Metalens [PCA]

Digital Twin Specification

Twin Code:	`CS-MPCA01`
Twin Name:	Metalens [PCA]
Category:	Component
Type:	Structure-Based
Version:	1.0
Package:	Flat Lens
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Description

The Metalens [PCA] twin models a metalens using the Periodic Cell Array (PCA) approximation [1]. Each meta-atom is treated as part of a locally idealized periodic array, analyzed using Rigorous Coupled-Wave Analysis (RCWA). The PCA approximation restores the local design principle while including evanescent coupling between identical neighbors — it is not a compromise, but the intelligent foundation for metalens design.

The twin enables:

- **Design** of metalenses based on target phase profiles
- **Simulation** of metalenses within complete optical systems
- **GDSII export** of the designed meta-atom layout for fabrication

Simulation and Design

The twin uses PCA for local design, the common phase framework for phase definition, and surrogate models for fast evaluation. Detailed theoretical foundations are provided in the three companion white papers referenced below.

Underlying White Papers

The Metalens [PCA] twin builds on three foundational white papers:

- **PCA White Paper [1]:** Explains why PCA is the foundation — restoring local design while including crosstalk — and why global optimization is not a viable option.
- **Phase Response White Paper [2]:** Defines the local common phase $\Psi = \arg(J_x^{\text{out}} + J_y^{\text{out}})$ as the design-relevant quantity, introduces the quality criterion σ^2 and optimal basis analysis (linear for pillars, circular for nanofins).
- **Surrogate Model White Paper [3]:** Describes the neural network surrogate model that replaces on-the-fly RCWA with fast inference, enabling large-scale metalens design.

Design Workflow

1. **Define the target phase profile** $\Delta\psi^{\text{profile}}(\boldsymbol{\rho})$ (e.g., spherical focusing, aspherical, or custom — rotationally symmetric).
2. **Select meta-atom type** (pillar or nanofin) and the surrogate model trained for the required parameter ranges (wavelength, angle, geometry).

3. **Select design polarization $\boldsymbol{J}_1$** (the optimal basis from the Phase Response Paper [2]):
    - Pillars: linear polarization $(1, 0)^T$
    - Nanofins: circular polarization $(1, i)^T$ (LCP) or $(1, -i)^T$ (RCP)
4. **Run the system simulation.** The design is triggered automatically on the first system run. This ensures that the metalens is designed with respect to the actual incident light angles, which requires simulating the input field first.
5. For each position $\boldsymbol{\rho}$, the twin performs an inverse query [3] to find the geometry $\boldsymbol{p} \in \mathcal{P}_{\text{struct}}$ that best matches the target phase at the local incident angle determined by the incident wavefront.
6. **The metalens is now designed.** The geometry distribution $\boldsymbol{p}(\boldsymbol{\rho})$ is stored and can be exported as GDSII for fabrication.

Simulation Workflow

After design, the metalens can be simulated for **any** incident field (any wavelength, angle, polarization, wavefront curvature):

1. The incident field is decomposed into the optimal basis $\boldsymbol{J}_1, \boldsymbol{J}_2$ [2].
2. For each mode, the surrogate model provides the common phases Ψ_1, Ψ_2 and the full Jones output.
3. The field tracing engine propagates the complete field through the system.
4. Aberrations, dispersion, efficiency, and higher orders can be analyzed.

The twin automatically detects whether the surrogate model's trained parameter range is violated (e.g., incident angle too large). In such cases, it issues a warning and uses the closest available response.

System Integration

A key capability of the Metalens [PCA] twin is its seamless integration with conventional optical elements within VirtualLab Fusion's field tracing engine. When a metalens is not the first element in an optical system, the incident field carries wavefront curvature, angular spectrum variations, and polarization modifications from preceding optics. The twin automatically accounts for this modified incident field, evaluating each meta-atom's response against the actual local field conditions.

This enables genuine system-level investigation: the metalens is simulated within its operational context, not in isolation.

Model Parameters

Meta-atom type Pillar (diameter-controlled) or nanofin (rotation-controlled)

Phase profile Spherical, aspherical, or user-defined — rotationally symmetric $\Delta\psi^{\text{profile}}(\boldsymbol{\rho})$

Design wavelength $\boldsymbol{\lambda_{\text{design}}}$ The wavelength of the incident light for which the metalens is designed. The design is performed for this wavelength and the actual incident angles.

Design polarization $\boldsymbol{J}_1$ Optimal basis from phase analysis [2] (linear for pillars, circular for nanofins)

Surrogate model Pre-trained model covering $(\lambda, \theta_x, \theta_y, \boldsymbol{p})$ ranges

Aperture size Diameter or side lengths

Typical Application Scenarios

1. **Flat Lens Design:** Design moderate-NA metalenses for focusing and imaging applications.
2. **Dispersion Characterization:** Investigate chromatic behavior across wavelength [3].
3. **Off-Axis Performance Investigation:** Analyze aberrations at different field angles using the common phase extraction framework [2].
4. **Hybrid System Design:** Combine metalenses with refractive or diffractive optics for chromatic correction.
5. **Polarization-Controlled Focusing:** Use nanofin meta-atoms with circular polarization design.
6. **Meta-optic Array Fabrication:** Design metalens arrays with GDSII export.
7. **Ultrafast Optics:** Analyze group delay and dispersion.

Software Usage

1. **Place the Metalens [PCA] twin** into an optical system containing sources, detectors, and other components as needed.
2. **Select the meta-atom type** (pillar or nanofin).
3. **For nanofins, select the design polarization** (LCP or RCP) — this defines the optimal basis $\boldsymbol{J}_1$.
4. **Specify the target phase profile** $\Delta\psi^{\text{profile}}(\boldsymbol{\rho})$ to be realized by the metalens.
5. **Bind a surrogate model** [3] trained for the selected meta-atom type and the required ranges of wavelength, incident angle, and geometry parameters.
6. **In the first system run,** the metalens designs its geometry distribution $\boldsymbol{p}(\boldsymbol{\rho})$ based on the incident light and the specified phase profile.
7. **After design,** you can run ray tracing or field tracing to investigate the metalens performance. The metalens is now designed and can simulate its response for any incoming light — including different wavelengths, angles, polarizations, and system configurations.
8. **Export GDSII** for fabrication.

Parameter range warnings: If the surrogate model's trained parameter space is violated (e.g., incident angle larger than trained range), the twin issues a warning and uses the closest available response for the affected meta-atoms.

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Related Twins:	Grating [RCWA], Diffractive Lens, Ideal Lens [Focusing], Gaussian Beam Mode, Metalens [LMGA] (in development)
White Papers:	[1], [2], [3]

References

[1] Frank Wyrowski. *PCA: The Foundation for Metalens Design*. White Paper WP-META-PCA. LightTrans International GmbH, 2026. link.

[2] Frank Wyrowski. *Designing and Analyzing the Phase Response of Metasurfaces*. White Paper WP-META-PHASE. LightTrans International GmbH, 2026. link.

[3] Frank Wyrowski. *Surrogate Modeling: Enabling Practical Metalens Design and Simulation*. White Paper WP-META-SURROGATE. LightTrans International GmbH, 2026. link.