

# LWIR Metalens for Monochromatic Lightweight Imaging Applications

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# REPORT DOCUMENTATION PAGE

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**CLOSEOUT MEMORANDUM FOR NRL BASE PROGRAM 996C20: INFRARED  
METALENSSES FOR LIGHTWEIGHT IMAGING APPLICATIONS**

**EXECUTIVE SUMMARY**

This document satisfies the closeout requirements for NRL base program 996C20: Infrared Metalenses for Lightweight Imaging Applications. It provides an overview of the technical objectives of the program, technical progress, and dissemination of research findings through publications, reports, and presentations.

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**1. PROGRAM DESCRIPTION**

The objective of this program is to develop a lightweight Long-Wave Infrared (LWIR) metalens to enable a 5x reduction in size weight and power (SWAP) for imaging systems in the LWIR waveband. Metalenses are artificially engineered subwavelength-spaced arrays of nanophotonic phase-shifting elements that can be configured to manipulate incident light. They consist of thin, patterned layers usually deposited on a flat substrate (e.g. Germanium on a Zinc Selenide substrate). These nanophotonic phase-shifting elements were designed and selected to produce an imaging lens. This work is focused on leveraging state-of-the-art advances in visible waveband metalenses, to advance complementary design and fabrication techniques to create metalenses in the LWIR. Progress has been made in the following areas: 1) Model development for improvement of accuracy in predicting performance of metalenses 2) Development of a polarization-independent meta-atom library containing NRL designed meta-atom component to be used in design of metalens 3) Fabrication of a germanium metalens on a zinc selenide substrate. More detailed descriptions of these topics are given below.

### 1.1. Metalens Forward Modeling

Metalenses are distinct from classical lenses in that the discretization of spatial phase must be considered to properly model the imaging performance. NRL was required to develop a new forward model to predict performance of fabricated lenses. The Angular Spectrum Method (ASM) was used to propagate electromagnetic fields and yielded accurate results. It is the technique that arises from solving the Helmholtz equation for a medium with uniform permittivity.

An initial simulation of a classical lens with circular aperture and an ideal lens phase front was compared to the analytical result of an Airy function and results are shown in fig. 1. Proof of concept was performed with an ideal phase profile and matching experimental parameters.

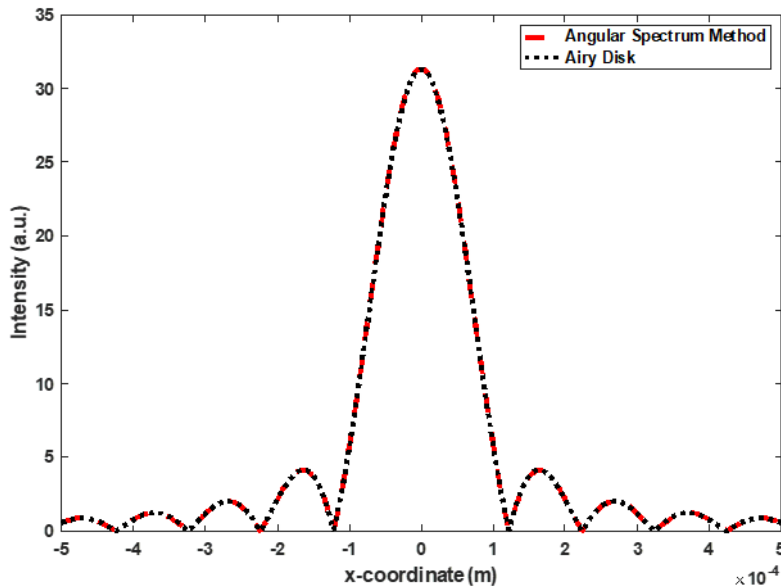


Figure 1. Comparison of ASM and Airy Disk.

Comparison to fabricated device was performed by simulating a system with the following parameters. The input field has the corresponding phase to each input with  $\Delta x, y = 4.1 \mu\text{m}$ , diameter of 4 mm, and matching a 6 mm focal length. Our model contains the spatial discretization of using a camera with finite pixel size. The detector has a pixel pitch of  $17 \mu\text{m}$ . In figure 2, the experimentally measured focal spot is compared to the simulated spot as well as the airy function and were found to be in good agreement. A FWHM of the distributions were found to be  $32.4 \mu\text{m}$ ,  $27.6 \mu\text{m}$ , and  $25.9 \mu\text{m}$  for the experimental, simulated, and airy disk, respectively.

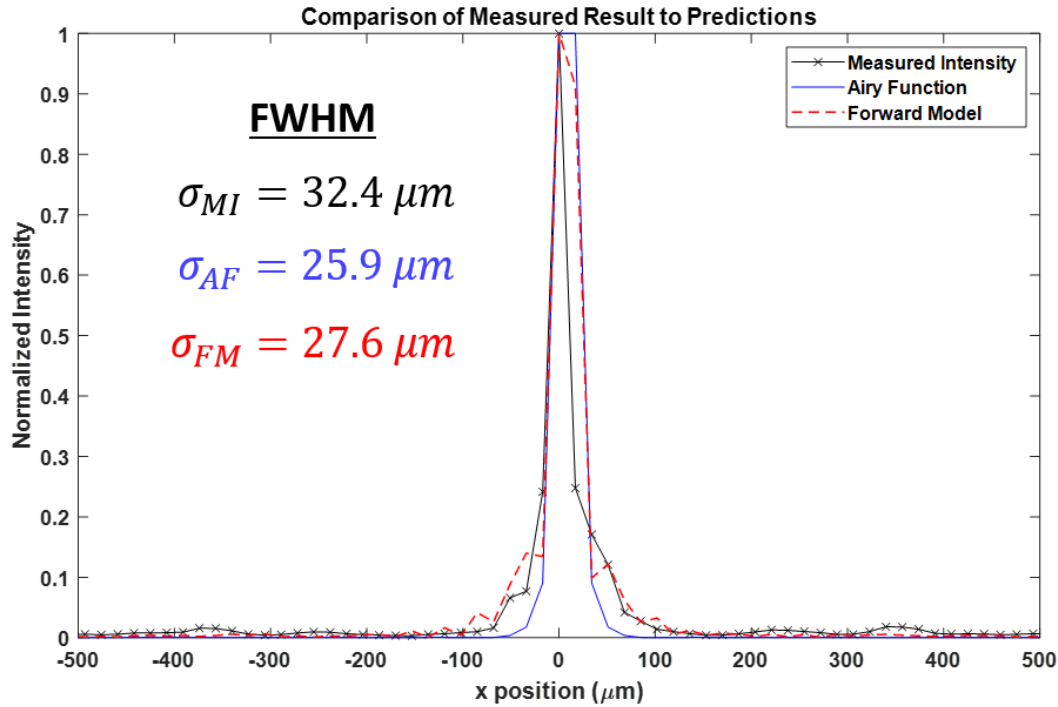


Figure 2. Comparison of experimental results to simulated and analytical predictions.

## 1.2. Meta-Atom Library

Metalenses are artificially engineered subwavelength-spaced arrays of nanophotonic phase-shifting elements that can be configured to manipulate incident light. These nanophotonic phase-shifting elements are called meta-atoms and a varied collection of these meta-atoms forms a meta-atom library. These meta-atoms were designed using MIRaGE software by Stellar Science Ltd, Company. MIRaGE is a finite-element method (FEM) modeling tool written to aid developers designing optically useful devices using meta-surfaces.

In order to design an effective metalens, a well-populated meta-atom library should contain a set of meta-atoms that induce a wide-array of phase changes (spanning from 0 to  $2\pi$ ) on the incident light, while also having high transmission. The NRL meta-atom library consists of six four-fold symmetry geometric classes of meta-atoms, as shown in figure 3. Four-fold symmetry was chosen to create meta-atoms that exhibit polarization independence. The meta-atoms were designed using a high-index of refraction material, Germanium (Ge), that sit upon a low-index of refraction material, Zinc Selenide (ZnSe), substrate. Both materials are transparent in the LWIR. The thickness of the Ge layer was  $1.5 \mu m$  and the maximum X-Y dimensions of any meta-atom was  $4.1 \times 4.1 \mu m$ . Note that these dimensions are subwavelength in size with respect to the incident light ( $8-12 \mu m$ ).

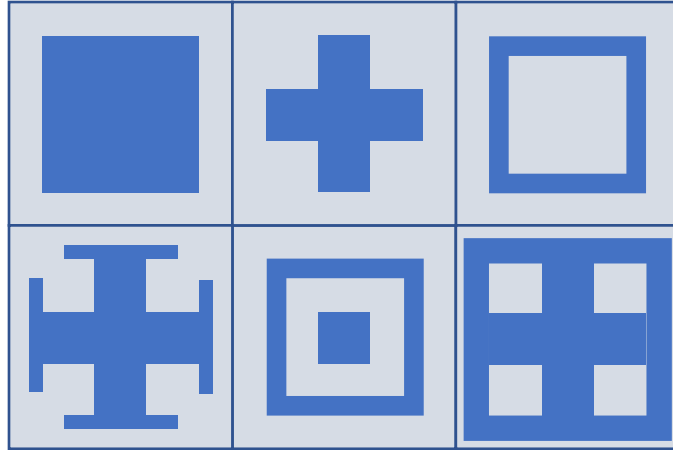


Figure 3. Meta-atom geometries.

These six different geometries were scaled in a periodic fashion in both the X-Y dimensions and in wall thickness. Meta-atom height ( $Z$ ) was held constant. This methodical change in geometries produced a very large set of meta-atoms where each meta-atom exhibited its own transmission and phase-changing characteristics that also varied with wavelength. The library consists of 100k+ of designs at discrete wavelengths across the LWIR band, making it useful to design both monochromatic and broadband lenses. Figure 4 shows a phase vs. transmission plot for 22k meta-atoms characterized at  $10\ \mu\text{m}$  for a monochromatic lens.

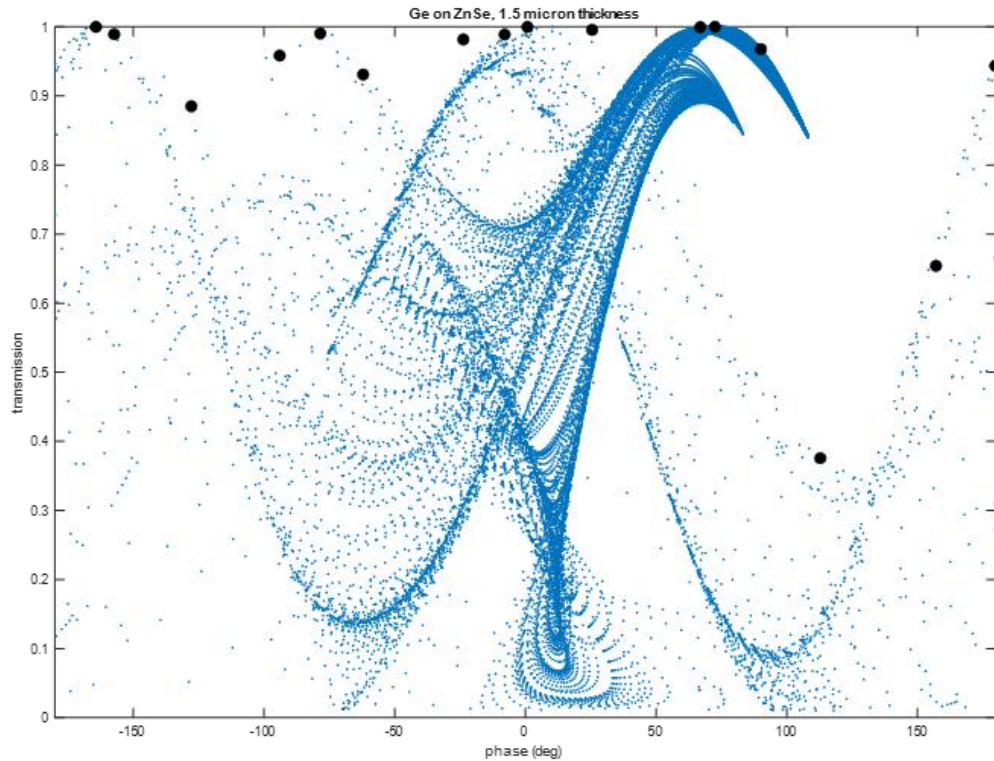


Figure 4. Meta-atom geometries.

The black dots represent the 16 meta-atoms selected for the required  $2\pi$  phase coverage in our monochromatic metalens.

### 1.3. Fabrication of Metalens

Our group designed, fabricated, and tested a 4 mm diameter LWIR lens. The ideal phase curve across the lens was discretized in a circularly symmetric manner into 16 annulus bins. Each bin was assigned the required average phase delay according to the ideal phase curve. As shown in figure 4, 16 meta-atoms (with the required phase delays that had the highest transmission) were chosen to populate the 16 bins. Designs that were deemed un-manufacturable were eliminated during the down-selection process. The selected meta-atom designs were laid out in a grid for fabrication.

Fabrication took place at NRL's Nanoscience Institute (NSI). The metalens design was converted to an e-beam lithography GDS design. A 1.56  $\mu\text{m}$  thick Ge film was deposited on a ZnSe substrate using an e-beam evaporator and was patterned with the Raith Voyager e-beam lithography machine. The etch mask was deposited and the pattern lifted by inductively coupled plasma etching of the Ge film. Figure 5 shows the fabricated metalens on the left and a section of meta-atoms on the right.

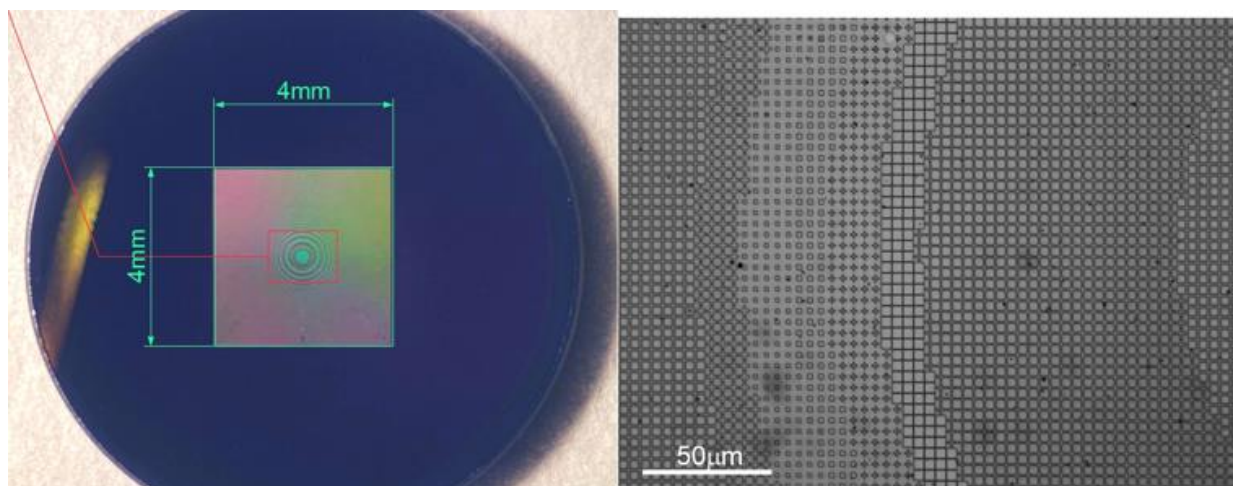


Figure 5: A 4-mm diameter, narrowband, on-axis lens was fabricated from an NRL design.

### 1.4. Metalens Performance

The NRL LWIR monochromatic metalens exhibited on-axis diffraction-limited performance. The lens was 4 x 4 mm and designed to be  $f/1.5$ . Lens performance was measured using custom Raytheon uncooled LWIR camera with a pixel size of 12 x 12  $\mu\text{m}$ . Source was a tunable quantum cascade laser operating at 10  $\mu\text{m}$ .

Figure 2 shows excellent agreement of the experimental results with the simulated and analytical predictions. Figure 6 shows the through-focus behavior on the camera.

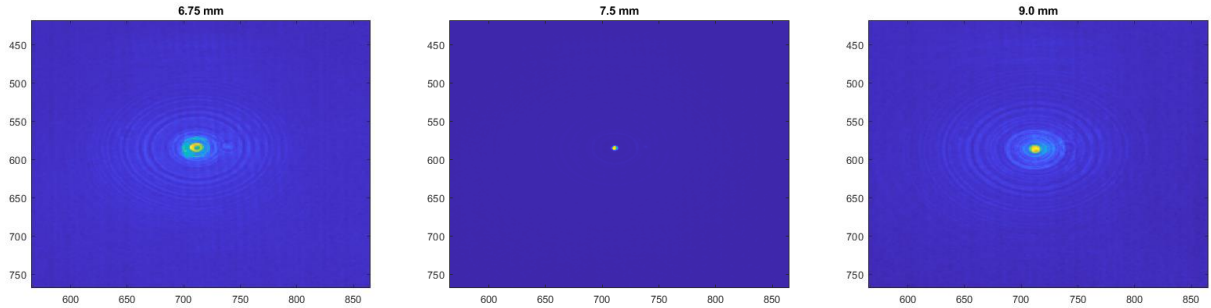


Figure 6. Through-focus behavior at 6.75, 7.5 and 9.0 mm.

## 2. DISSEMINATION

### 2.1. Refereed conference papers

Scott Sarama, Erin Fleet, Heath Gemar, Michael Yetzbacher, Chul Soo Kim, Mijin Kim, Jacobs Technology Inc, Josiah Brinson, Naval Research Enterprise Internship Program. LWIR Metalens for Monochromatic Lightweight Imaging Applications. 2024 Parallel (BSD, Materials & Detectors, and Passive Sensors) Conference, February 26-29, 2024, Orlando, FL, USA