High-Performance Broadband Infrared Silicon-based Doublet Metalenses Imaging: Evolution from Grayscale to One-Bit Binary Lithography(9-11 µm)

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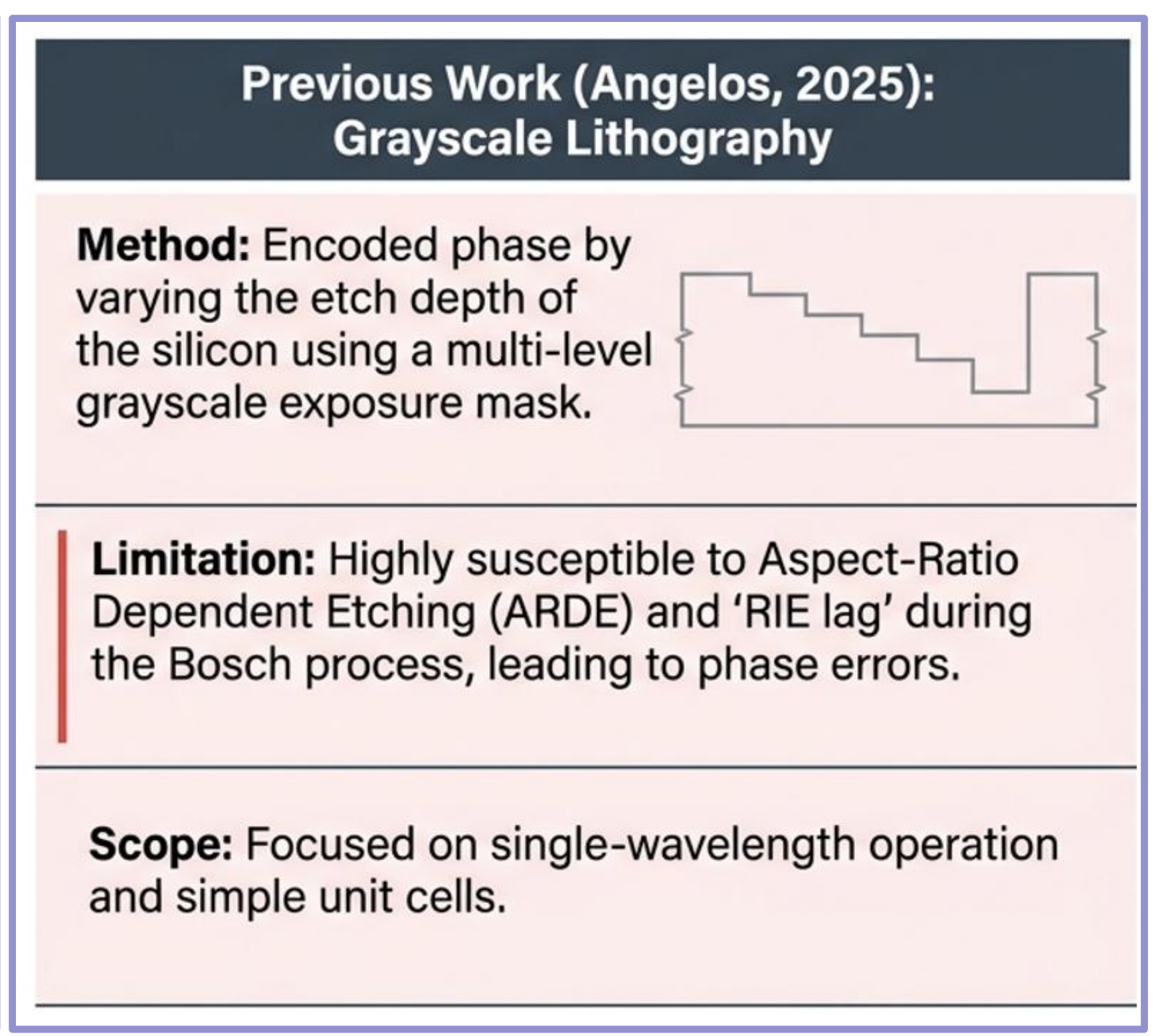
Objectives and Evolution

The Challenge: Traditional refractive lenses and standard diffractive elements suffer from severe chromatic aberration across the Long-Wave Infrared (LWIR) spectrum.

The Objective: To design, optimize, and fabricate a polarization-independent, all-silicon achromatic doublet metalens operating across the 9 µm to 11 µm broadband spectrum.

The Innovation: Transitioning from complex grayscale lithography to a highly manufacturable "One-Bit Binary" strategy, utilizing complex multi-geometry meta-atom families to achieve high focusing efficiency and true achromaticity.

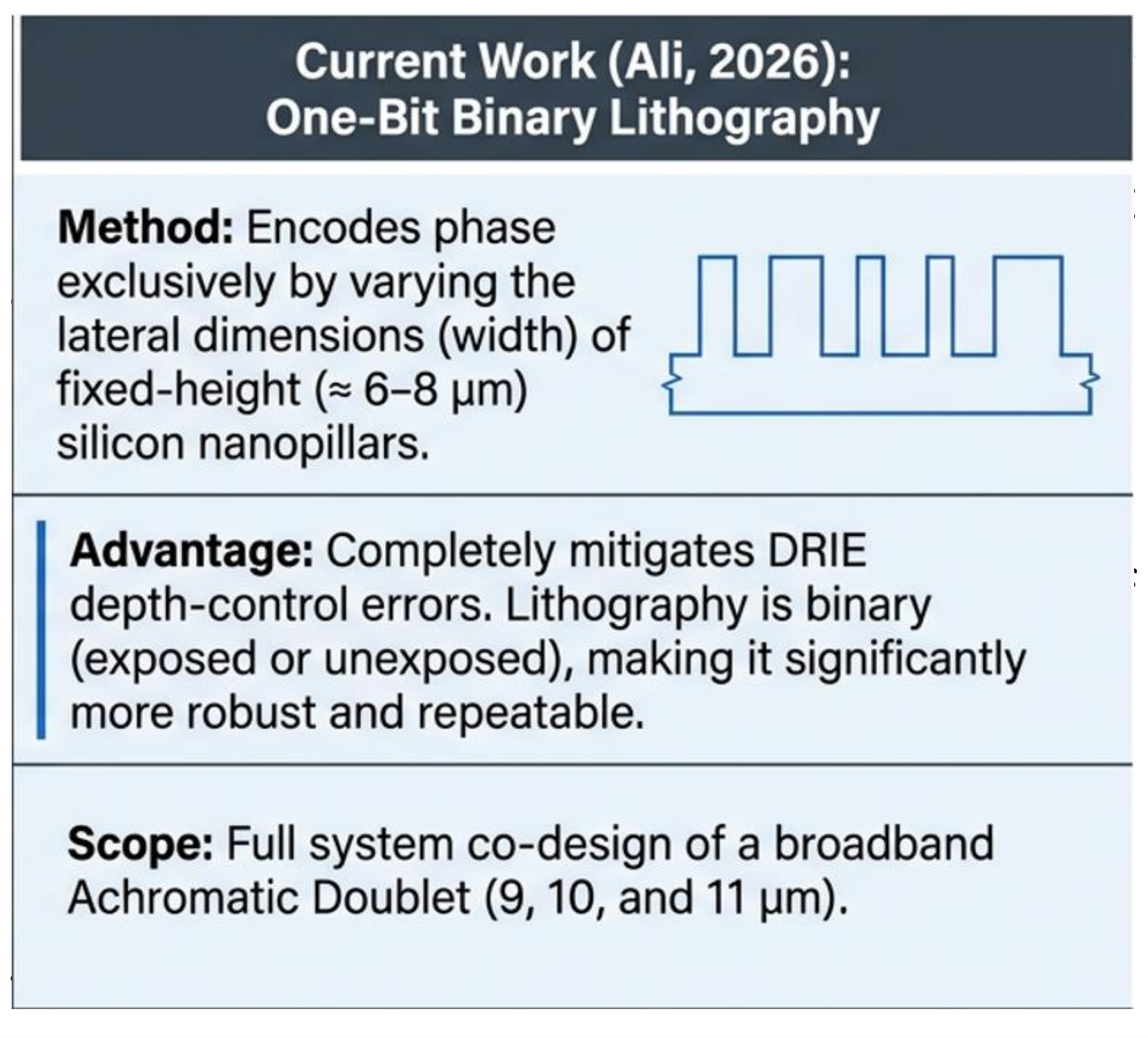


Previous Work (Angelos, 2025): Grayscale Lithography

Method: Encoded phase by varying the etch depth of the silicon using a multi-level grayscale exposure mask.

Limitation: Highly susceptible to Aspect-Ratio Dependent Etching (ARDE) and 'RIE lag' during the Bosch process, leading to phase errors.

Scope: Focused on single-wavelength operation and simple unit cells.

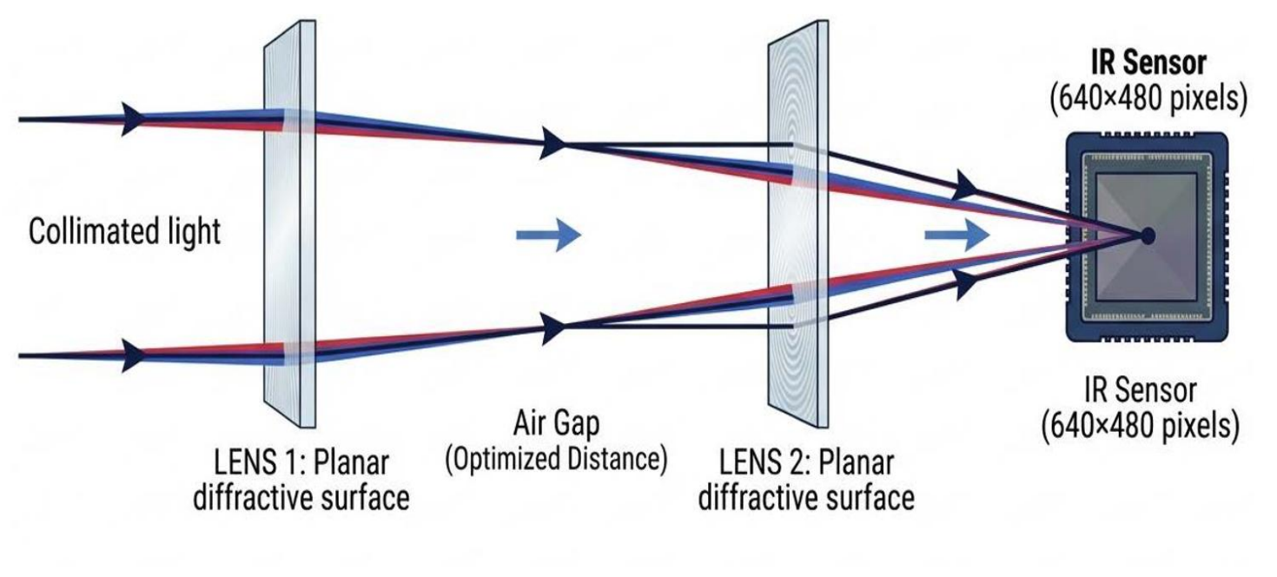


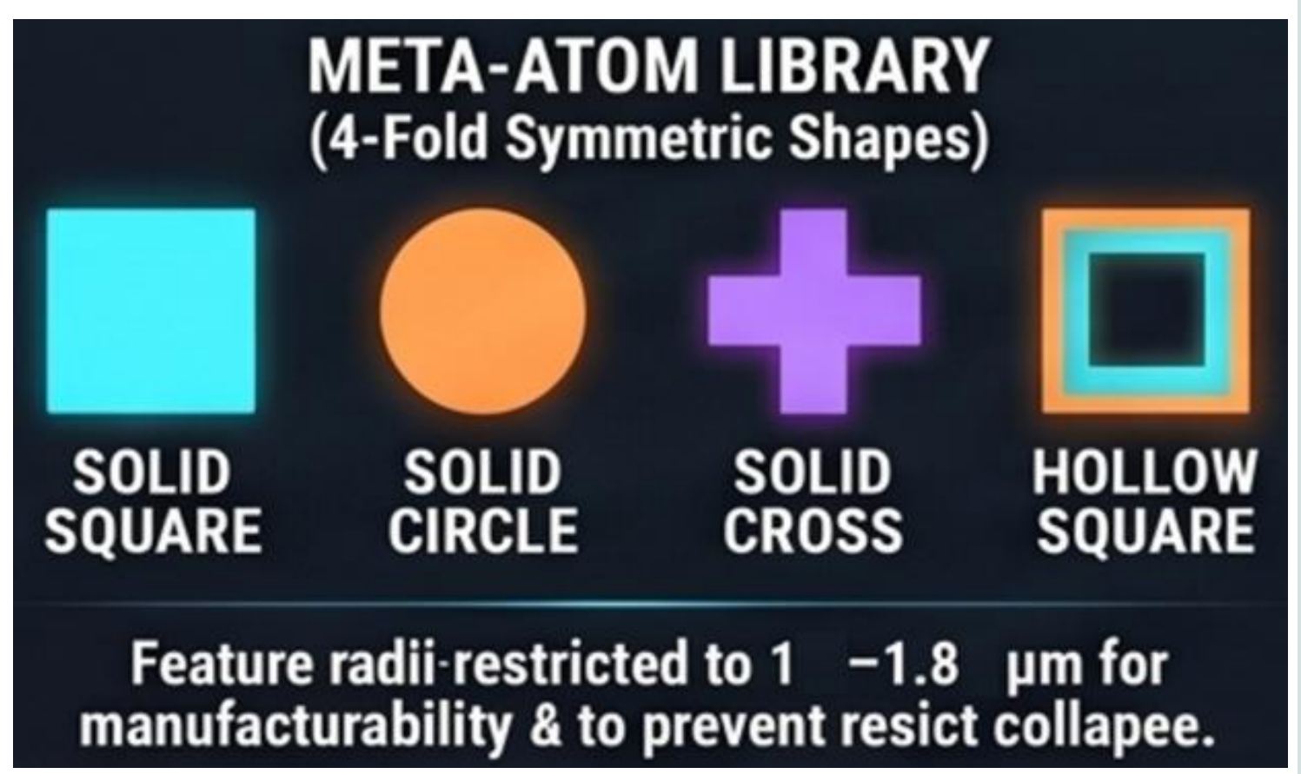
Current Work (Ali, 2026): One-Bit Binary Lithography

Method: Encodes phase exclusively by varying the lateral dimensions (width) of fixed-height (≈ 6–8 µm) silicon nanopillars.

Advantage: Completely mitigates DRIE depth-control errors. Lithography is binary (exposed or unexposed), making it significantly more robust and repeatable.

Scope: Full system co-design of a broadband Achromatic Doublet (9, 10, and 11 µm).





Feature radii-restricted to 1 −1.8 µm for manufacturability & to prevent resict collapee.

Theoretical Design

The 3-Stream Co-Design Workflow

To achieve broadband achromaticity, a custom closed-loop design pipeline was developed:

Macro-Optics (Zemax OpticStudio):

- Designed a Silicon Doublet architecture to overcome the "High Dispersion Gap" of single lenses.
- Optimized Binary-2 polynomial phase coefficients simultaneously for 9, 10, and 11 µm wavelengths to minimize RMS wavefront error and focal spot blooming

Micro-Physics (COMSOL Multiphysics):

Constructed a rigorous Meta-Atom Library using Full-Wave Electromagnetic simulations.

Utilized multiple 4-fold symmetric shape families: Solid Square, Solid Circle, Solid Cross, and Hollow Square.

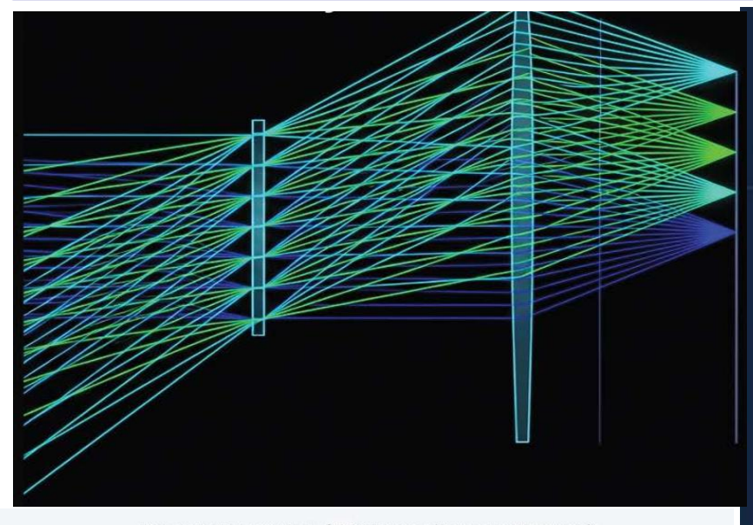
Extracted phase and transmission responses, restricting feature radii strictly to 1.0 – 1.85 µm to guarantee cleanroom manufacturability and prevent resist collapse.

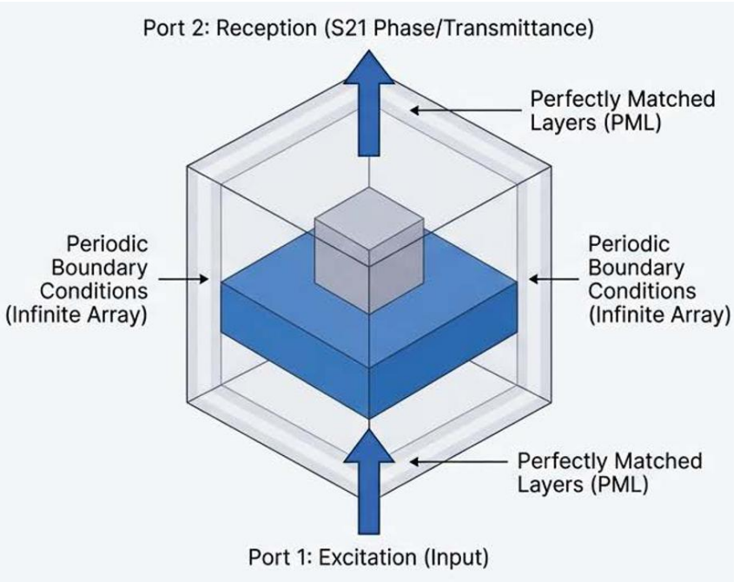
Digital Integration (Python Optimizer):

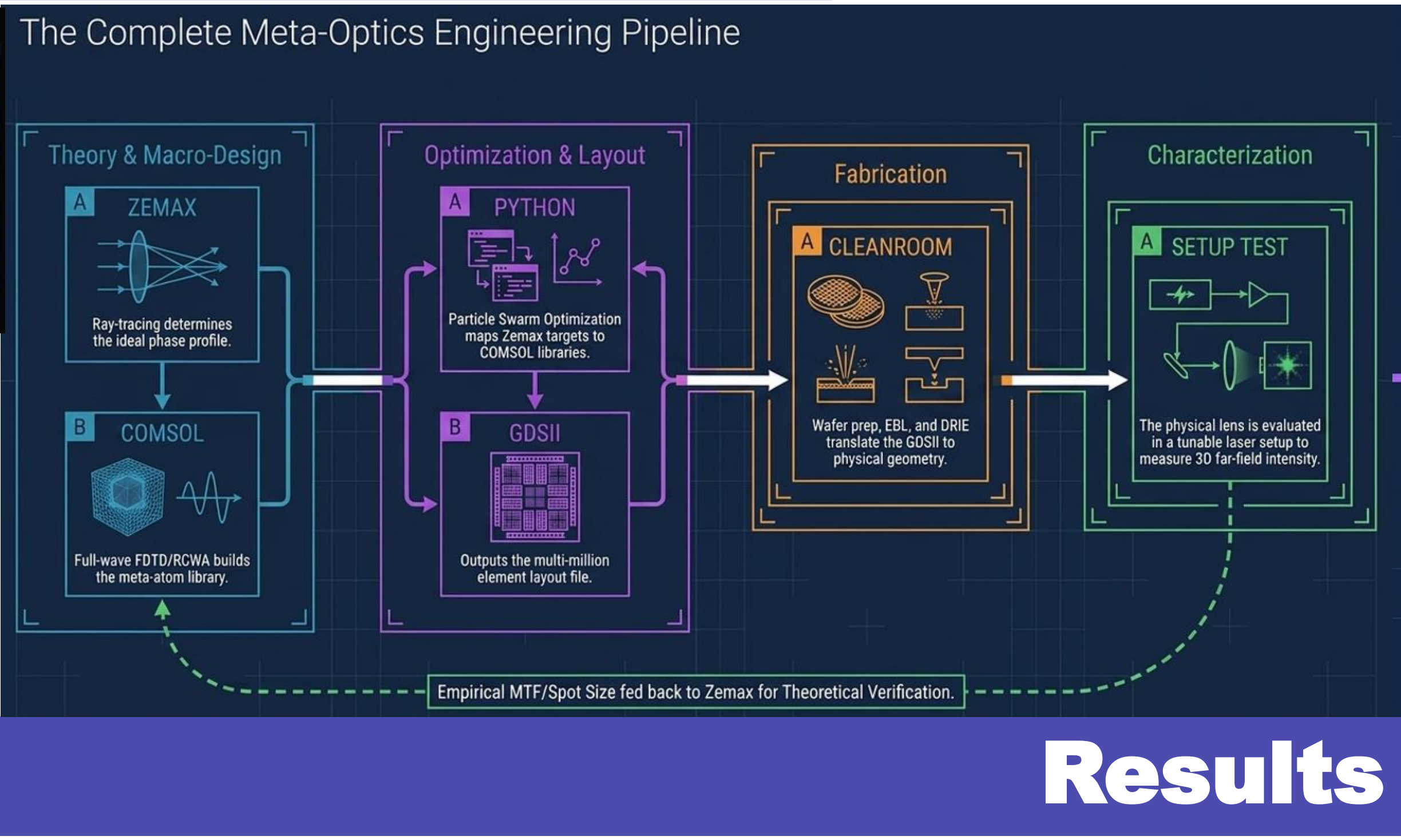
Developed a custom Python application utilizing **Particle Swarm Optimization (PSO).**

The Matchmaker: The algorithm scans the COMSOL library to find the exact geometry (e.g., a specific Square) that simultaneously satisfies the ideal Zemax phase target for all three wavelengths at every coordinate on the lens.

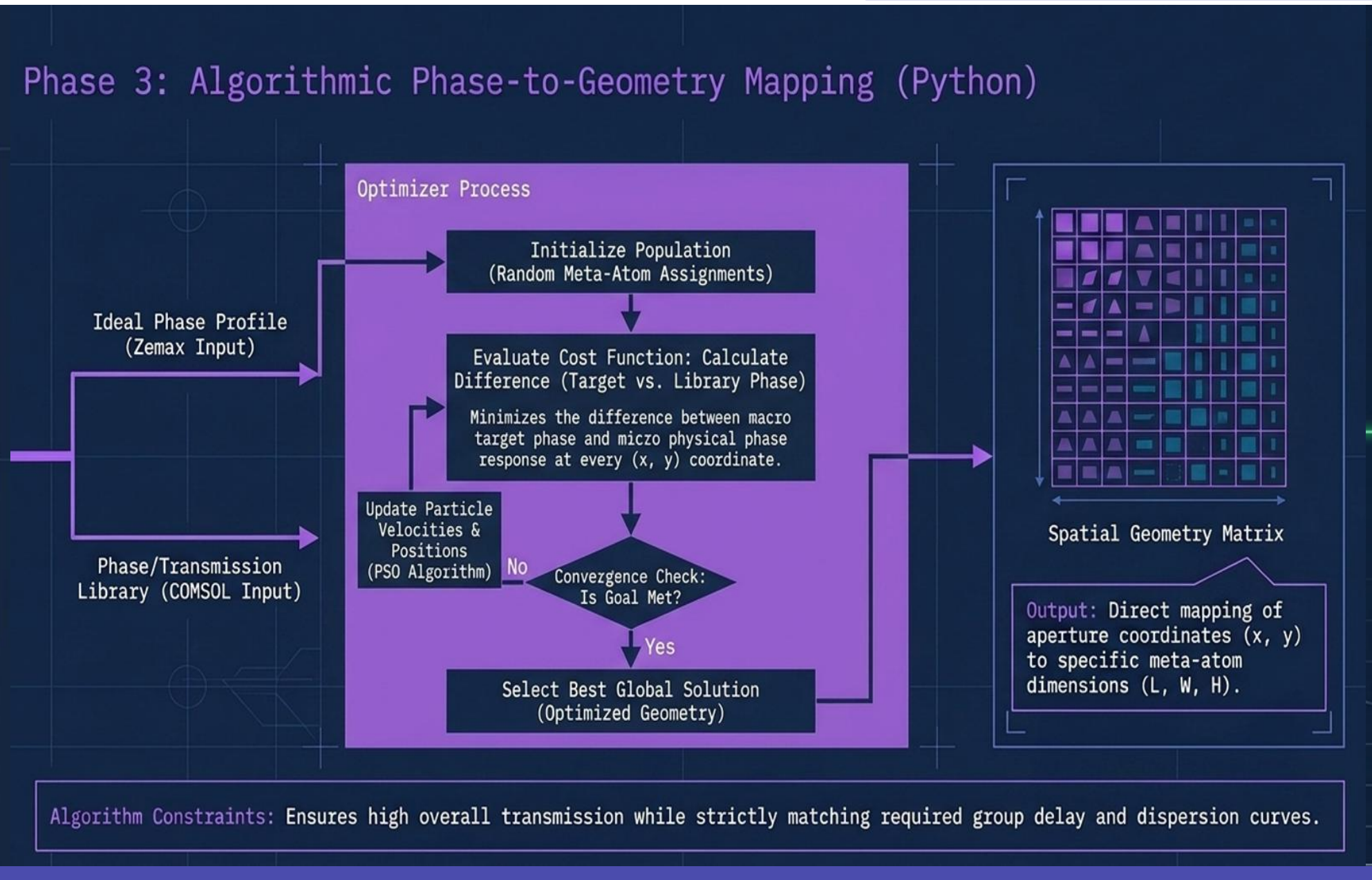
Mask Generation: The optimized outputs are translated into high-density GDSII mask files for direct cleanroom fabrication.





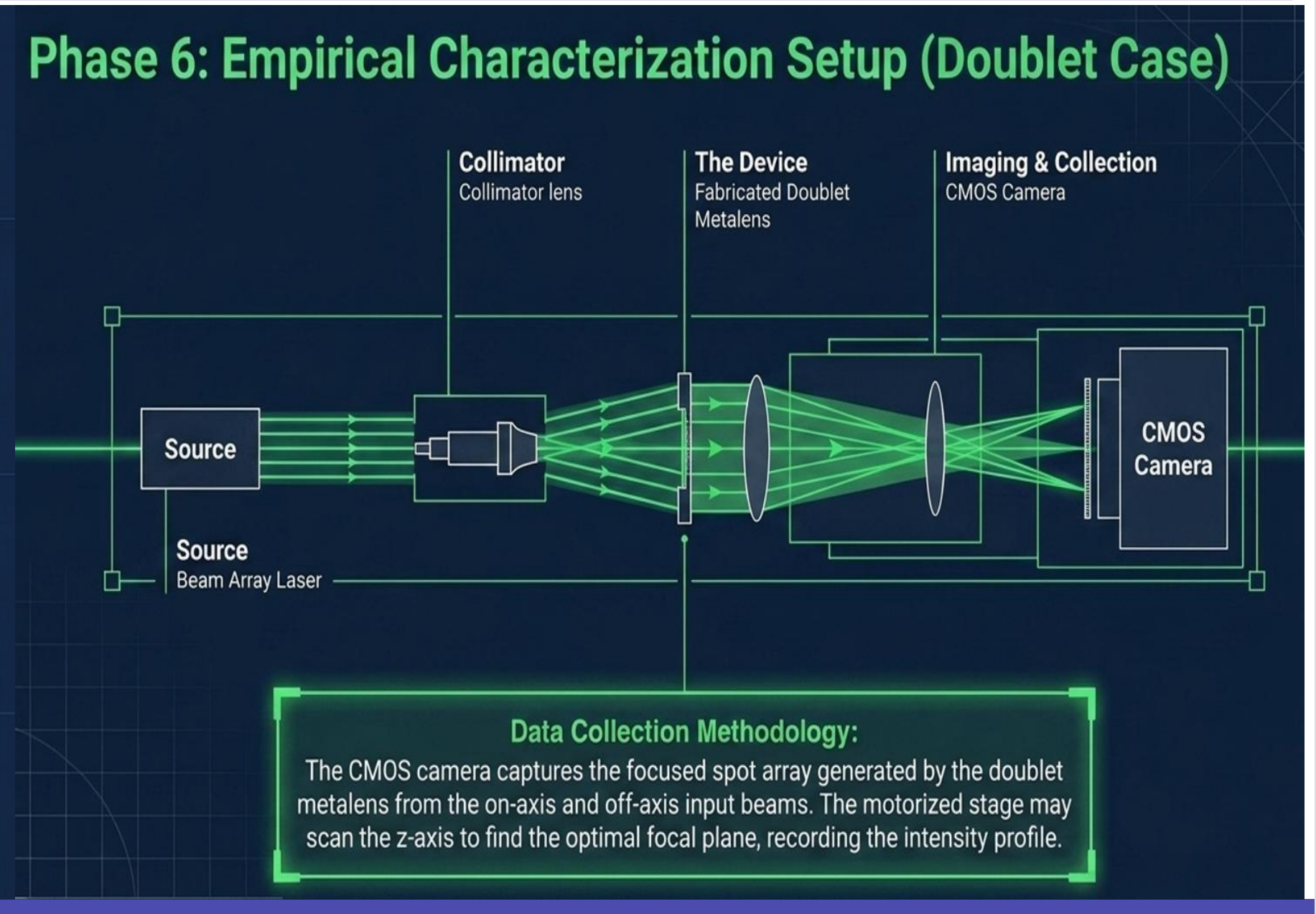


The Complete Meta-Optics Engineering Pipeline



Phase 3: Algorithmic Phase-to-Geometry Mapping (Python)

Algorithm Constraints: Ensures high overall transmission while strictly matching required group delay and dispersion curves.



Phase 6: Empirical Characterization Setup (Doublet Case)

Data Collection Methodology: The CMOS camera captures the focused spot array generated by the doublet metalens from the on-axis and off-axis input beams. The motorized stage may scan the z-axis to find the optimal focal plane, recording the intensity profile.

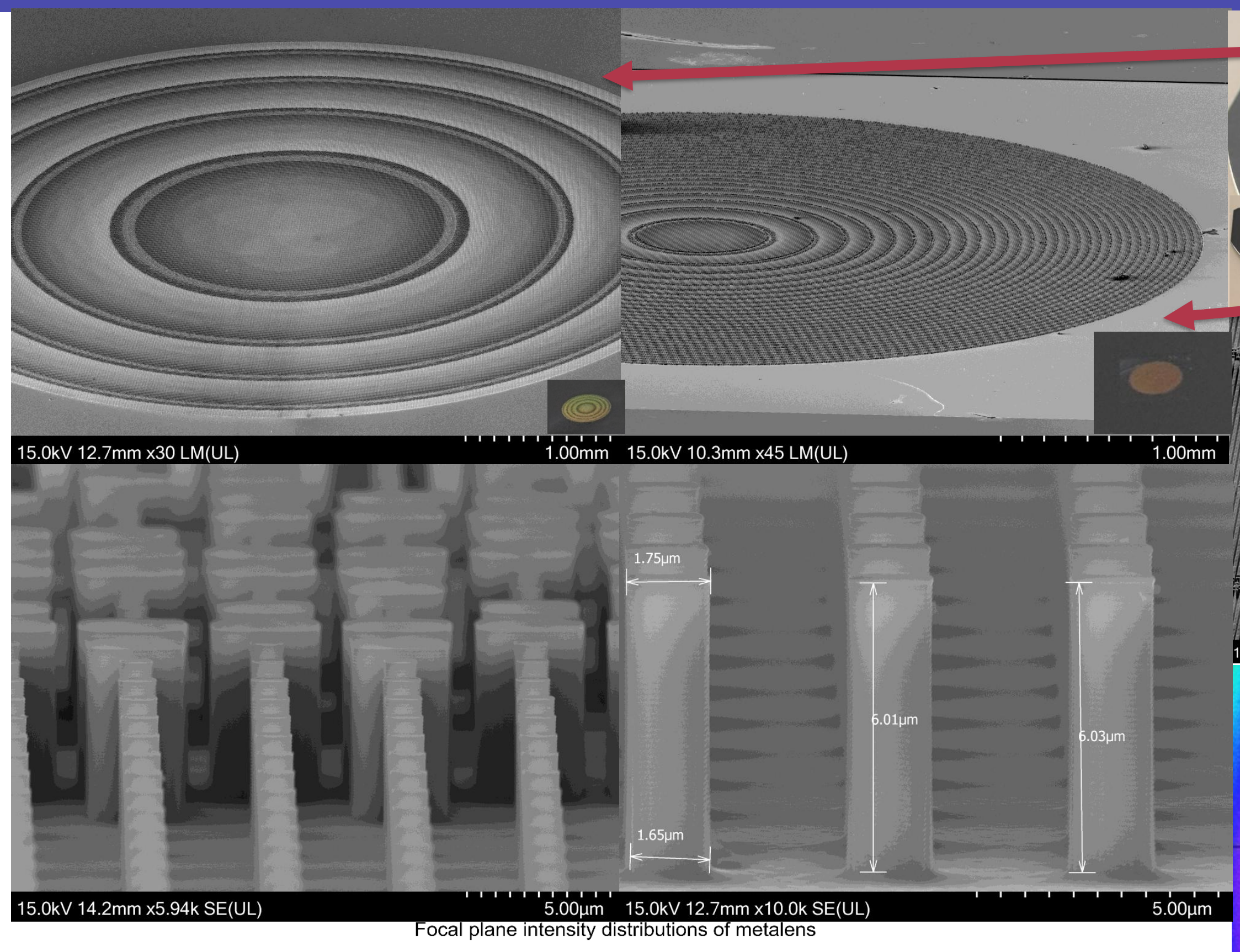
Results & Discussion

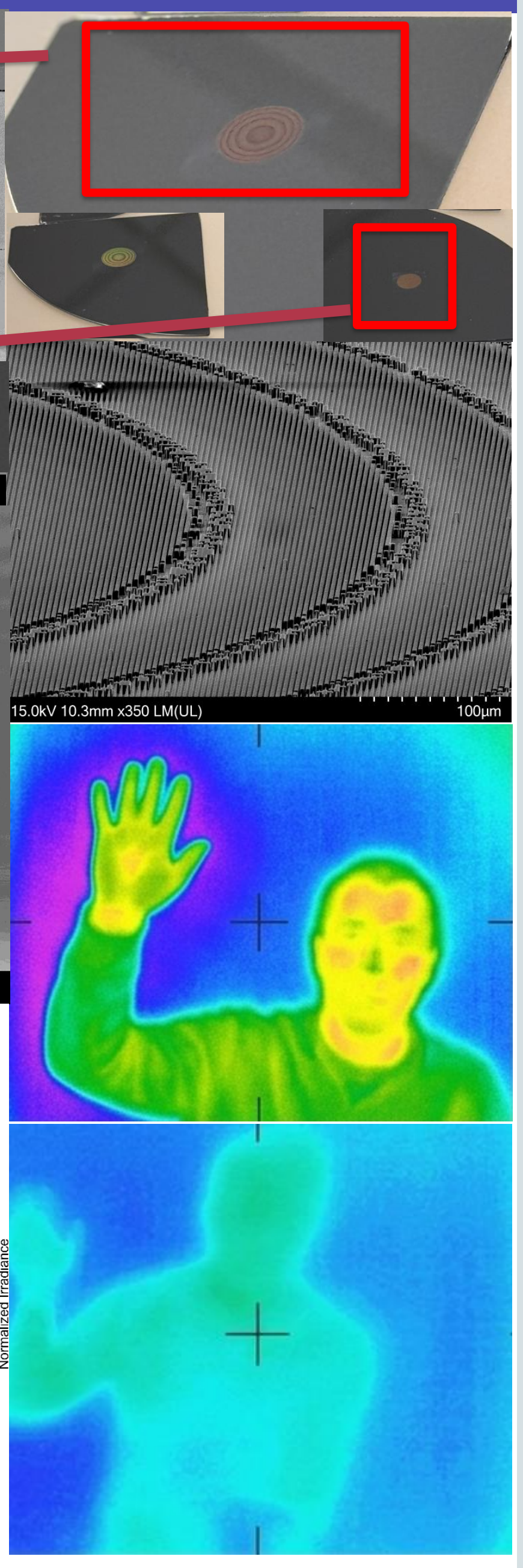
Broadband Achromatic Silicon Doublet Metalens

A flat, one-bit binary diffractive silicon doublet metalens was designed and fabricated for achromatic imaging across 9, 10, and 11 µm wavelengths. To completely avoid the DRIE lag associated with grayscale methods, we utilized a fixed 6–8 µm etch depth. The ideal continuous phase profile from Zemax was discretized using a custom Particle Swarm Optimization (PSO) algorithm, which mapped the target phases to four distinct meta-atom families: solid squares, solid circles, solid crosses, and hollow squares.

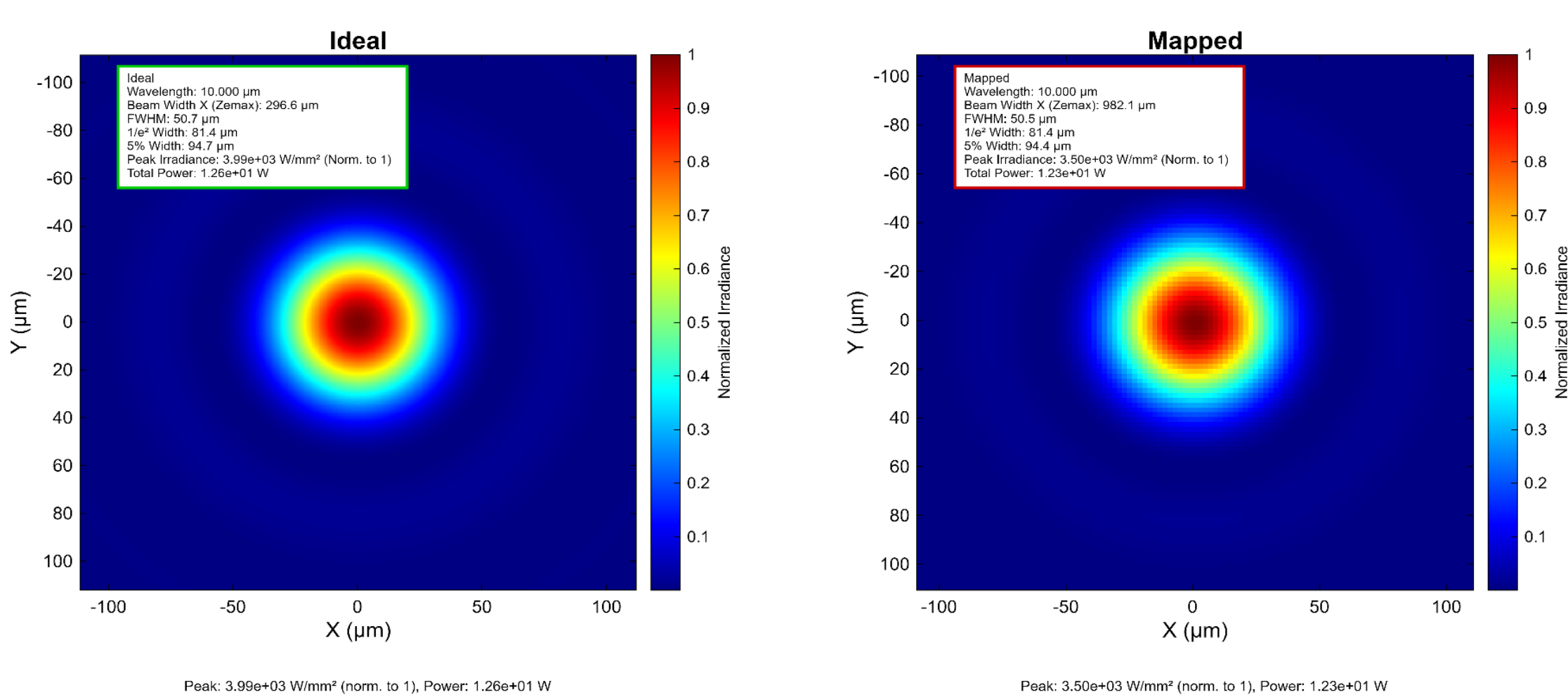
The meticulously optimized cleanroom process began with a water-free isopropanol RCA clean and O_2 plasma surface activation. An S1813 photoresist (1.7 µm) was applied with an extended 3.5-minute soft bake at 115 °C to maximize adhesion. Patterns were exposed via maskless laser lithography at an optimal dose of 100 mJ/cm², developed in fresh MF-319 for exactly 30 seconds, and after hard baking at 120 °C for 5 minutes, etched into the silicon using a tuned DRIE Bosch process.

In order to analyze fabrication accuracy, optical and SEM microscopy were utilized. Initial testing revealed that highly dense or ultra-small features suffered from photoresist merging and severe DRIE scalloping. This issue was completely resolved in the final design cycle by strictly limiting the allowable meta-atom feature sizes to a safe, manufacturable range of 1.0 to 1.8 µm. This constraint ensured the flawless structural transfer of all four geometry families including the delicate hollow squares onto the final silicon wafer.





Focal plane intensity distributions of metalens



Conclusions

In summary, we have established a complete, closed-loop co-design and fabrication pipeline for a high-performance, broadband achromatic silicon doublet metalens operating in the 9–11 µm long-wave infrared (LWIR) spectrum. By transitioning from error-prone, depth-dependent grayscale lithography to a robust "one-bit binary" architecture, we successfully mitigated the severe aspect-ratio-dependent etching (ARDE) and RIE lag issues that traditionally restrict diffractive optics. Utilizing a custom Particle Swarm Optimization (PSO) algorithm, we seamlessly mapped the continuous ideal phase profiles generated in Zemax to a discrete, multi-family meta-atom library simulated in COMSOL, which utilized four distinct four-fold symmetric geometries: solid squares, solid circles, solid crosses, and hollow squares. Crucially, by incorporating direct empirical feedback from our cleanroom fabrication, specifically limiting the meta-atom feature dimensions to a strict 1.0 to 1.8 µm range, we prevented structural collapse, photoresist merging, and severe DRIE sidewall scalloping during the Bosch process. This highly constrained, multi-family approach successfully bridges the gap between theoretical optical system design and practical, high-yield nano-fabrication. Ultimately, our PSO-driven pipeline mathematically and practically proves that broadband achromaticity is achievable in all-silicon doublets using standard maskless lithography, paving the way for the scalable cheap manufacturing of ultra-compact, lightweight, and flat thermal imaging cameras.

Acknowledgements

Joint European Union Erasmus Mundus Master of Science Smart Systems Integrated Solutions (SSIs) is acknowledged for funding through EU.
The Norwegian Research Council is gratefully acknowledged for funding through FRINATEK (#275182, “4D CT).