers the span of the wavelength range divided by the center frequency, and the monochromatic case is considered to be a bandwidth of 0.

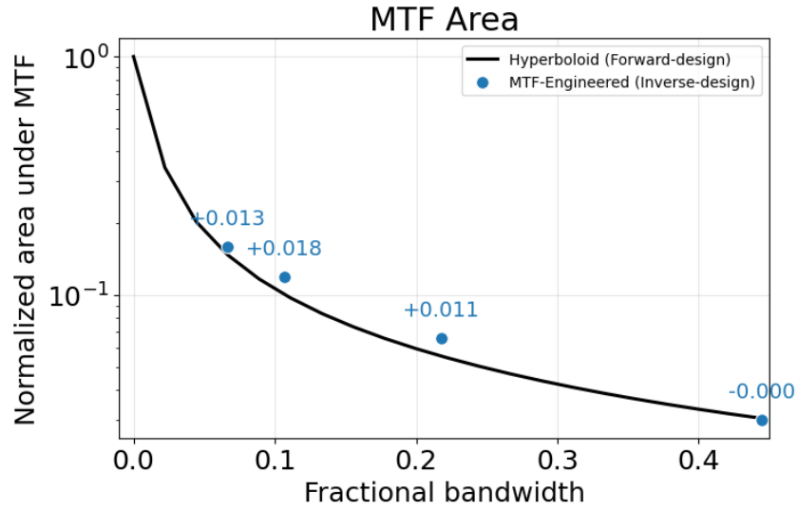


Figure 3.5 Comparison of simulated MTF performance of forward and inverse meta-optic designs.

To calculate the PSF, the angular spectrum method is used and the broadband PSF is obtained by integrating the non-normalized PSFs over the wavelengths across given bandwidth.³⁵ The MTF is computed from the FFT of the PSF. Next, to find the MTF area, the MTF values are integrated between spatial frequency values between 0 to 100 cycles/mm across increasing bandwidths in the 10 nm intervals. Integration is performed using the numpy trapz function.⁴⁵ The MTF area is normalized by the hyperboloid reference at zero bandwidth (monochromatic). This approach is done for the hyperboloid phase profile and the four MTF-engineered phase profiles. A direct comparison is considered to find the difference between the MTF area between the MTF-engineered and hyperboloid at those specific bandwidth ranges.

3.3.2 MWIR Broadband Imaging

In contrast to the previous work our group has shown in the visible and LWIR, the broadband imaging method followed in this project used a single-wavelength hyperboloid metalens to

demonstrate broadband imaging. The optical frontend is replaced with a forward-designed diffraction-limited phase profile paired with a computational backend that particularly focuses on intensity restoration for an enhanced monochromatic image. While we predicted the best optical performance with a hyperboloid phase profile, the overall image quality remains poor for raw image captures and does necessitate computational reconstruction. This computational reconstruction method is created by our collaborators at UNC with the experimental data we collected to train the model. The model results do show improvement over the original images captured solely with the meta-optic and sensor. Our design therefore changed from an optimized broadband phase profile with inverse-design, to a high-quality single wavelength hyperboloid phase profile that is in principle diffraction-limited. With the addition of a filter at the design wavelength of the meta-optic, the captured images act as an intermediary that are enhanced with a restoration algorithm.⁴⁶

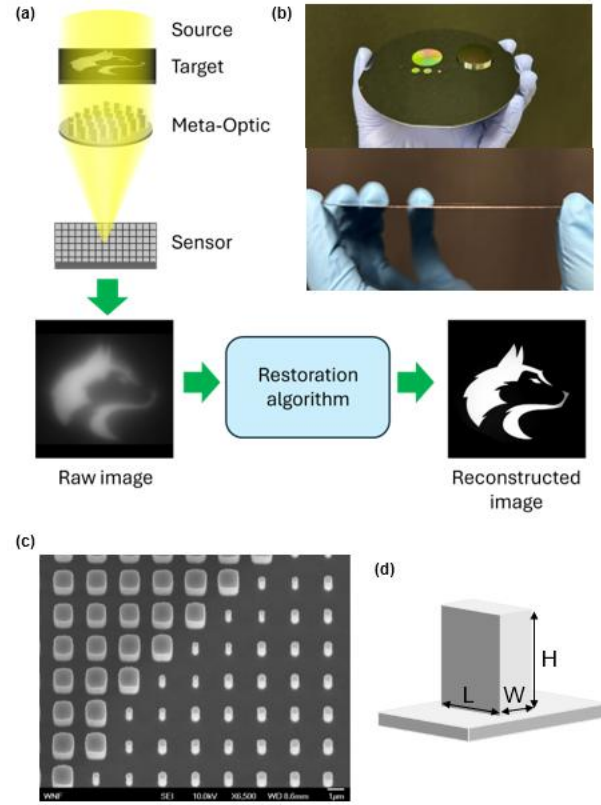


Figure 3.6 Overview of the proposed broadband MWIR imaging system with an all-Silicon hyperboloid metalens. (a) Schematic description of the broadband imaging pipeline. A hot-plate heated between $100 - 200^{\circ}\text{C}$ produces the MWIR signal and the images captured by a fabricated hyperboloid metalens is recorded by a monochromatic MWIR camera. (b) Comparison of the bulk reduction from the Silicon-based metalens over a commercial off the shelf (COTS) Ge refractive lens.⁴⁷ Side-perspective image of the ultra-thin form factor with all-Silicon fabricated metalens. (c) SEM of the fabricated all-Si meta-atoms. (d) Schematic of a meta-atom pillar. The height is $4\text{ }\mu\text{m}$ and the periodicity is $2\text{ }\mu\text{m}$.

An important detail from this work is the low amount of training data used in the image reconstruction process. One of the bottlenecks in neural network training stems from the large amount of data typically required for training and validation, which can be both tricky from a collection and curation standpoint. Surprisingly, the restoration model, developed by our collaborators known as the UnSCAR model, consisted of a fewer than five image prior to train and reconstruct the final image set.⁴⁶ Importantly, we see in experimental characterization that restoration of fine details from target objects, which also suggests that a single-wavelength

metalens under MWIR operating conditions is sufficient to capture broadband intensity compared to an inverse-design lens specifically designed for broadband operation.

3.3 Fabrication and Characterization

We fabricate a 20 mm aperture hyperboloid metalens with a nominal focal length of 20 mm ($F/\#$ 1) with a central focusing wavelength of 4.5 μm . A 300 μm thick double-sided polished Silicon wafer was coated with a layer of HMDS to promote resist adhesion. A layer of positive resist (AZ 1505) was deposited (4k rpm, $\sim$ 500 nm thickness), followed by a 60 s soft-bake at 100°C on a hot plate. The resist layer was then patterned with direct-write lithography (Heidelberg DWL66+), followed by a post-exposure bake for 60 s at 100°C on a hot plate. The resist was developed in a commercial developer solution (AZ 726) for 60 s. Subsequently, the resist pattern was transferred into the bulk Silicon with deep reactive-ion etching (SPTS DRIE) to a target depth of 3 μm to form the Silicon nanopillars. The residual photoresist was stripped using oxygen plasma.

Raw image measurements are captured with a commercial FLIR sensor (A6751 InSb) and a restoration algorithm is used for image post-processing. The set of image captures is formed by matte-black aluminium targets to pattern contrast and the image intensity is recorded on the camera sensor.

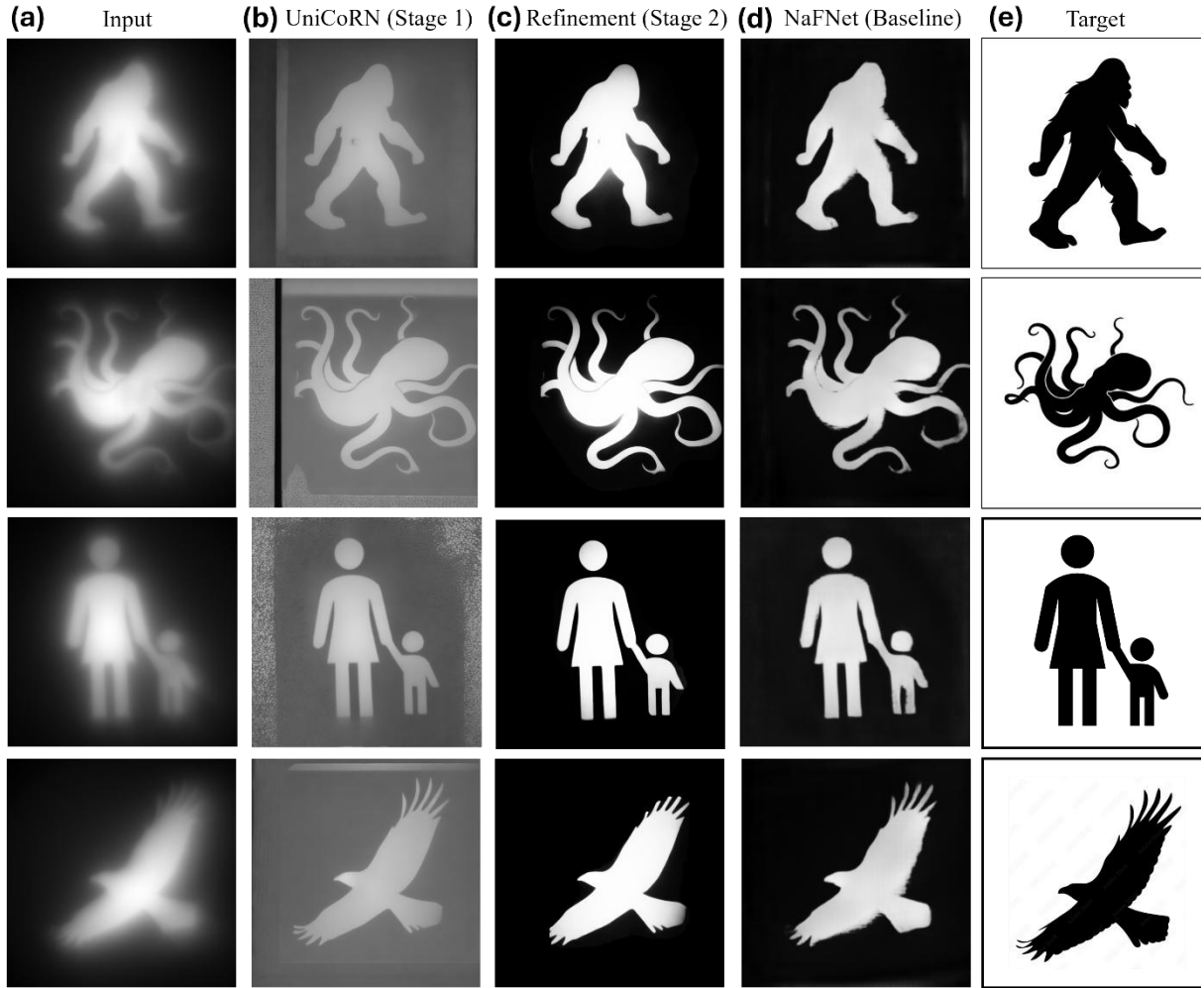


Figure 3.7 Imaging Results and Characterization. (a) Broadband MWIR images with all-Silicon hyperboloid metalens using a monochromatic detector (FLIR A6751). (b-d) Restored images following computational reconstruction. (e) Ground truth target images for comparison.

Figure 3.7 (a) shows a column of raw intensity images produced by the meta-optic and captured on a commercial FLIR sensor (A6781). The chromatic blur introduced by the broadband meta-optic from phase wrapping conditions worsen image quality through boundary degradation and loss of high spatial frequency content. Figure 3.7 (b-d) shows the corresponding images after the image restoration process including color refinement. The restoration model, despite image input with chromatically degradation and blur, sufficiently restores broadband contrast from target

objects with identifiable structural boundaries such as the individual curled limbs of the octopus stencil. The restoration of fine features showcases successful reconstruction across multiple target classes, including the silhouette details from the Bigfoot outline, the object boundaries from the dolphin stencil, and the wingtip contours of the flying bird targets. Similarly, the model restores the target outlines from fish fin stencils and reconstructs a clear outline between the women and child silhouettes with an uniform intensity.

Figure 3.7 (e) depict the ground truth comparison to the restored images and demonstrates that the proposed restoration model effectively compensates for the chromatic blur introduced by the meta-optic while preserving the scene-specific content such as high frequency details at target edges and boundaries.

3.4 Discussion

In this work we investigated, to the best of our knowledge, the first systematic comparison of a MWIR hyperboloid metalens and an inverse design counterpart with matched aperture as a function of fractional bandwidth. Our results demonstrate that over the full MWIR bandwidth, a hyperboloid metalens can successfully enable broadband MWIR imaging when combined with computational image restoration.

A central finding of this work is that a broadband computational imaging system does not necessarily require a broadband or achromatic meta-optic design. This insight is supported by an analysis of integrated modulation transfer function (MTF) area as a function of fractional bandwidth, which predicts that inverse design and forward design meta-optics provide comparable imaging performance at the full MWIR bandwidth. Notably, an inverse design meta-optic has a larger integrated MTF area compared to a forward design meta-optic with matched

numerical aperture and focal length roughly between $\sim 0.1 - 0.2$ fractional bandwidth, while at the extremes of the varying bandwidth range we find a specific improvement in the forward design performance by 9% at the full bandwidth ($\Delta\lambda = 2.0 \mu\text{m}$) and 3% at the narrowest bandwidth ($\Delta\lambda = 0.3 \mu\text{m}$). The experimental imaging results further demonstrate that image intensity capture from a single wavelength hyperboloid metalens can sufficiently preserve spectral intensity information for high quality image restoration despite significant chromatic defocus. Broadband image reconstruction is addressed with algorithmic post-processing and does not require inverse design or multi-layer optics. We have demonstrated broadband imaging with a hyperboloid metalens designed at $4.5 \mu\text{m}$ single wavelength that is compatible with a computational reconstruction framework from a sparse image set. At the time of this writing, I was only able to find one other reference that directly implemented a hyperboloid metalens for broadband computational imaging.⁴⁸

This finding suggest two implications for experimental study. First, the question remains why the same trend, with a seemingly wavelength-scaled approach is not found from the visible to MWIR (200 nm to 2000 nm). The second asks the question of which approaches are available towards achieving a broadband imaging system. In addition, it should be mentioned additional nuances to the MWIR optimization that add contributing detail. The first is that the phase diversity is not the same between the visible and MWIR bands. In the visible implementations of inverse design lenses, the material platform is often SiN on a low index bulk substrate.^{15,49} For the MWIR design, our engineering approach constrains an all-silicon stack, where there is no contrast difference between the metasurface layer and bulk substrate, that changes the transmission and phase diversity in the available meta-atom geometry. Second, the application and use cases for MWIR lenses often necessitate large aperture. It is well-understood that

achieving a large focusing bandwidth is a direct competitor to numerical aperture constrained by the space-bandwidth product. With these two details in mind, I do hope that further investigation may go into quantifying which parameters may be identified as universal scalers for broadband designs across different bandwidths of interest.

This work is being prepared for submission to Nature Communications as a co-authored manuscript with our collaborators at UNC, under the title, “*Broadband Mid-Wave Infrared Imaging Enabled by All-Silicon Hyperboloid Metalens*”.

Chapter 4. Synthetic Aperture Imaging

4.1 Introduction

One mode of understanding inverse design through a MTF-engineered approach is that broadband performance is achieved through a redistribution of spatial frequencies across a bandwidth that corresponds with lower SNR for imaging contrast.^{39,50} A field that is well-studied in RF and information theory is in synthetic aperture design.⁵¹ This field of study is of primary interest for astronomy and long-range imaging, and most recently has garnered interest from industry-motivated applications in free-space optical communication for low Earth orbit satellites and NASA's James Webb Telescope.^{52,53} This approach for synthetic apertures is well-suited for metasurface design that can be directly tuned by the lightfield parameters, namely wavelength, polarization, and phase. There are well-established configurations for sparse aperture configurations. The main topic investigated in the following chapter looks into sparse apertures with various Golay configurations motivated for long-range MWIR imaging. My main contributions to this end were in the fabrication and preliminary characterizations along with my former group mate, Anna Wirth-Singh.

A sparse or synthetic aperture uses a collection of smaller sub-apertures that coordinate together to give an effective result mimicking a larger, single aperture. The benefit of this technique, like a Fresnel lens, is reduced active area of the lens. The trade-off, however, being loss of resolution particularly in the high-frequency details. In coordination with an optimization technique, the traditional Golay layout can be improved upon with inverse-design to extend the bandwidth of the sparse aperture by maximizing the volume of the MTF curve.

Sparse aperture designs traditionally consider spatial frequency in their design by adjusting the sparsity and sub-aperture arrangement to produce a smooth PSF and corresponding MTF that

captures a portion of the MTF that the larger aperture would have captured.^{39,51} This value is quantified through the geometric-specific fill-factor, which relates the collection area of the sparse aperture to the collection area of the filled aperture.

A Golay lens is a type of sparse aperture design where the effective aperture is comprised of six sub-apertures. The fill-factor for a traditional Golay 6 design is,

$$F_{Golay\ 6} = \frac{6d^2(1 - \varepsilon_{sub}^2)}{D_{encircled}^2}$$

Where F is the fill factor defined by the ratio between the active area of the sparse to filled aperture regions, d is the sub-aperture diameter, ε_{sub} is the obscured fraction of an individual sub-aperture, and $D_{encircled}$ is the diameter of the aperture the encircles the whole layout.⁵⁰ Each sparse aperture design corresponds with a different fill factor which can be tuned by the parameters described above. Adjusting the fill factor ratio directly influences the MTF as expected since the configuration affects the light collection (SNR) and PSF value. The fill factor for a Tri-Arm Golay is,

$$F_{Tri-Arm} = \frac{(3n + 1)(1 - \varepsilon_{sub}^2)d^2}{D_{encircled}^2}$$

Where n is the total number of sub-apertures.

Interestingly, Tri-Arm Golay configurations have also been used in telescopes like the Very Large Array (VLA).^{54,55}

4.2 Fabrication and Characterization

The first Golay we fabricated had a Golay 6+1 configuration where the additional aperture was a hyperboloid at the center of the effective aperture. Our group also designed the meta-atom library for the sparse aperture.

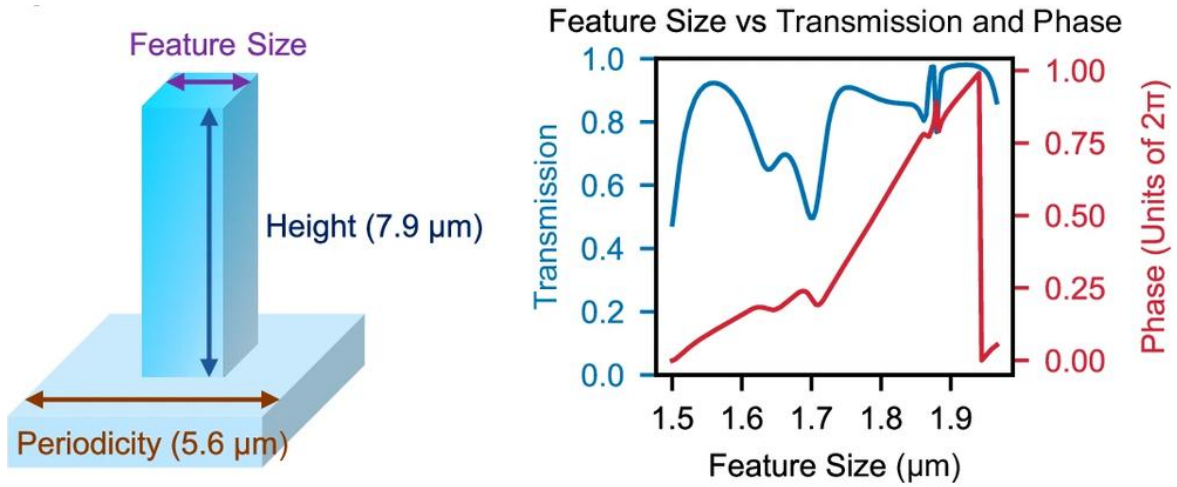


Figure 4.1 Schematic of a single meta-atom scatterer (left). The unit cell periodicity is 5.6 μm and the pillar height is 7.9 μm . Transmission and phase plot of the simulated meta-atoms (right).⁵⁶

The metalenses were fabricated on a 300 μm thick, double-side polished silicon wafer. The aperture diameter is 89 mm with 356 mm focal length, constrained only by the fabrication method available in the university cleanroom. First, the area surrounding the sub-apertures was coated in a 200 nm thick Cr layer to act as an aperture, blocking illumination outside the sub-aperture metalenses. This helped to reduce noise in imaging experiments. In greater detail, the sub-apertures were formed by first writing the pattern in negative resist (NR9G-3000-PY) using direct-write lithography (Heidelberg DWL-66+). Then, the Cr layer was deposited on the photoresist using electron beam evaporation (CHA Solution) and subsequently lifted off in acetone to construct the metal mask around each subaperture. The result was bare silicon surface within each sub-aperture area. To pattern the meta-optics, the wafer was coated with positive

photoresist (AZ1512) and exposed using direct-write lithography (Heidelberg DWL-66+) within the previously defined apertures. Finally, we used deep reactive ion etching (SPTS DRIE) to etch to a target depth of $7.9\text{ }\mu\text{m}$ using the photoresist as the etching mask. This formed the silicon pillars. Any residue was removed with a final oxygen plasma step.

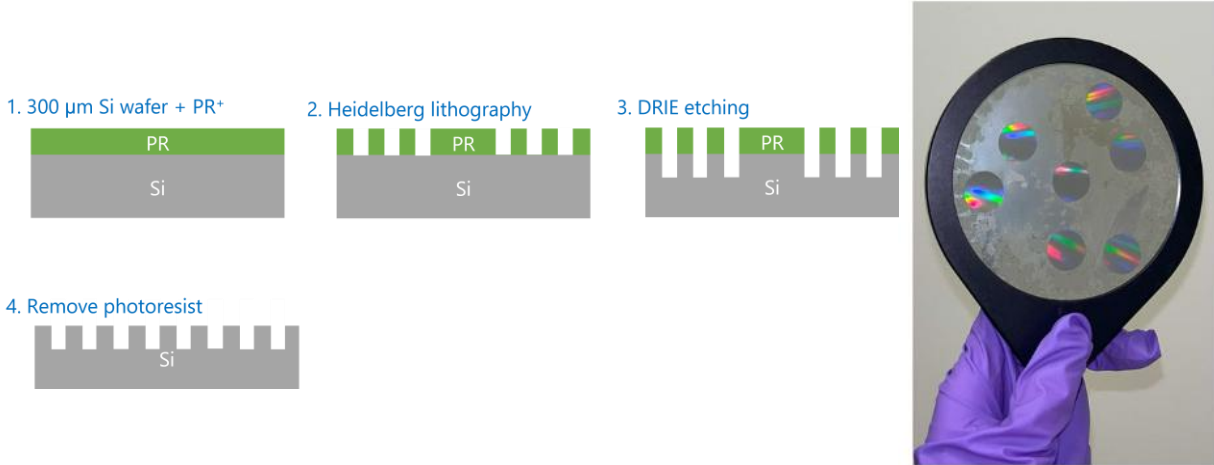


Figure 4.2 Photolithography process flow with direct laser writing (left). This fabrication is completed prior to the addition of a Cr aperture mask. Camera image of the completed Golay 6+1 metalens.

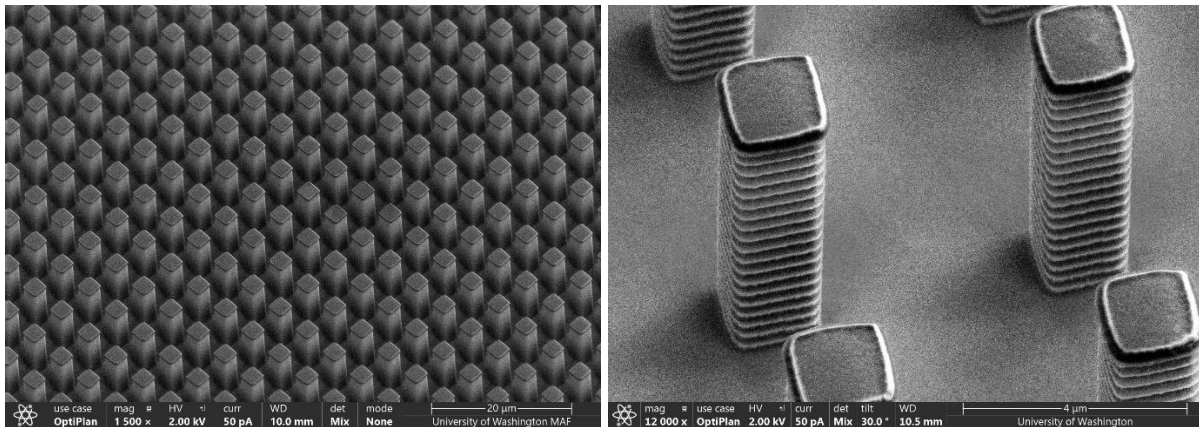


Figure 4.3 SEM of the etched scatterers for a sparse aperture Golay. At 1500x magnification and a 30° tilted perspective at 12000x magnification. Feature sizes are between $1.3\text{ }\mu\text{m}$ – $2.0\text{ }\mu\text{m}$ widths with a height of $7.9\text{ }\mu\text{m}$.

A second project with a separate Golay design is also completed for MWIR broadband imaging. In this work, we demonstrated a slight improvement over an unoptimized hyperboloid lens that focuses at a single wavelength to demonstrate the principle of broadband sparse imaging with inverse design. Two separate designs are compared through a polychromatic metalens designed for five discrete wavelengths (Design A) and a broadband lens optimized across 1,001 separate wavelengths (Design B). A hyperboloid metalens designed for 4.5 μm single-wavelength was used as an imaging reference. The improvement is quantified by the PSF and MTF characteristics, showing approximately 3 times resolution improvement between the optimized and unoptimized lenses. The Golay configuration is a Triangle₇ metalens with an 89-mm diameter with 356 nm focal length across the entire MWIR range. Harnessing the capability of large aperture, scalable fabrication with direct laser writing and the hardware/software co-optimization feasibility for computational imaging reconstruction, we experimentally demonstrate enhanced imaging performance for long range imaging at up to 8 m distances.

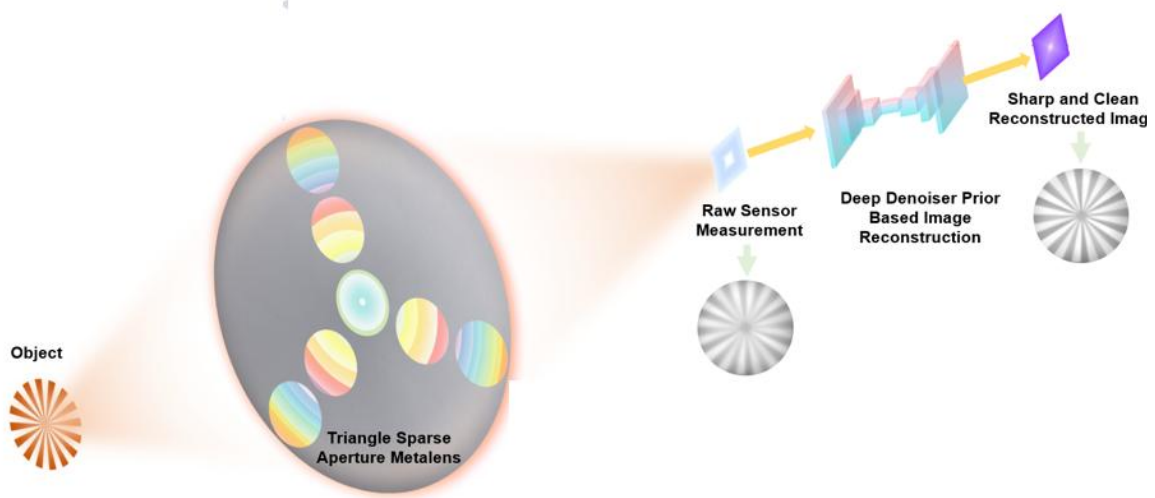


Figure 4.4 Proposed metasurface imaging pipeline with a deep learning-based image restoration algorithm to enhance the image from ambient noise. The metalens is designed to be broadband across 3 – 5 microns and is designed with an optimized Tri-arm sparse aperture geometry. This figure is adapted from our submitted paper, “Sparse Aperture Metalenses for Long-Range Broadband Mid-Wave Infrared Imaging”.

This work was presented in a collaboration paper with Rice University, under the title, “*A golay metalens for long-range, large aperture, thermal imaging via sparse aperture computational imaging*”, published in Nature Communications. An additional paper in collaboration is currently under review and titled, “*Sparse Aperture Metalenses for Long-Range Broadband Mid-Wave Infrared Imaging*” that investigates expanded design techniques.

Chapter 5. Polarization Optics

5.1 Introduction

An unique advantage to meta-optics is the direct design flexibility to the polarization state of an incident wavefront.^{5,6,57–59} These are referred to as polarization-sensitive metasurfaces. In particular, polarization control has applications in polarimetric imaging, biometric sensing, and atmospheric monitoring.^{7,29,57,60–63} In comparison to refractive optics, polarization selectivity can be directly incorporated into a metasurface phase profile. Whereas for traditional refractive lenses, an additional component is necessary to control the polarization state. This an added benefit towards metasurfaces to further reduce the size of an optical assembly.

One interesting example of a polarizaiton-sensitive MWIR sensor was developed by Greg Roberts at Caltech achieved with a volume optics approach.⁶⁴ Volume optics can be difficult to fabricate because it aims to create a 3-dimensional nanopatterned device. This can be achieved with a two-photon polymerization process, which acts somewhat like a fancy 3D printer. At the UW WNF, we also have the capability to run this type of fabrication with the Nanoscribe tool. Our group has also previously demonstrated polarization-sensitive metasurfaces for an application known as foveated imaging. In this case, two separate degrees of focusing states are achieved in a single-layer all-Silicon metasurface by routing the imaging into orthogonal states

of polarization.⁶⁵ The ability to modulate the functionality of a metasurface through separate polarization states is a powerful approach to build multifunctionality into a single optical layer.

5.2 Multifunctional Design and Simulation

5.1.2 Motivation

As discussed in the earlier chapters, forward-designed metasurfaces are often worse at imaging tasks in direct comparison to refractive counterparts due to aberrations. Starting from a design that is in principle diffraction-limited, a metasurface can be engineered to not only capture 2D intensity maps but axial (depth) resolution in a single, real-time snapshot. This is achieved by calibrating the captured image intensity to the change in incident polarization. Here the absolute imaging quality is not only considered, but the simultaneous, multi-modal resolution in the transverse and axial directions. Additionally, we capitalize on the single-wavelength nature of the metasurface design that detects the strong emission peak of CO₂, centered at 4.2 μm , inherently obscuring extraneous signal that may be present in a real-world scene.

For tasks in object detection and chemical monitoring, a camera sensor needs to be long-range from the source (“remote”).^{24,66–68} Conventional imaging at long-range requires bulky optics for adequate SNR and radius of curvature. Preserving image quality at low size and weight is potentially ameliorated with a metasurface-based assembly. An ubiquitous chemical in product manufacturing and atmospheric monitoring is carbon dioxide (CO₂) which exhibits a signature peak at 4.2 μm wavelength in the mid-wave infrared (MWIR) band. Ability to accurately monitor at long-range and in real-time is of interest for systems that enable large area, lightweight sensors.

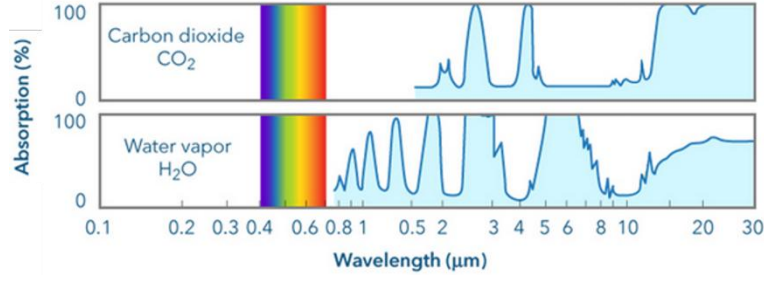


Figure 5.1 Absorption spectrum of carbon dioxide and water vapor between 0.1 – 30 μm . Positioned in the MWIR band at 4.2 μm , there is a transmission window for an absorption peak of CO_2 .⁶⁹

5.2.2 Approach

This approach looks into metasurfaces that generate two separate (conjugate) single-helix PSFs that encode depth information with the rate of rotation of the PSF through the Fresnel zone phase technique.⁶ I would like to thank my former group mate Shane Colburn for helping me with these designs. The Fresnel zone phase considers a phase profile,

$$\psi_r(u, \varphi_u) = \left\{ l\varphi_u \left| \left(\frac{l-1}{L} \right)^\varepsilon \leq u \leq \left(\frac{l}{L} \right)^\varepsilon, l = 1, \dots, L \right. \right\}$$

Where u is the normalized radial coordinate, φ_u is the azimuth angle at the entrance pupil plane, and L, ε are parameters that adjust the PSF rotation speed and size. Adjusting L and ε create a number of successive zones where the phase is changing and thus rotates the PSF. The full phase profile of the metasurface also includes a focusing term,

$$\psi_{fx}(x, y) = -\frac{2\pi}{\lambda} \sqrt{(x - x_i)^2 + y^2 + f^2} - f$$

Where x, y are the radial coordinates, x_i sets the focusing off-set from the center, f is the focal length, and λ is the design wavelength. Together, the full phase profile for a single rotating PSF is the combination of the two terms,

$$\psi_x = \psi_r + \psi_{fx}$$

And the full depth estimation lens is an addition of two conjugate PSFs, displaced by an offset distance from the center of the optical axis,

$$\psi_{meta} = \psi_x + \psi_y$$

Where ψ_y sets the PSF focusing off-set to some distance y_i , by an analogous ψ_{fy} . In this case, we look to investigate the depth sensitivity captured by a single aperture as it is affected by the lens diameter. For the same defocus range with increasing aperture size, it is expected that the depth sensitivity will increase quadratically. Put another way, we hypothesize that at a given object distance, the depth estimation error is inversely proportional to the square of the aperture diameter. This proportionality is reported in a published work by *Shen et al*,

$$\frac{\partial \varphi}{\partial z_{obj}} \propto \frac{\partial \xi}{\partial z_{obj}} = -\frac{\pi D^2}{\lambda} \frac{1}{4 z_{obj}^2}$$

Where $D = 2R$ is the diameter of the metasurface aperture and the defocus parameter of the in-focus diffraction spot is,

$$\xi = \frac{\pi}{\lambda} \left(\frac{1}{z_{obj}} - \frac{1}{z_f} \right) R^2$$

Where R is the radius of entrance pupil, z_{obj} is the actual object depth, and z_f is depth of the in-focus object plane

When the object distance is held constant, the proportionality can be expressed as,

$$\partial \varphi \propto \partial \xi = -\frac{D^2}{z_{obj}}$$

Where the rate of rotation is inversely proportional to the aperture diameter.⁶

Here the mean absolute error, MAE , of the estimated depth is similarly proportional to the decrease of the square in aperture size and the increase at a given object depth.

From the Fisher information of a single-helix PSF, one can calculate the lower limit of the estimation error from resolvable object depth,

$$FI_z(\mathbf{r}) = \frac{1}{\sigma_N^2} \sum_{u=1}^{N_u} \sum_{v=1}^{N_v} \left(\frac{\partial PSF(u, v; \mathbf{r})}{\partial z} \right)^2$$

Together with the Fisher information and minimum error of depth estimation, an inequality bound for the mean absolute error, MAE , is used to determine how the varying lens aperture can perform to some minimally achievable depth accuracy at further distances. Therefore, the hypothesis is that based on the inverse relationship between estimated error, $NMAE$ and the square of aperture, both of which are proportional to object depth, z_{obj} , our method seeks to explore this relationship experimentally. Our test designs include a set of alignment and calibration lenses with small aperture sizes to ensure our design pipeline is running as intended. The full design comparison considers a series of aperture sizes ranging from 0.5 mm to 4 cm. This is easily extendable by changing the size of the phase mask, while keeping the phase terms the same.

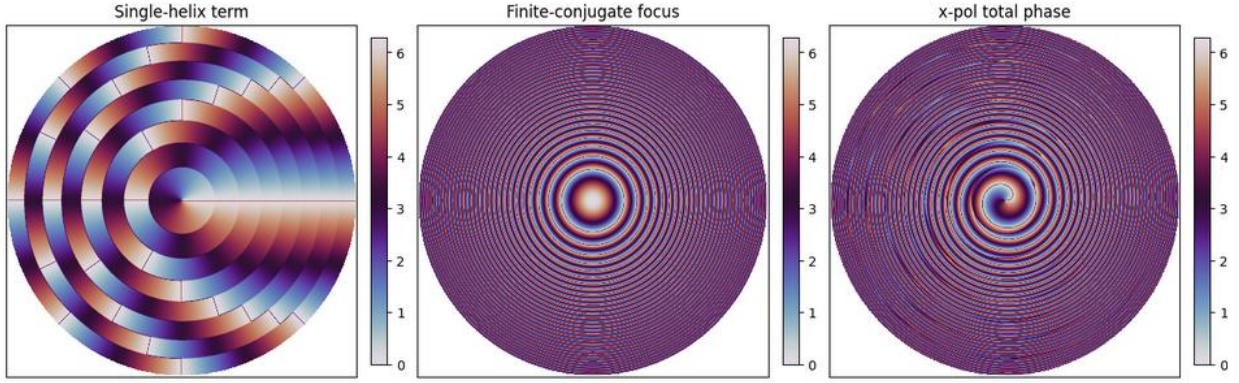


Figure 5.2 Decoupled phase components of the depth sensing metasurface. The total phase (right) is a combination of the single-helix spiral term (left) and a finite-conjugate focus term (middle).

5.3.2 RCWA Simulation

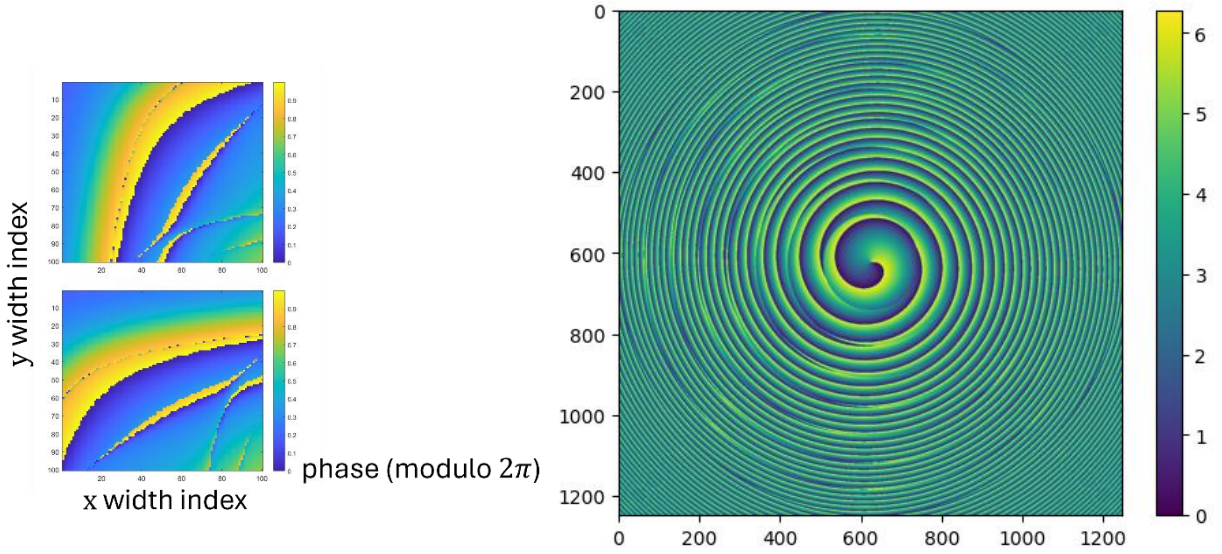


Figure 5.3 RCWA simulation of MWIR polarization-sensitive meta-atoms (left). Total phase profile of a single-helix PSF at $\lambda = 4.0 \mu\text{m}$ (right). The periodicity is $1.6 \mu\text{m}$ with Fresnel zone parameters, $L = 8$ and $\epsilon = 0.8$.

In comparison to the previous work our group as considered with foveated imaging, the polarization-selectivity for the depth-estimation apertures no longer consider a constant polarization state in one configuration, but require a $0-2\pi$ phase shift in both configurations. To

this end, the scatterers were simulated with RCWA and a total of 25 unique scatterers were selected to sample this range.

5.3 Fabrication

To impart polarization sensitivity to single-layer meta-optics, the meta-atoms must have shape asymmetry. Rectangular pillars are one simple approach to achieve this. We note that due to the method of exposure with direct laser writing, meta-atom features can lose their intended shape profile, resulting in cylindrical or rounded edges. This effect is exacerbated with smaller meta-atom sizes. To help retain the rectangular shape profile, optical proximity correction (OPC) attributes are preliminarily added to the meta-atom pattern files. This fabrication solution does not require additional processing steps to correct for the unavoidable spreading of the beam dose through the photoresist which smears fine feature details.

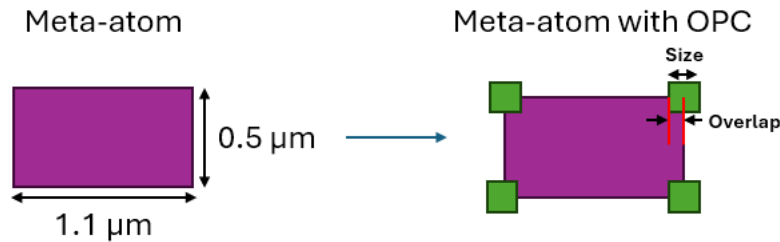


Figure 5.4 OPC addition with mouse-bite serifs. The size and overlap positions are adjusted to match the intended meta-atom size as closely as possible.

5.1.3 Optical Proximity Correction

Calibration to process drift is necessary for achieving high fidelity features within the 500 nm – 2 μm feature sizes for the MWIR and LWIR wavelengths with photolithography methods in a shared fabrication facility. During the initial design phase, I looked into additional ways to improve the fabrication robustness of polarization-sensitive scatterers. For this, I would like to thank my former group member, Zheyi Han for sharing with me some test results of previously

fabricated lenses with the same photolithography tool. First, to identify the optical proximity correction serifs is necessary to improve the final designs. The aspect ratio desired for the scatterers is also important. Through the addition of an alumina hardmask, the etching process can be prolonged due to a higher selectivity between the alumina and silicon material, compared to photoresist as a masking layer.

This process was carried out for a set of eight, unique rectangular meta-atom shapes with polarization sensitivity, where the minimum feature size was 500 nm. The serif attribute selected were mouse-bite patterns placed at the edge of each corner of the meta-atom pattern. An additional process sweep is made to understand the optimal size and placement of these serifs so that the compensating factor results in geometry fidelity and not additional feature resolution. Thus, the process can be split into three steps,

- (1) Determine if the problem is reproducible in exposure (find consistent exposure parameters)
- (2) Run a process sweep for the required meta-atom sizes to determine exposure offset
- (3) Run a process sweep for the optical proximity correction serifs based on the tool features

Ideally, steps (2) and (3) can be run simultaneously if the exposure settings are consistent.

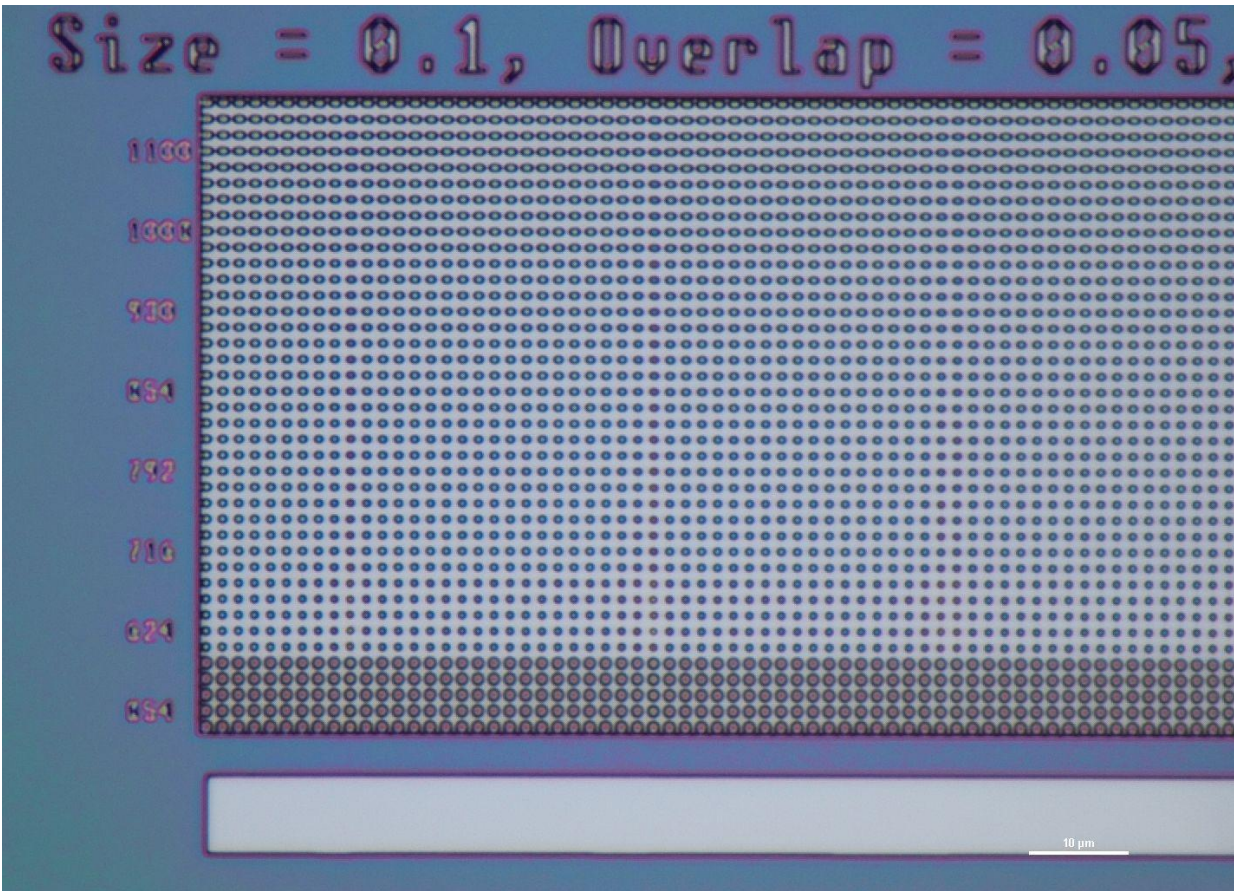


Figure 5.5 OPC test array with a constant serif size of 100 nm and overlap distance of 50 nm. There are a total of 8 unique scatterer with varying width and length sizes. The etch depth is 3 μm .

Once the exposure parameters are known, there are two main pathways to transfer the pattern into the bulk silicon layer. The first is with deep reactive ion etching (DRIE), which uses an etching method known as the Bosch process. Additionally, inductively-coupled plasma (ICP) etching can be done. This process is desirable when the metasurface is fabricated with a hardmask. The common hardmask material we have looked into was alumina, but any material with a high selectivity to the silicon etch layer would be sufficient with a calibrated recipe.

In a pinch, understanding the direct contributions of a particular tool allows for a temporary adjustment to GDSII parameters. What this means is that a physical bias can compensate for

feature deviations due to the exposure process, where laser power or focus may be misaligned to the standard operating specifications. In these cases, a small test pattern can be used to quantify this difference. Because a known look-up table is used when mapping the phase to scatterers, the test pattern can be quickly generated for the required geometry values, or a discrete, linearly spaced pattern can be used to approximate such values. For asymmetric geometry, I found that using the direct values is often valuable, because the more that the values deviate from square pillars, the size variation becomes more severe. Once the feature differences are known, this factor can be easily added into the GDSII writing phase and loaded again into the laser writer as a one-step solution for a particular device pattern.

With a poor fabrication run, a polarization-sensitive meta-atom ends up with a deviated shape, often becoming rounded or circular. When the corners are too large, the serif feature is actually exposed into the resist. This shows up in the final etched pattern. Adding in an array of serif features to the intensity/focus matrix test is an efficient way to find appropriate size serif attributes.

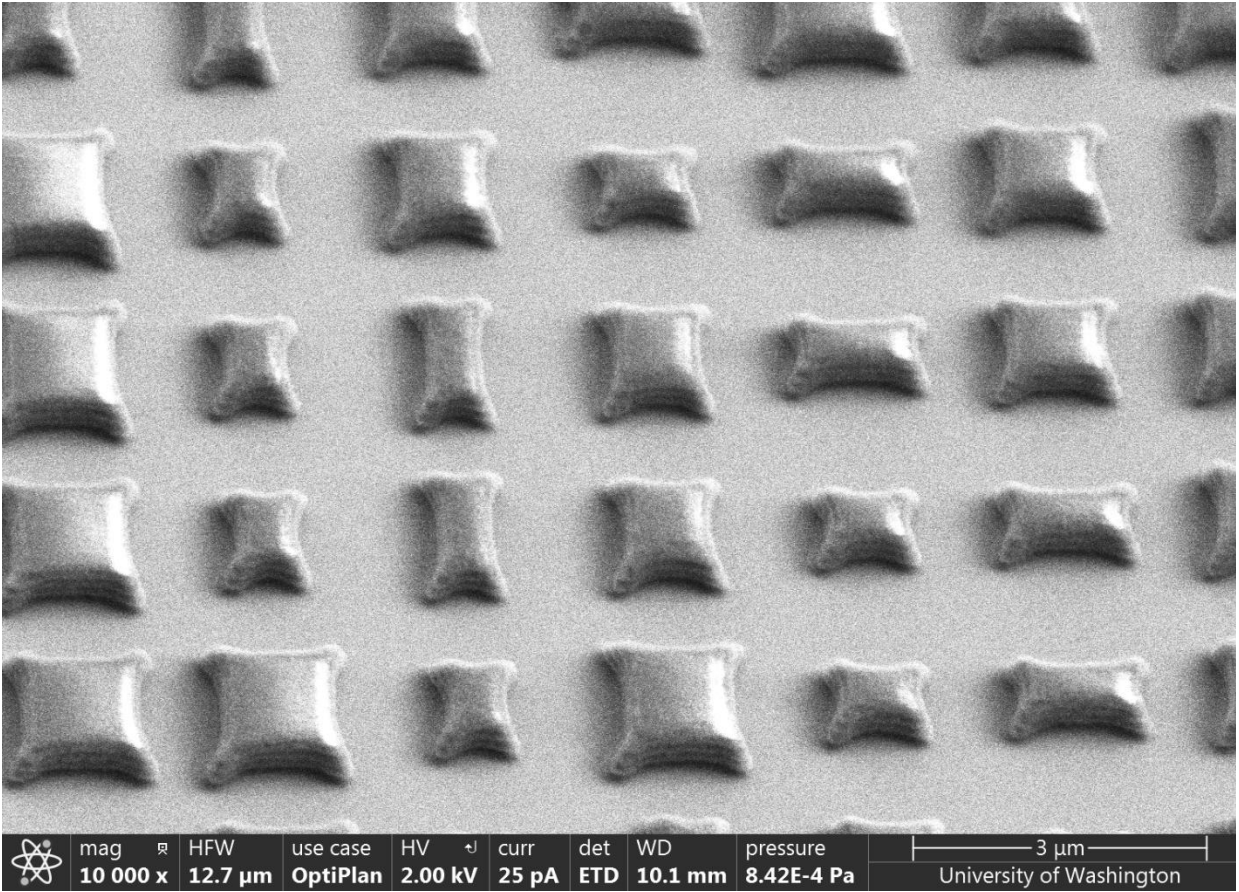


Figure 5.6 SEM characterization of meta-atoms where the serif size is too large. In this case, it leads to a rounded profile that is transferred into the bulk silicon layer after etching.

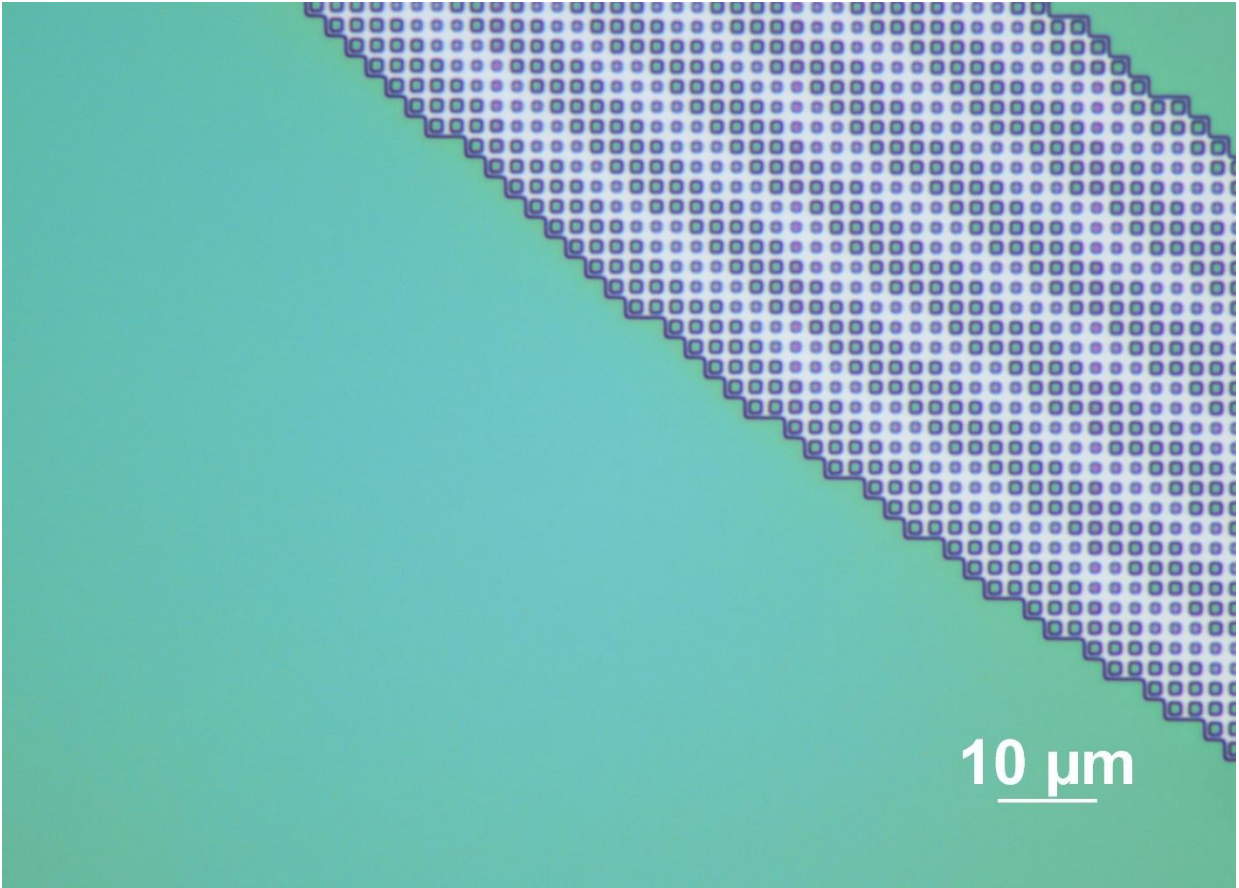


Figure 5.7 Optical microscope image of a fabricated all-Silicon meta-optic with added serifs.

5.4 Discussion

5.1.4 Preliminary Characterization

The first measurement test performed included a set of 1 mm apertures. However, I quickly found that the contrast was extremely low and the extent of polarization change was difficult to determine in experiment. Therefore, I redesigned the apertures to include a more comprehensive set of test lenses for characterization. Particularly for the infrared-wavelength metasurfaces, there can be a high degree of process variability in the photolithography fabrication step, even though the features are much larger than are necessary in the visible. This detail becomes especially important when characterizing meta-optics with polarization sensitivity because the asymmetry in the feature size is what impacts the polarization selectivity. This will directly impact the

intensity and SNR that emerges during characterization. From a set of 1 mm test apertures, we characterized the polarization sensitive meta-optics and found that there is a low contrast without the use of a metal aperture. The metal aperture improves imaging contrast to scatter reflections in the bulk layer and block stray light through the system.

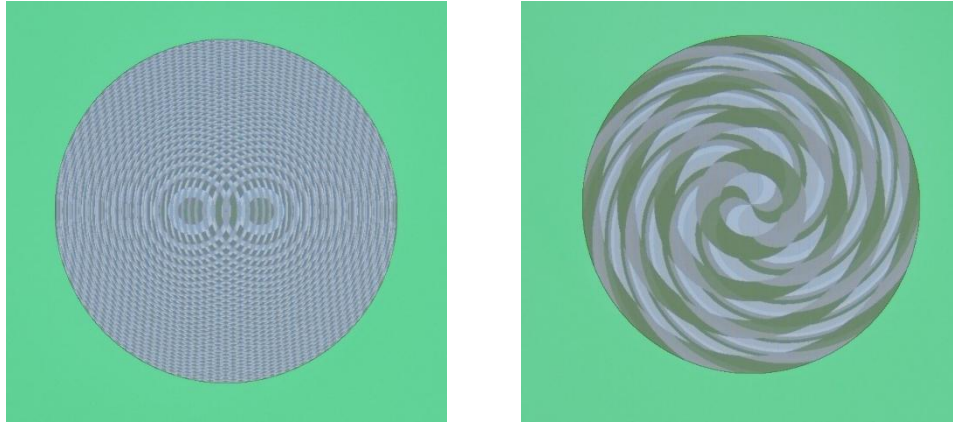


Figure 5.8 Polarization-multiplexed metasurface (left) and single-helix phase metasurface (right). The aperture size is 6 mm with an $f/10$ F-number.

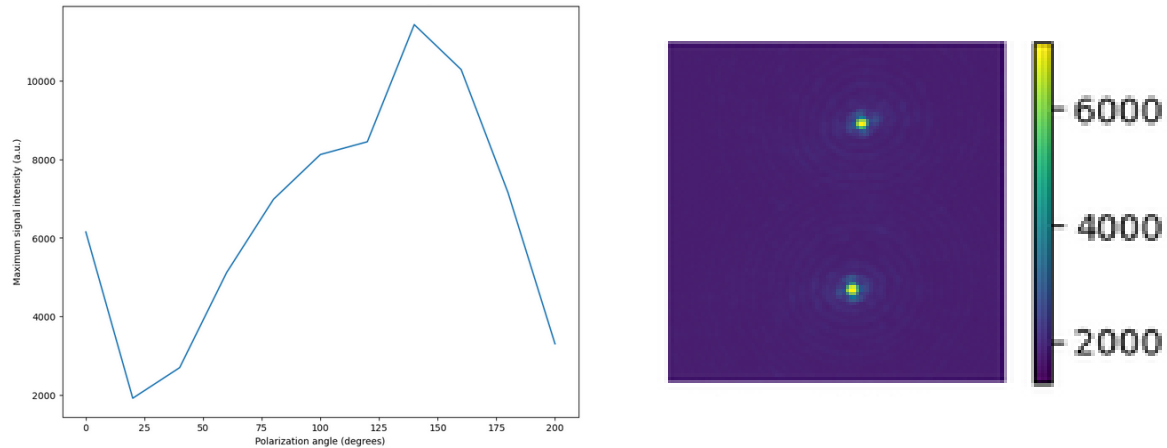


Figure 5.9 Signal intensity with varying polarization angle (left) and the PSF characterization of the two lobes of the polarization-multiplexed metasurface. The fabricated lens is shown in the figure above with an added metal aperture.

To further address the low signal contrast that constrained my preliminary characterization tests, I designed a set of decoupled functionality lenses were designed to troubleshoot the fabrication and characterization fidelity.

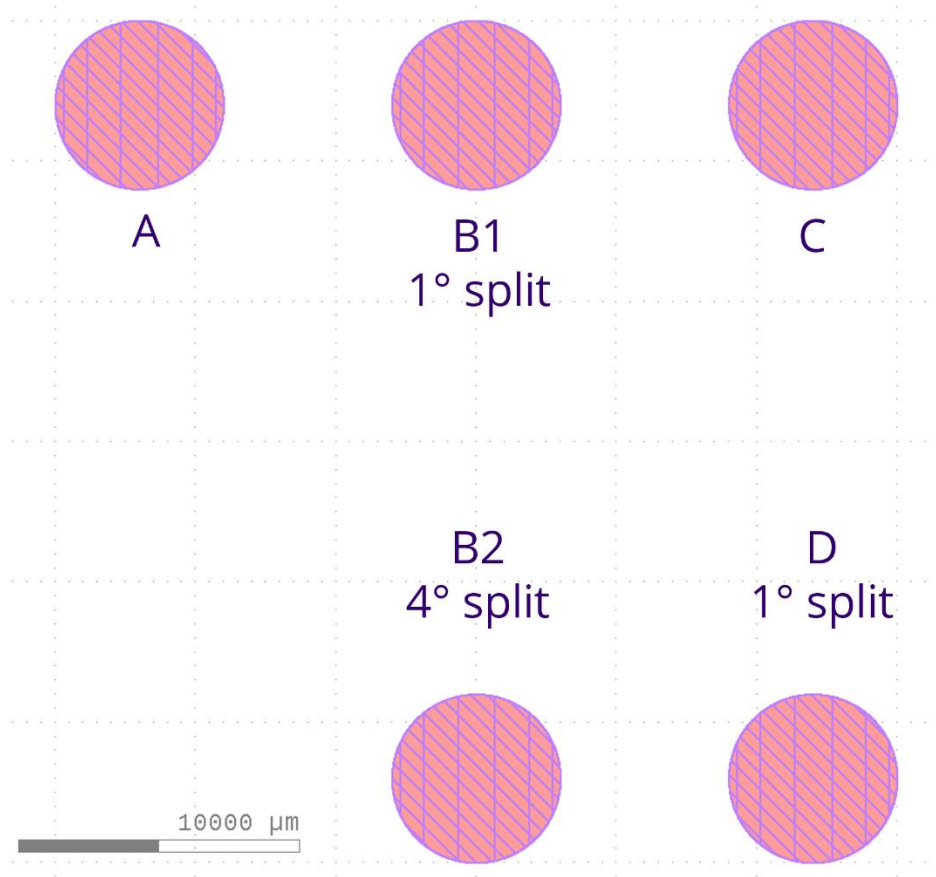


Figure 5.10 GDS of depth estimation apertures with decoupled functionality. Lens A: hyperboloid. Lens B1/B2: dual beam deflector with varying deflection angles. Lens C: beam rotator. Lens D: dual beam rotator.

Here, “Lens A” is the typically hyperboloid phase profile,

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

Where λ is the design wavelength and f is the focal length.

“Lens B” refers to the beam deflector which is the hyperboloid phase profile with an asymmetric focus in the x-coordinate. The deflection angle can be computed directly from the focal length.

“Lens C” is the beam rotator which is based on the Fresnel zone phase term for a single-helix PSF,

$$\psi_r(u, \varphi_u) = \left\{ l\varphi_u \left| \left(\frac{l-1}{L} \right)^\varepsilon \leq u \leq \left(\frac{l}{L} \right)^\varepsilon, l = 1, \dots, L \right. \right\}$$

Where u is the normalized radial coordinate, φ_u is the azimuth angle in the entrance pupil plane, and $[L, \varepsilon]$ are tunable design parameters that adjust the lobe confinement.

“Lens D” is the full design phase with a conjugate pair of single-helix PSFs at orthogonal polarization states.

5.2.4 Optimized Process Parameters

Due to the low SNR in the imaging measurements, I was unable to fully characterize the depth estimation apertures in experiment at my time at UW. However, I believe this is mostly due to technical error from fabrication and process drift than in the design itself which has been based on similar accounts in the published literature.^{70,71} In particular, the photolithography process variability provided an additional challenge to decouple the fabrication and characterization deviations from the simulated design. However, this additionally allowed me to develop a robust OPC calibration scheme for polarization-sensitive metasurfaces in the MWIR.

The current optimized process parameters are summarized in Table 1. In the cleanroom, the infrared (M/LWIR) metasurfaces use a Heidelberg DWL 66+ tool, as the typical aperture sizes (several centimeters) are infeasible to write with E-beam lithography. For typical MWIR fabrication, we use the Hi-Res write mode which, by manufacturer specifications is capable of resolving down to 300 nm features. From the metasurfaces that I have fabricated, the material is

all-silicon with a positive-tone photoresist, however negative photoresists are also possible. While I was not able to achieve the 300 nm benchmark, during my time in the WNF cleanroom, we were able to pattern ~500 nm features consistently.

Table 5.1 Fabrication parameters for polarization-sensitive meta-atoms

Attribute	Description of Fabrication
Material Platform	All-Si
Pillar Height	Fixed height (1 μm – 10 μm)
Minimum feature size	500 nm
Maximum aperture size	8 cm (4 in. wafer)
Etching scheme	Positive photoresist + DRIE

All-silicon based photolithography enables direct pattern-transfer of metasurface features from the photoresist to silicon substrate in a single-step exposure and development; without the use of a hard mask. Lithography with electron-beam (EBL) or deep ultraviolet (DUV) is capable of defining features with higher resolution, however the required fabrication process incurs material, etch depth, and aperture size constraints.^{72,73} Indeed, the facile processing scheme with direct-write lithography allows for large-aperture fabrication, only limited by the downstream fabrication equipment available at the UW cleanroom.

Our group has successfully demonstrated polarization-selective meta-optics operating in the LWIR range with feature sizes greater than 1.5 μm . For translating this work into the MWIR, the meta-atom feature sizes are reduced and the photolithography is achieved with a different write mode capable of the highest resolution. This alternate write mode increases the overall write time as compared to the LWIR process, and a new set of fabrication parameters are established.

The fabrication process operates on 525- μm thick double-sided polished silicon wafers. All wafers are primed with HMDS vapor to promote resist adhesion directly before spin-coating photoresist. Positive tone AZ1505 photoresist is spun to a thickness of ~ 500 nm and the metasurface pattern is exposed into the resist with a Heidelberg DWL66+ direct laser writer. The photoresist is developed with AZ726 MiF commercial developer and the pattern is transferred into the silicon substrate with deep reactive ion etching (DRIE) to the specified etch depth.

Chapter 6. Concluding Remarks

In the final chapter of this dissertation, I summarize my findings of meta-optics in the infrared and discuss possible directions for future work. I have proposed the strong advantages of metasurface adoption for SWaP-C applications and demonstrate examples of such cases in the infrared bandwidth ranges. However, one of the key applications in broadband imaging must address the challenge of chromatic aberrations. This is primarily approached with a computational imaging system to improve the raw imaging performance. Further, while an all-silicon platform is viable with key benefits in cost, fabrication complexity, and availability, one also must balance the reduction in transmission efficiency and contrast as costs to the overall performance. While there have been successful accounts of broadband, or full-color imaging through dispersion-engineering methods, there is still no gold standard example that achieves a large bandwidth, large aperture size, and appreciable NA at the time of this writing. Therefore, it is technology that does not necessitate the maximum resolution quality or imaging performance where meta-optics have a strong advantage to compete with traditional components owing largely to their form-factor and high degree of tunability.

I began this dissertation with a general overview of where meta-optics are categorized as a type of subwavelength diffractive optical element. In the case of transmissive metasurfaces, by designing the phase and amplitude response of the individual meta-atom scatterers, we are able to create a multitude of unique phase profiles from imaging to spectroscopy applications. To address the need of broadband imaging, a metalens can be designed directly or its phase mask can be optimized from a objective function set by the designer from the outset. This ends up being a successful approach in computational imaging systems for visible wavelengths. In the MWIR range, we showcase a direct comparison between the forward and inverse design cases

and demonstrate broadband imaging with a traditional hyperboloid metalens. This work also extends to the LWIR, where broadband intensity capture can be leveraged for thermometry applications to reconstruct 2D and 3D temperature maps. We then summarized our work with the fabrication of sparse apertures that follow an inverse design method to optimize the spatial frequency distribution and achieve a high-quality imaging system with a large, 89-mm diameter meta-optic. After providing several examples of forward and inverse designed meta-optics paired with computational reconstruction algorithms, we highlight the our work related to polarization-sensitive meta-optics towards the single-wavelength application of CO₂ sensing.

From my experience, the significant advantages of meta-optics are in their fabrication and design engineering utility. Search for any mainstream commercial simulation software we can find recent application examples for metasurfaces over the past five years. In addition, the advent of agentic AI may expedite the metasurface design process, either in discrete steps like RCWA simulation or the for end-to-end workflow. While it was not highlighted in this dissertation, I comment that multi-layer metasurfaces or hybrid assemblies may also be a promising direction to continue in the infrared bandwidths to address the particular challenge of small size and high imaging performance systems.^{74,75}

I encountered the field of meta-optics by happenstance. While the research has certainly matured over the past 10-15 years, it is still an exciting time to be a part of the meta-optics community. In particular, there is a growing interest in meta-optics at infrared wavelengths in the defense and aerospace industries. I've also had the opportunity to learn about metasurface integration in the private sector. As design and simulation tools become increasingly robust and integrated with AI tools, I hope that the nanofabrication and characterization techniques I have additionally attempted to highlight in this dissertation is useful to future researchers.

Bibliography

- (1) Liu, K.; Sun, S.; Majumdar, A.; Sorger, V. J. Fundamental Scaling Laws in Nanophotonics. *Sci. Rep.* **2016**, *6* (1), 37419. <https://doi.org/10.1038/srep37419>.
- (2) Hecht, E. *Optics*, 5 ed.; Pearson Education, Inc: Boston, 2017.
- (3) Arbabi, A.; Faraon, A. Fundamental Limits of Ultrathin Metasurfaces. *Sci. Rep.* **2017**, *7* (1), 43722. <https://doi.org/10.1038/srep43722>.
- (4) Presutti, F.; Monticone, F. Focusing on Bandwidth: Achromatic Metalens Limits. *Optica* **2020**, *7* (6), 624. <https://doi.org/10.1364/OPTICA.389404>.
- (5) Colburn, S.; Majumdar, A. Metasurface Generation of Paired Accelerating and Rotating Optical Beams for Passive Ranging and Scene Reconstruction. *ACS Photonics* **2020**, *7* (6), 1529–1536. <https://doi.org/10.1021/acsp Photonics.0c00354>.
- (6) Shen, Z.; Zhao, F.; Jin, C.; Wang, S.; Cao, L.; Yang, Y. Monocular Metasurface Camera for Passive Single-Shot 4D Imaging. *Nat. Commun.* **2023**, *14* (1), 1035. <https://doi.org/10.1038/s41467-023-36812-6>.
- (7) Bian, L.; Wang, Z.; Zhang, Y.; Li, L.; Zhang, Y.; Yang, C.; Fang, W.; Zhao, J.; Zhu, C.; Meng, Q.; Peng, X.; Zhang, J. A Broadband Hyperspectral Image Sensor with High Spatio-Temporal Resolution. *Nature* **2024**, *635* (8037), 73–81. <https://doi.org/10.1038/s41586-024-08109-1>.
- (8) Sitzmann, V.; Diamond, S.; Peng, Y.; Dun, X.; Boyd, S.; Heidrich, W.; Heide, F.; Wetzstein, G. End-to-End Optimization of Optics and Image Processing for Achromatic Extended Depth of Field and Super-Resolution Imaging. *ACM Trans. Graph.* **2018**, *37* (4), 1–13. <https://doi.org/10.1145/3197517.3201333>.
- (9) Peng, Y.; Fu, Q.; Heide, F.; Heidrich, W. The Diffractive Achromat Full Spectrum Computational Imaging with Diffractive Optics. *ACM Trans Graph* **2016**, *35* (4), 31:1–31:11. <https://doi.org/10.1145/2897824.2925941>.
- (10) Aieta, F.; Genevet, P.; Kats, M. A.; Yu, N.; Blanchard, R.; Gaburro, Z.; Capasso, F. Aberration-Free Ultrathin Flat Lenses and Axicons at Telecom Wavelengths Based on Plasmonic Metasurfaces. *Nano Lett.* **2012**, *12* (9), 4932–4936. <https://doi.org/10.1021/nl302516v>.

- (11) Yu, N.; Genevet, P.; Kats, M. A.; Aieta, F.; Tetienne, J.-P.; Capasso, F.; Gaburro, Z. Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction. *Science* **2011**, *334* (6054), 333–337. <https://doi.org/10.1126/science.1210713>.
- (12) Arbabi, A.; Horie, Y.; Ball, A. J.; Bagheri, M.; Faraon, A. Subwavelength-Thick Lenses with High Numerical Apertures and Large Efficiency Based on High-Contrast Transmitarrays. *Nat. Commun.* **2015**, *6* (1), 7069. <https://doi.org/10.1038/ncomms8069>.
- (13) Yu, N.; Genevet, P.; Kats, M. A.; Aieta, F.; Tetienne, J.-P.; Capasso, F.; Gaburro, Z. Light Propagation with Phase Discontinuities: Generalized Laws of Reflection and Refraction. *Science* **2011**, *334* (6054), 333–337. <https://doi.org/10.1126/science.1210713>.
- (14) Colburn, S.; Zhan, A.; Majumdar, A. Tunable Metasurfaces via Subwavelength Phase Shifters with Uniform Amplitude. **2016**. <https://doi.org/10.48550/ARXIV.1610.01966>.
- (15) Colburn, S.; Zhan, A.; Majumdar, A. Varifocal Zoom Imaging with Large Area Focal Length Adjustable Metalenses. *Optica* **2018**, *5* (7), 825. <https://doi.org/10.1364/OPTICA.5.000825>.
- (16) Colburn, S.; Zhan, A.; Majumdar, A. Metasurface Optics for Full-Color Computational Imaging. *Sci. Adv.* **2018**, *4* (2), eaar2114. <https://doi.org/10.1126/sciadv.aar2114>.
- (17) Huang, L.; Colburn, S.; Zhan, A.; Majumdar, A. Full-Color Metaoptical Imaging in Visible Light. *Adv. Photonics Res.* **2022**, *3* (5), 2100265. <https://doi.org/10.1002/adpr.202100265>.
- (18) Bayati, E.; Pestourie, R.; Colburn, S.; Lin, Z.; Johnson, S. G.; Majumdar, A. Inverse Designed Extended Depth of Focus Meta-Optics for Broadband Imaging in the Visible. *Nanophotonics* **2022**, *11* (11), 2531–2540. <https://doi.org/10.1515/nanoph-2021-0431>.
- (19) Huang, L.; Whitehead, J.; Colburn, S.; Majumdar, A. Design and Analysis of Extended Depth of Focus Metalenses for Achromatic Computational Imaging. *Photonics Res.* **2020**, *8* (10), 1613. <https://doi.org/10.1364/PRJ.396839>.
- (20) Tseng, E.; Colburn, S.; Whitehead, J.; Huang, L.; Baek, S.-H.; Majumdar, A.; Heide, F. Neural Nano-Optics for High-Quality Thin Lens Imaging. *Nat. Commun.* **2021**, *12* (1), 6493. <https://doi.org/10.1038/s41467-021-26443-0>.
- (21) Fröch, J. E.; Chakravarthula, P. K.; Sun, J.; Tseng, E.; Zhan, A.; Miller, F.; Wirth-Singh, A.; Tanguy, Q. A. A.; Böhringer, K. F.; Heide, F.; Majumdar, A. Beating Bandwidth Limits for Large Aperture Broadband Nano-Optics.

- (22) Huang, L.; Han, Z.; Wirth-Singh, A.; Saragadam, V.; Mukherjee, S.; Fröch, J. E.; Tanguy, Q. A. A.; Rollag, J.; Gibson, R.; Hendrickson, J. R.; Hon, P. W. C.; Kigner, O.; Coppens, Z.; Böhringer, K. F.; Veeraraghavan, A.; Majumdar, A. Broadband Thermal Imaging Using Meta-Optics. *Nat. Commun.* **2024**, *15* (1), 1662. <https://doi.org/10.1038/s41467-024-45904-w>.
- (23) Wirth-Singh, A.; Brook, A. M.; Johnson, R.; Froch, J. E.; Majumdar, A. Meta-Optical Imaging at Thermal Wavelengths.
- (24) Wirth-Singh, A.; Jimenez, A. M.; Choi, M.; Fröch, J. E.; Johnson, R.; Le, T.; Coppens, Z.; Majumdar, A. Meta-Optics Triplet for Zoom Imaging at Mid-Wave Infrared.
- (25) Cirjulina, D.; Zhang, Z.; Hayee, A.; Ostrovskis, A.; Schatz, R.; Dely, H.; Sun, Y.; Salgals, T.; Spolitis, S.; Bobrovs, V.; Zhang, L.; Gacemi, D.; Vasanelli, A.; Sirtori, C.; Yu, X.; Ozolins, O.; Pang, X. Mid-Infrared Free-Space Optical Communications: Technologies, Demonstrations and Future Directions. *IET Optoelectron.* **2026**, *20* (1), e70034. <https://doi.org/10.1049/ote2.70034>.
- (26) Zhou, H.; Chen, L.; Shen, F.; Guo, K.; Guo, Z. Broadband Achromatic Metalens in the Midinfrared Range. *Phys. Rev. Appl.* **2019**, *11* (2), 024066. <https://doi.org/10.1103/PhysRevApplied.11.024066>.
- (27) Li, X.; Chen, S.; Wang, D.; Shi, X.; Fan, Z. Transmissive Mid-Infrared Achromatic Bifocal Metalens with Polarization Sensitivity. *Opt. Express* **2021**, *29* (11), 17173. <https://doi.org/10.1364/OE.424887>.
- (28) Yuan, Y.; Yan, Z.; Zhang, P.; Chang, Z.; Peng, F.; Chen, R.; Yang, Z.; Chen, S.; Zhao, Q.; Huang, X. A Broadband Achromatic Dielectric Planar Metalens in Mid-IR Range. *Photonic Sens.* **2023**, *13* (1), 230126. <https://doi.org/10.1007/s13320-022-0667-4>.
- (29) Sandler, D. G.; Hyman, H.; Brinkley, T. J.; Leslie, D. H. MWIR Adaptive Optics System for Imaging Missile Defense Tests Using the 3.7-m AEOS Telescope; Bilbro, J. W., Breckinridge, J. B., Carreras, R. A., Czyzak, S. R., Eckart, M. J., Fiete, R. D., Idell, P. S., Eds.; San Diego, CA, 2000; pp 283–291. <https://doi.org/10.1117/12.405787>.
- (30) Swami, S. S.; Mohd, B.; Schmitt, M.; Mundt, C. On-Board Detection of Fast-Moving Targets Using an MWIR Sensor on a Small Satellite. In *Artificial Intelligence and Image and Signal Processing for Remote Sensing XXX*; Bruzzone, L., Bovolo, F., Eds.; SPIE: Edinburgh, United Kingdom, 2024; p 7. <https://doi.org/10.1117/12.3031665>.

- (31) Huang, L.; Han, Z.; Wirth-Singh, A.; Saragadam, V.; Mukherjee, S.; Fröch, J. E.; Tanguy, Q. A. A.; Rollag, J.; Gibson, R.; Hendrickson, J. R.; Hon, P. W. C.; Kigner, O.; Coppens, Z.; Böhringer, K. F.; Veeraraghavan, A.; Majumdar, A. Broadband Thermal Imaging Using Meta-Optics. *Nat. Commun.* **2024**, *15* (1), 1662. <https://doi.org/10.1038/s41467-024-45904-w>.
- (32) Saragadam, V.; Han, Z.; Boominathan, V.; Huang, L.; Tan, S.; Fröch, J. E.; Böhringer, K. F.; Baraniuk, R. G.; Majumdar, A.; Veeraraghavan, A. Foveated Thermal Computational Imaging Prototype Using All-Silicon Meta-Optics. *Optica* **2024**, *11* (1), 18. <https://doi.org/10.1364/OPTICA.502857>.
- (33) Presutti, F.; Monticone, F. Focusing on Bandwidth: Achromatic Metalens Limits. *Optica* **2020**, *7* (6), 624. <https://doi.org/10.1364/OPTICA.389404>.
- (34) Engelberg, J.; Levy, U. Achromatic Flat Lens Performance Limits. *Optica* **2021**, *8* (6), 834. <https://doi.org/10.1364/OPTICA.422843>.
- (35) Colburn, S.; Zhan, A.; Majumdar, A. Full-Color Imaging with PSF-Engineered Metasurfaces and Computational Reconstruction. In *Frontiers in Optics 2017 (2017)*, paper FM4A.4; Optica Publishing Group, 2017; p FM4A.4. <https://doi.org/10.1364/FIO.2017.FM4A.4>.
- (36) Liu, V.; Fan, S. S4 : A Free Electromagnetic Solver for Layered Periodic Structures. *Comput. Phys. Commun.* **2012**, *183* (10), 2233–2244. <https://doi.org/10.1016/j.cpc.2012.04.026>.
- (37) *How to model diffractive optics using the Binary 2 surface*. Ansys Optics. <https://optics.ansys.com/hc/en-us/articles/42661706685075-How-to-model-diffractive-optics-using-the-Binary-2-surface> (accessed 2026-08-21).
- (38) Wirth-Singh, A.; Fröch, J. E.; Yang, F.; Martin, L.; Zheng, H.; Zhang, H.; Tanguy, Q. T.; Zhou, Z.; Huang, L.; John, D. D.; Stamenic, B.; Hu, J.; Gu, T.; Majumdar, A. Wide Field of View Large Aperture Meta-Doublet Eyepiece. *Light Sci. Appl.* **2025**, *14* (1), 17. <https://doi.org/10.1038/s41377-024-01674-0>.
- (39) Wang, J.; Wirth-Singh, A.; Saragadam, V.; Johnson, R.; Majumdar, A.; Veeraraghavan, A. A Golay Metalens for Long-Range, Large Aperture, Thermal Imaging via Sparse Aperture Computational Imaging. *Nat. Commun.* **2025**, *16* (1), 10281. <https://doi.org/10.1038/s41467-025-65188-y>.

- (40) Vo, C.; Anderson, O.; Wirth-Singh, A.; Johnson, R.; Majumdar, A.; Coppens, Z. Broadband Long-Range Thermal Imaging via Meta-Correctors.
- (41) Colburn, S.; Majumdar, A. Inverse Design and Flexible Parameterization of Meta-Optics Using Algorithmic Differentiation. *Commun. Phys.* **2021**, *4* (1), 65.
<https://doi.org/10.1038/s42005-021-00568-6>.
- (42) Bayati, E.; Pestourie, R.; Colburn, S.; Lin, Z.; Johnson, S. G.; Majumdar, A. Inverse Designed Metalenses with Extended Depth of Focus. *ACS Photonics* **2020**, *7* (4), 873–878.
<https://doi.org/10.1021/acsp Photonics.9b01703>.
- (43) Bayer Filter. *Wikipedia*; 2026.
- (44) *Vision Glossary > N ~ Z*.
https://www.icpdas.com/products/Vision/mavis/vision_glossary_n~z.htm (accessed 2026-08-21).
- (45) *numpy.trapz — NumPy v1.25 Manual*.
<https://numpy.org/doc/1.25/reference/generated/numpy.trapz.html> (accessed 2026-08-21).
- (46) Mandal, D.; Chattopadhyay, S.; Wang, Y.; Niethammer, M.; Chakravarthula, P. UnSCAR: Universal, Scalable, Controllable, and Adaptable Image Restoration. arXiv March 8, 2026.
<https://doi.org/10.48550/arXiv.2603.07406>.
- (47) *25mm Dia. x 25mm FL, 3 - 5μm Coated, Ge Plano-Convex Lens*.
<https://www.edmundoptics.com/p/25mm-dia-x-25mm-fl-3-5mum-coated-ge-plano-convex-lens/23930/> (accessed 2026-08-21).
- (48) Dong, Y.; Zheng, B.; Li, H.; Tang, H.; Zhao, H.; Huang, Y.; An, S.; Zhang, H. Achromatic Single Metalens Imaging via Deep Neural Network. *ACS Photonics* **2024**, *11* (4), 1645–1656. <https://doi.org/10.1021/acsp Photonics.3c01870>.
- (49) Zhan, A.; Colburn, S.; Trivedi, R.; Fryett, T. K.; Dodson, C. M.; Majumdar, A. Low-Contrast Dielectric Metasurface Optics. *ACS Photonics* **2016**, *3* (2), 209–214.
<https://doi.org/10.1021/acsp Photonics.5b00660>.
- (50) Fiete, R. D. Image Quality of Sparse-Aperture Designs for Remote Sensing. *Opt. Eng.* **2002**, *41* (8), 1957. <https://doi.org/10.1117/1.1490555>.
- (51) Fiete, R. D. Image Quality of Sparse-Aperture Designs for Remote Sensing. *Opt. Eng.* **2002**, *41* (8), 1957. <https://doi.org/10.1117/1.1490555>.

- (52) *James Webb Space Telescope - NASA Science*. <https://science.nasa.gov/mission/webb/> (accessed 2026-08-21).
- (53) Lagunas, E.; Chatzinotas, S.; Ottersten, B. Low-Earth Orbit Satellite Constellations for Global Communication Network Connectivity. *Nat. Rev. Electr. Eng.* **2024**, *1* (10), 656–665. <https://doi.org/10.1038/s44287-024-00088-9>.
- (54) Perley, R. A.; Chandler, C. J.; Butler, B. J.; Wrobel, J. M. THE EXPANDED VERY LARGE ARRAY: A NEW TELESCOPE FOR NEW SCIENCE. *Astrophys. J.* **2011**, *739* (1), L1. <https://doi.org/10.1088/2041-8205/739/1/L1>.
- (55) Selina, R.; McKinnon, M.; Beasley, A. J.; Murphy, E.; Carilli, C.; Butler, B.; Clark, B.; Erickson, A.; Grammer, W.; Jackson, J.; Kent, B.; Mason, B.; Morgan, M.; Ojeda, O.; Shillue, W.; Sturgis, S.; Urbain, D. The Next-Generation Very Large Array: A Technical Overview. In *Ground-based and Airborne Telescopes VII*; Gilmozzi, R., Marshall, H. K., Spyromilio, J., Eds.; SPIE: Austin, United States, 2018; p 55. <https://doi.org/10.1117/12.2312089>.
- (56) Wang, J.; Wirth-Singh, A.; Saragadam, V.; Johnson, R.; Majumdar, A.; Veeraraghavan, A. A Golay Metalens for Long-Range, Large Aperture, Thermal Imaging via Sparse Aperture Computational Imaging. *Nat. Commun.* **2025**, *16* (1), 10281. <https://doi.org/10.1038/s41467-025-65188-y>.
- (57) Roberts, G.; Ballew, C.; Zheng, T.; Garcia, J. C.; Camayd-Muñoz, S.; Hon, P. W. C.; Faraon, A. 3D-Patterned Inverse-Designed Mid-Infrared Metaoptics. *Nat. Commun.* **2023**, *14* (1), 2768. <https://doi.org/10.1038/s41467-023-38258-2>.
- (58) Ou, K.; Yu, F.; Li, G.; Wang, W.; Miroshnichenko, A. E.; Huang, L.; Wang, P.; Li, T.; Li, Z.; Chen, X.; Lu, W. Mid-Infrared Polarization-Controlled Broadband Achromatic Metadevice. *Sci. Adv.* **2020**, *6* (37), eabc0711. <https://doi.org/10.1126/sciadv.abc0711>.
- (59) Huang, P.-S.; Chu, C. H.; Huang, S.-H.; Su, H.-P.; Tanaka, T.; Wu, P. C. Varifocal Metalenses: Harnessing Polarization-Dependent Superposition for Continuous Focal Length Control. *Nano Lett.* **2023**, *23* (22), 10432–10440. <https://doi.org/10.1021/acs.nanolett.3c03056>.
- (60) Intaravanne, Y.; Chen, X. Recent Advances in Optical Metasurfaces for Polarization Detection and Engineered Polarization Profiles. *Nanophotonics* **2020**, *9* (5), 1003–1014. <https://doi.org/10.1515/nanoph-2019-0479>.

- (61) Kuang, Y.; Wang, S.; Mo, B.; Sun, S.; Xia, K.; Yang, Y. Palm Vein Imaging Using a Polarization-Selective Metalens with Wide Field-of-View and Extended Depth-of-Field. *Npj Nanophotonics* **2024**, *1* (1), 24. <https://doi.org/10.1038/s44310-024-00027-4>.
- (62) Ni, Y.; Chen, C.; Wen, S.; Xue, X.; Sun, L.; Yang, Y. Computational Spectropolarimetry with a Tunable Liquid Crystal Metasurface. *eLight* **2022**, *2* (1), 23. <https://doi.org/10.1186/s43593-022-00032-0>.
- (63) Kuznetsov, A. I.; Brongersma, M. L.; Yao, J.; Chen, M. K.; Levy, U.; Tsai, D. P.; Zheludev, N. I.; Faraon, A.; Arbabi, A.; Yu, N.; Chanda, D.; Crozier, K. B.; Kildishev, A. V.; Wang, H.; Yang, J. K. W.; Valentine, J. G.; Genevet, P.; Fan, J. A.; Miller, O. D.; Majumdar, A.; Fröch, J. E.; Brady, D.; Heide, F.; Veeraraghavan, A.; Engheta, N.; Alù, A.; Polman, A.; Atwater, H. A.; Thureja, P.; Paniagua-Dominguez, R.; Ha, S. T.; Barreda, A. I.; Schuller, J. A.; Staude, I.; Grinblat, G.; Kivshar, Y.; Peana, S.; Yelin, S. F.; Senichev, A.; Shalae, V. M.; Saha, S.; Boltasseva, A.; Rho, J.; Oh, D. K.; Kim, J.; Park, J.; Devlin, R.; Pala, R. A. Roadmap for Optical Metasurfaces. *ACS Photonics* **2024**, *11* (3), 816–865. <https://doi.org/10.1021/acsp Photonics.3c00457>.
- (64) Roberts, G.; Ballew, C.; Zheng, T.; Garcia, J. C.; Camayd-Muñoz, S.; Hon, P. W. C.; Faraon, A. 3D-Patterned Inverse-Designed Mid-Infrared Metaoptics. *Nat. Commun.* **2023**, *14* (1), 2768. <https://doi.org/10.1038/s41467-023-38258-2>.
- (65) Saragadam, V.; Han, Z.; Boominathan, V.; Huang, L.; Tan, S.; Fröch, J. E.; Böhringer, K. F.; Baraniuk, R. G.; Majumdar, A.; Veeraraghavan, A. Foveated Thermal Computational Imaging Prototype Using All-Silicon Meta-Optics. *Optica* **2024**, *11* (1), 18. <https://doi.org/10.1364/OPTICA.502857>.
- (66) Vo, C.; Anderson, O.; Wirth-Singh, A.; Johnson, R.; Majumdar, A.; Coppens, Z. Broadband Long-Range Thermal Imaging via Meta-Correctors. *Appl. Opt.* **2025**, *64* (13), 3473–3479. <https://doi.org/10.1364/AO.553334>.
- (67) Zhang, J.; Sun, Q.; Wang, Z.; Zhang, G.; Liu, Y.; Liu, J.; Martins, E. R.; Krauss, T. F.; Liang, H.; Li, J.; Wang, X.-H. A Fully Metaoptical Zoom Lens with a Wide Range. *Nano Lett.* **2024**, *acs.nanolett.4c00328*. <https://doi.org/10.1021/acs.nanolett.4c00328>.
- (68) Yang, F.; Lin, H.; Shalaginov, M. Y.; Stoll, K.; An, S.; Rivero-Baleine, C.; Kang, M.; Agarwal, A.; Richardson, K.; Zhang, H.; Hu, J.; Gu, T. Reconfigurable Parfocal Zoom

- Metalens. *Adv. Opt. Mater.* **2022**, *10* (17), 2200721.
<https://doi.org/10.1002/adom.202200721>.
- (69) *NASA PACE - Section III: Light & the Atmosphere*.
https://pace.oceansciences.org/atmos_light.cgi (accessed 2026-08-21).
- (70) Colburn, S.; Majumdar, A. Metasurface Generation of Paired Accelerating and Rotating Optical Beams for Passive Ranging and Scene Reconstruction. *ACS Photonics* **2020**, *7* (6), 1529–1536. <https://doi.org/10.1021/acsphotonics.0c00354>.
- (71) Shen, Z.; Zhao, F.; Jin, C.; Wang, S.; Cao, L.; Yang, Y. Monocular Metasurface Camera for Passive Single-Shot 4D Imaging. *Nat. Commun.* **2023**, *14* (1), 1035.
<https://doi.org/10.1038/s41467-023-36812-6>.
- (72) Beisenova, A.; Adi, W.; Wu, W.; Biswas, S. K.; Rosas, S.; Stamenic, B.; John, D. D.; Yesilkoy, F. Wafer-Scale All-Dielectric Quasi-BIC Metasurfaces: Bridging High-Throughput Deep-UV Lithography with Nanophotonic Applications. *Nano Lett.* **2026**, *26* (6), 2059–2067. <https://doi.org/10.1021/acs.nanolett.5c05226>.
- (73) Yoon, G.; Tanaka, T.; Zentgraf, T.; Rho, J. Recent Progress on Metasurfaces: Applications and Fabrication. *J. Phys. Appl. Phys.* **2021**, *54* (38), 383002. <https://doi.org/10.1088/1361-6463/ac0faa>.
- (74) Shih, K.-H.; Renshaw, C. K. 1 Hybrid Meta/Refractive Lens Design with 2 Inverse Design Using Physical Optics.
- (75) Pinilla, S.; Frösch, J. E.; Miri Rostami, S. R.; Katkovnik, V.; Shevkunov, I.; Majumdar, A.; Egiazarian, K. Miniature Color Camera via Flat Hybrid Meta-Optics. *Sci. Adv.* **2023**, *9* (21), eadg7297. <https://doi.org/10.1126/sciadv.adg7297>.