

Understanding the Metalens Design Workflow

From Meta-Atoms to Manufacturable Optical Systems

Introduction

Metalenses have emerged as a promising alternative to traditional optical elements, offering opportunities for optical system miniaturization, advanced wavefront control, and new optical architectures. Applications range from imaging and sensing systems to augmented reality, LiDAR, and scientific instrumentation. However, unlike conventional optics, metalens development requires engineers to bridge multiple disciplines, including electromagnetic simulation, optical system design, optimization, manufacturability analysis, and experimental validation.

This application note examines the metalens design workflow and the methodologies engineers can use to move from meta-atom development to manufacturable optical systems.

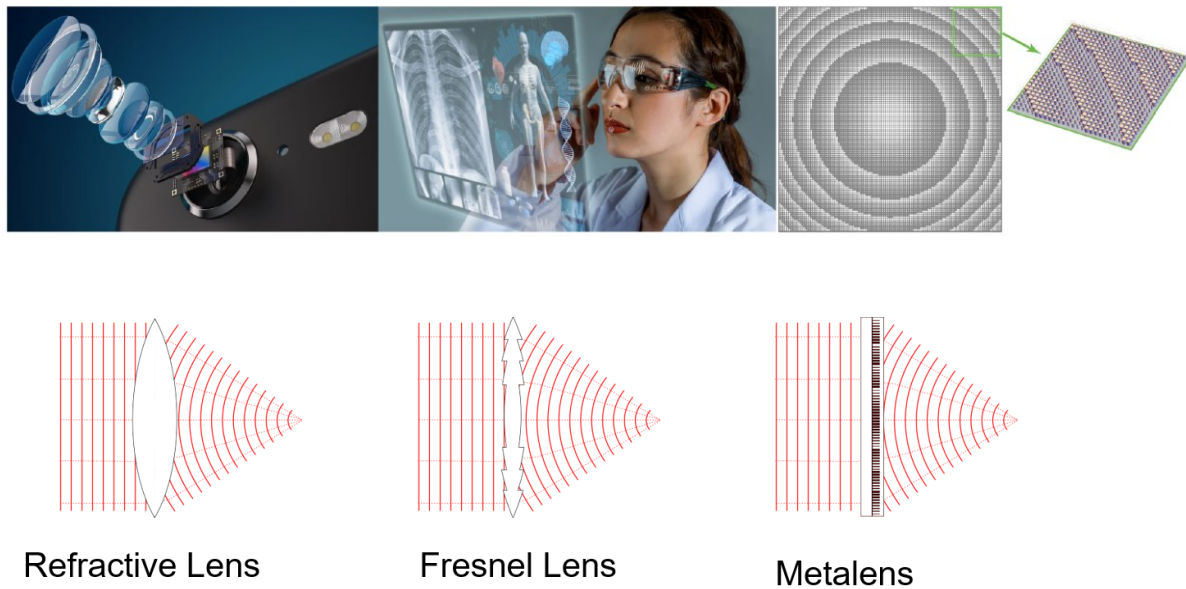


Figure 1. Typical applications include an imaging lens for mobile phones and metaform combiners for augmented reality. Classical optical lenses typically include curved glass surfaces that create a phase profile to bend the light. Metalenses are typically thin and flat and have a nanostructure (i.e., meta-atom) with subwavelength spacing on the surface.

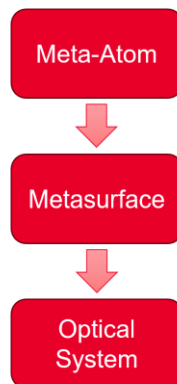
Why Metalenses are Different

Traditional optical systems rely on curved refractive surfaces to manipulate light. Metalenses instead use engineered subwavelength structures, often called meta-atoms, to create spatially varying phase profiles across a flat surface. The geometry, material properties, and orientation of these structures determine how light propagates through the device.

While this approach enables highly compact optical systems, it also introduces new design challenges. Engineers must consider:

- Subwavelength electromagnetic behavior
- Material properties
- Polarization response
- Wavelength dependence
- Manufacturing variation
- System-level optical performance

A successful design requires understanding both the behavior of individual meta-atoms and the performance of the complete optical system.



Approaches to Metalens Design

Metalens development can incorporate multiple design methodologies, each suited to different objectives and stages of the workflow. The most common approaches include electromagnetic simulation, ray-based optical design, and wave-based inverse design.

Electromagnetic Analysis

Rigorous electromagnetic simulation is often used to characterize meta-atoms and predict how individual structures interact with light. Methods such as Finite-Difference Time-Domain (FDTD) and Rigorous Coupled-Wave Analysis (RCWA) can provide highly accurate predictions of phase and amplitude response.

These analyses form the foundation for understanding the relationship between geometric design parameters and optical behavior.

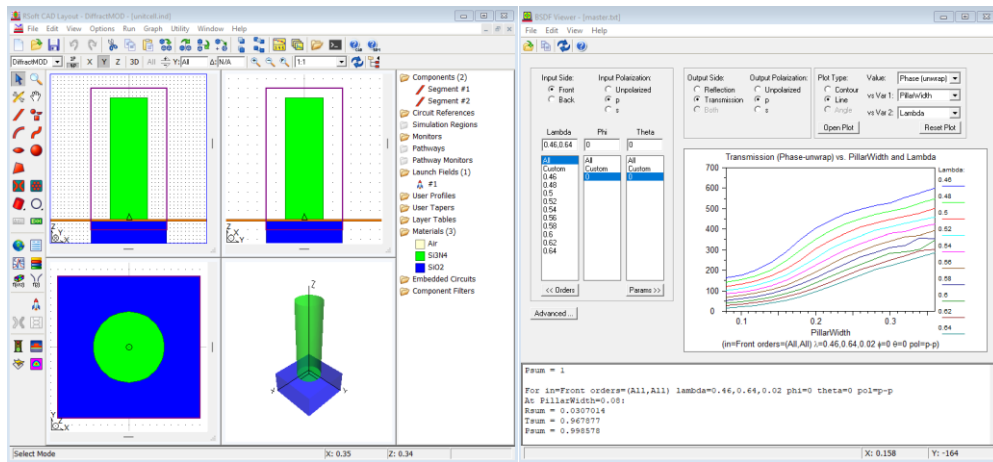


Figure 2. On Left: design of a Meta-Atom (SiO₂/Si₃N₄) in RSoftCAD, the diameter of the pillar is defined by the variable PillarWidth. On Right: Calculated phase (Using RCWA) in transmission for different PillarWidth and wavelength.

Ray-Based Design for Optical Systems

As metalens dimensions increase and complete optical systems become more complex, engineers often complement electromagnetic analysis with ray-based design techniques. Ray-based methods provide a practical approach for evaluating imaging systems, exploring design tradeoffs, and co-designing metalenses alongside conventional optical elements.

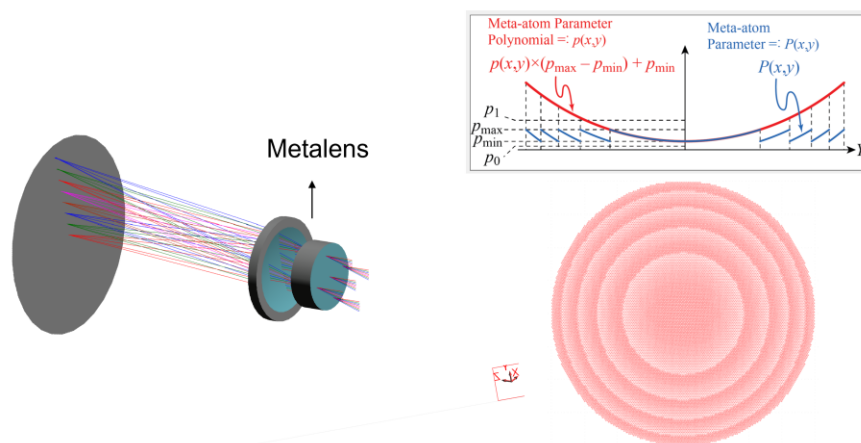


Figure 3. Ray-based metalens design for hybrid optical system – co-optimization of metalens and refractive element. On Right: schematic of the optimized meta-atom parameter function and the generated layout (GDS, Oasis)

These approaches can provide a useful starting point for system-level optimization before more computationally intensive analysis is performed.

Wave-Based Inverse Design

In addition to traditional design techniques, inverse design has emerged as a powerful approach for metalens development. Rather than manually defining every aspect of a metasurface, inverse design begins with a set of performance goals and automatically generates candidate layouts intended to meet those requirements.

Inverse design techniques can explore larger portions of the design space and may be especially useful for:

- Achromatic metalenses
- Wide-angle designs
- Beam-shaping applications
- Holographic optical elements
- Polarization-dependent devices

The approach often relies on optimization algorithms that efficiently evaluate design sensitivity and iteratively improve performance.

The forward model is to propagate the input beam to the image plane. In the backward propagation, instead of adjusting the weight for each layer, we adjust the meta-atom design parameters at each location on the metasurface. The final design is the metalens layout that minimizes the difference between the system output field and the desired output.

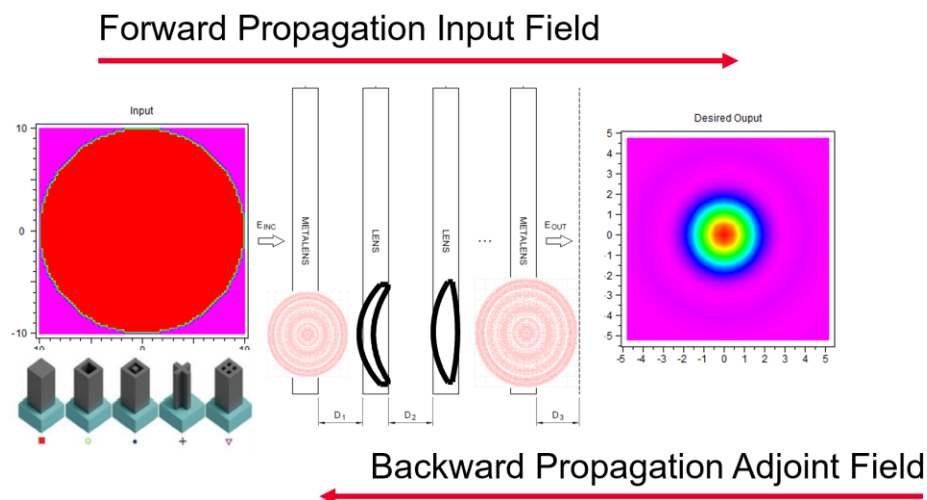


Figure 4. Inverse design uses a forward propagation and a backward propagation adjoint field.

A Connected Metalens Development Workflow

While various design methodologies are available, many projects benefit from combining them into a connected workflow. A typical process can be illustrated in this Ultra-Wide Angle Metalens Case Study.

Step 1: Design and Characterize Meta-Atoms

Engineers evaluate geometry, array, material selection, and optical response to generate metasurfaces capable of achieving the desired phase profile.

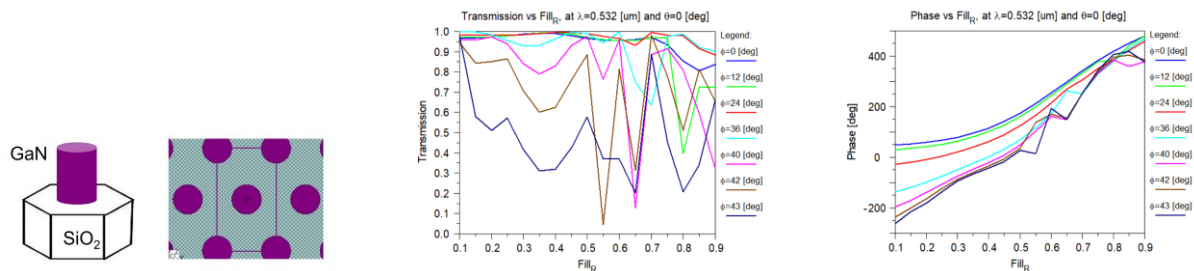


Figure 5. Meta-Atom response (amplitude and phase vs Filling factor) at 532 nm and various angles of incidence.

Step 2: Design and Optimization Wide-Angle Metalens in Ray-Tracing

Directly design metalens with nanostructures (meta-atoms) by CODE V Meta Optic Design Feature and meta-atom BSDF database. Unlike phase profile traditionally used, amplitude and phase will both vary with wavelength, incident angle, or polarization on metasurface. In the approach, Meta-atom distribution is described by a polynomial, and we can set its coefficients as variables and go for optimization of them using ray-tracing software.

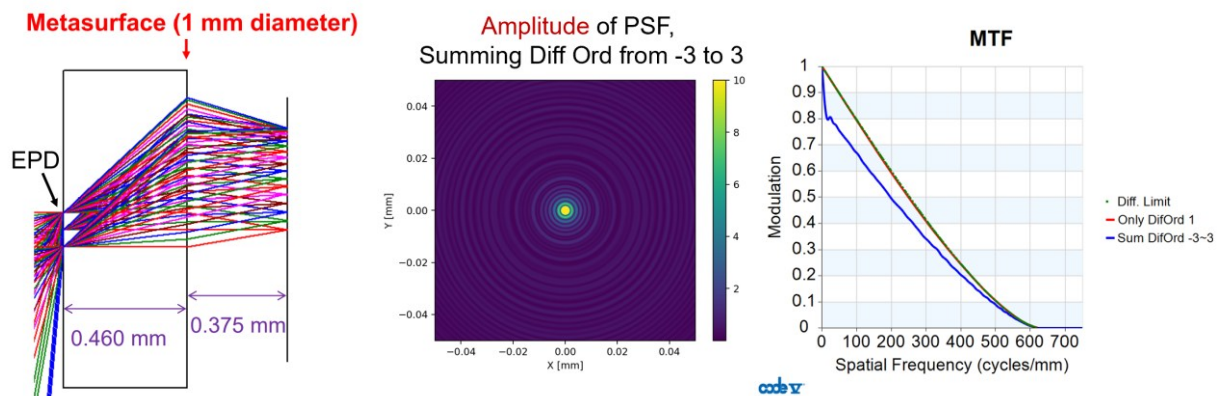


Figure 6. Optimization of a metalens in CodeV. Evaluation of the performance metric as PSF and MTF at normal incidence.

System-level analysis helps predict how metalenses perform within complete optical assemblies. Important metrics include:

- Imaging performance
- Aberrations
- Field of view
- Stray light

Illumination behavior

This allows engineers to evaluate system behavior before fabrication.

Step 3: Further Optimization using Inverse Design Technic.

Depending on project needs, optimization may be performed using ray-based techniques, wave-based inverse design methods, or a combination of both. Our flow allow a compatibility of a design generated in Ray-tracing software in a inverse design approach that allows further optimization.

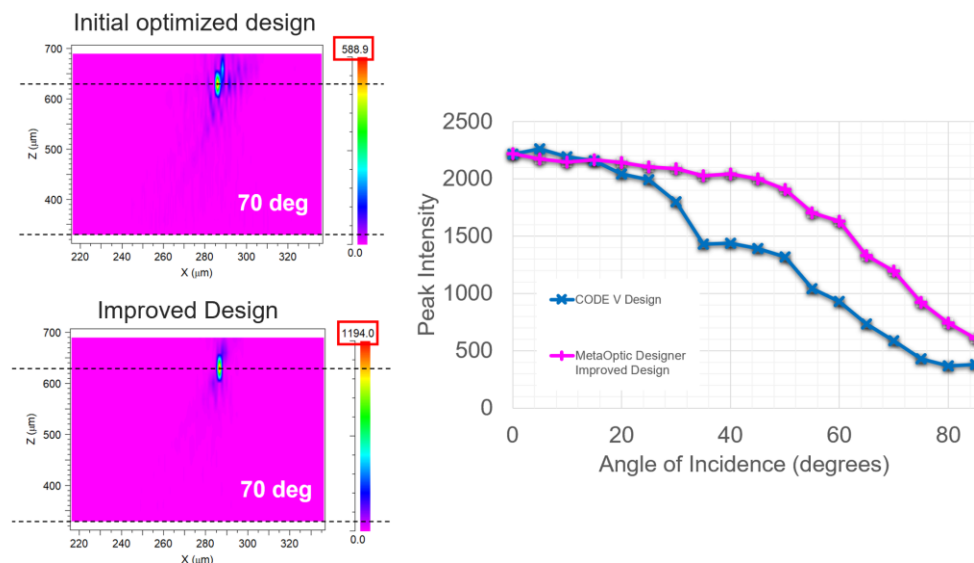


Figure 7. On top left: Evaluation of the intensity map (AOI = 70°) of the design optimized using raytracing as explained in Step2. On bottom left: using CodeV design as a starting point, improved design performance by using inverse design technic. On right: Improvement of the peak intensity for different AOI demonstrating an overall improvement of the metasurface.

Designing for Manufacturability

Optical performance alone is not sufficient for a successful metalens design. Manufacturing processes can introduce variations that significantly affect device behavior. Examples include:

- Corner rounding
- Sidewall angle variation
- Feature size variation
- Etch effects
- Surface roughness
- Lithography limitations

Manufacturing-aware analysis helps engineers understand how these effects influence optical performance before fabrication begins.

By incorporating manufacturing considerations earlier in the workflow, engineering teams can identify potential risks, evaluate robustness, and improve confidence in final designs.

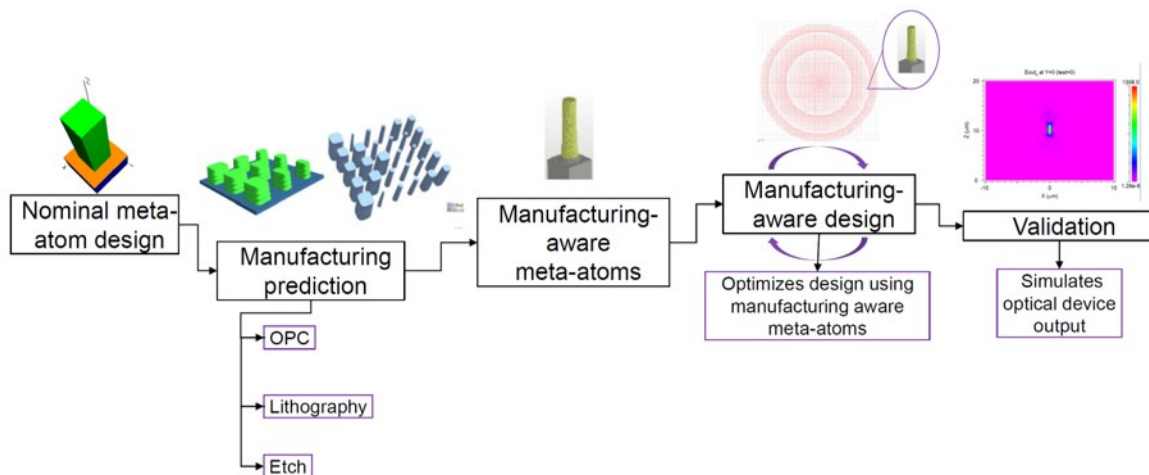


Figure 8. A manufacturing-aware design flow

Bringing Metalenses from Concept to Reality

Metalens development extends beyond the design of individual meta-atoms. Engineers must connect electromagnetic behavior, optical system performance, optimization methods, manufacturability, and validation to achieve successful results.

By combining rigorous simulation, system-level analysis, inverse design techniques, and manufacturing-aware workflows, engineering teams can gain deeper insight into performance before fabrication and better understand the tradeoffs that influence real-world optical systems.

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