# Enhancing Robustness in Meta Optics Design

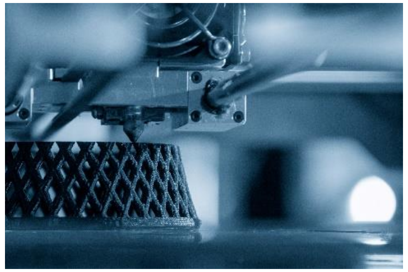
Dominik Schulz

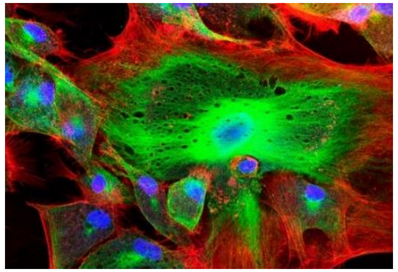
EPIC Technology Meeting on Photonics for Miniaturized Optics: From Components to Use-cases at Sony DADC

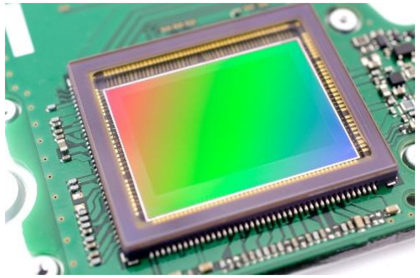
# Manufacturable lens and system designs from PPE

## From concept to supply chain

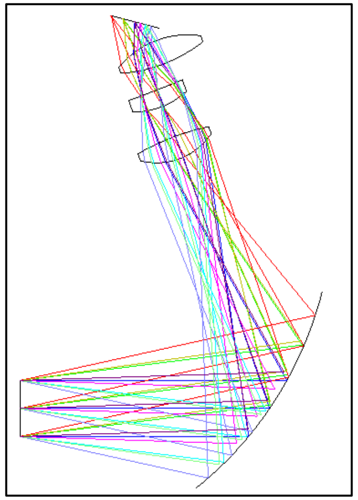
photonics
precision engineering



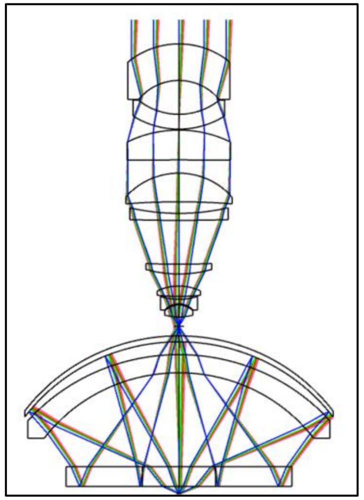




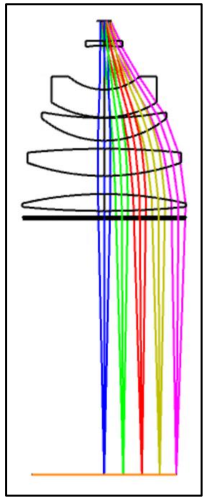
**Augmented reality** | **Lithography & Inspection** | **Laser processing 3D-Printing** | **Bio Photonics** | **Industrial & Consumer Optics**



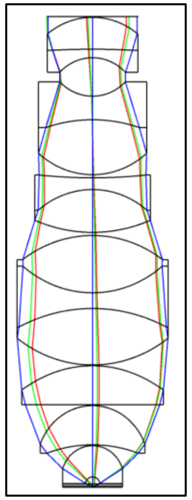
Glass, Helmet, Head-up



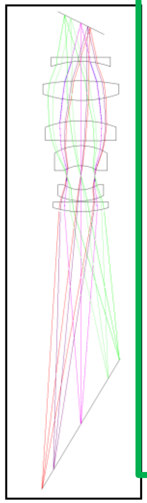
Aerial Image Analysis



DOE and system design



High NA – Large field Multi-Channel Systems



Meta optics Hybrid Designs

**Optical Design. System Engineering. Prototyping.**

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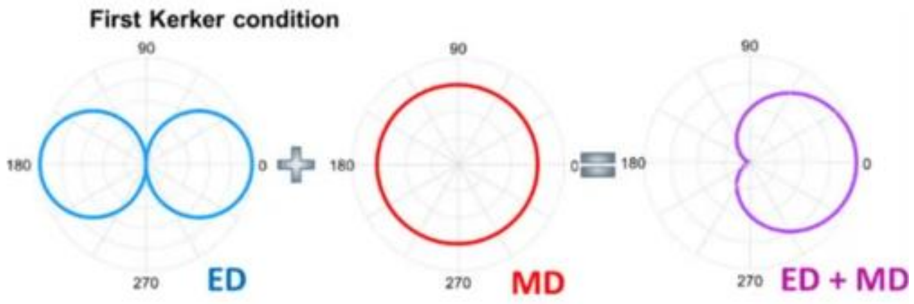
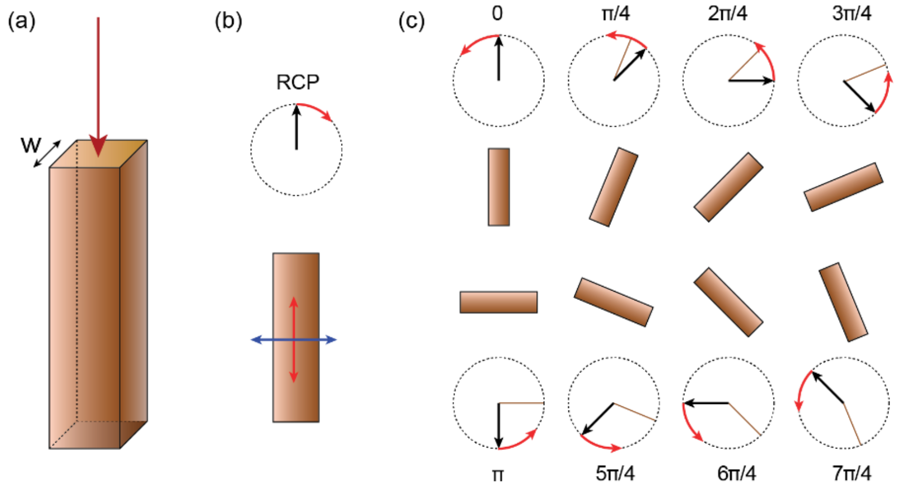
# Short reminder:
# What is a (dielectric) metaoptic and why is it interesting?

- array of subwavelength dielectric structures (metaatoms) to control phase and amplitude
- Physical effects:
  - Thin types ($H \ll \lambda$ Huygens' metalens) employ resonances
  - $H \approx \lambda$ truncated waveguides → propagation phase
  - Pancharatnam-Berry (geometric) phase
- Materials for dielectric metalenses:
  - Visible: $\mathrm{TiO_2}$, $\mathrm{GaN}$, $\mathrm{Si_3N_4}$, polymers, ($\mathrm{c\text{-}Si}$)
  - Near to mid infrared: $\mathrm{c\text{-}Si}$, $\mathrm{a\text{-}Si{:}H}$, $\mathrm{PbTe}$, $\mathrm{GaSb}$



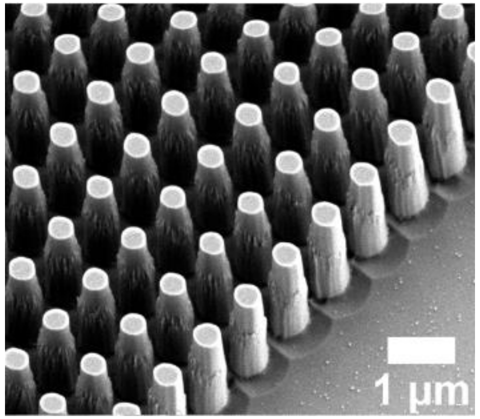

https://doi.org/10.3390/photonics9010006



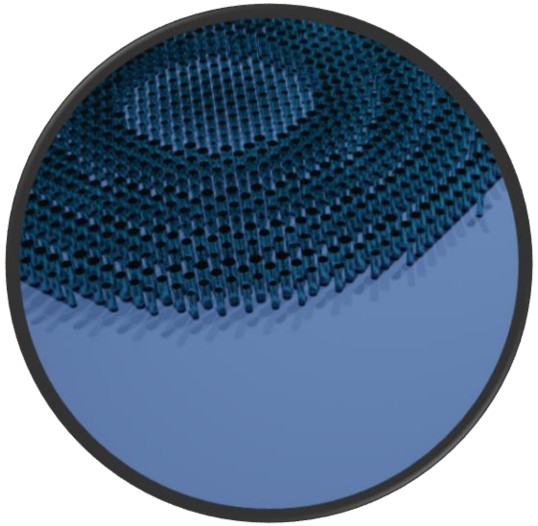

http://dx.doi.org/10.48550/arXiv.2206.12175

# Manufacturing uncertainties

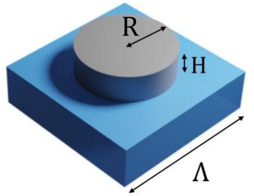
- Introduce defects/uncertainties to the metasurface
  - Side wall angle
  - Corner roundings
  - Change in critical dimension or other lengths (e.g., LCDU)
  - Surface and edge roughness
  - …



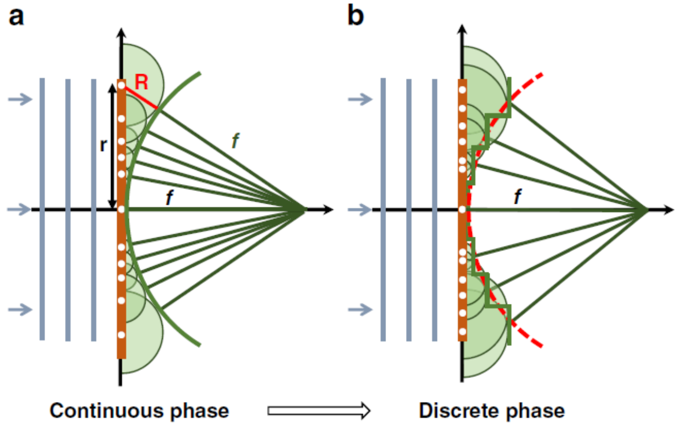

- ➢ Need of transfer function knowledge
- ➢ Still some uncertainties in the metaatom parameters



# Simple example:
# Cylindrical metaatoms

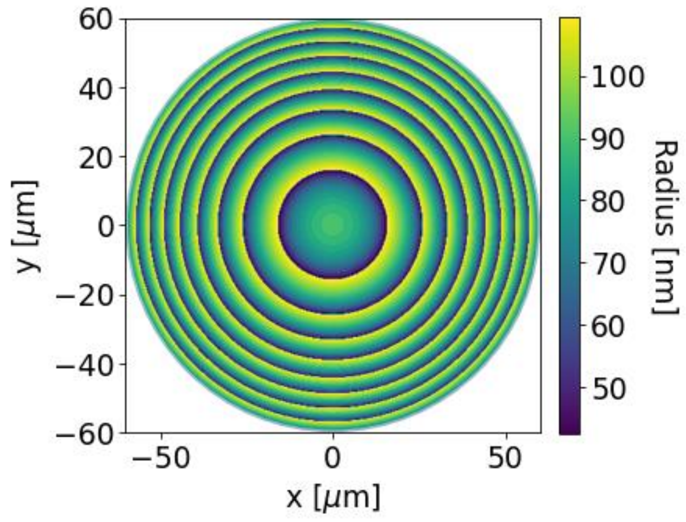


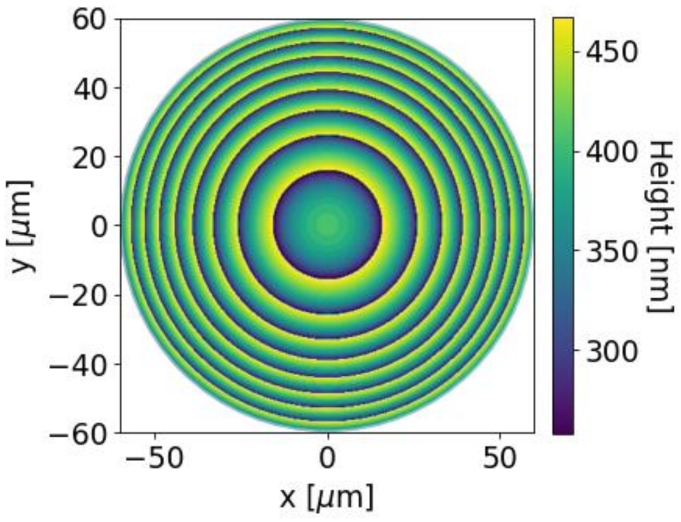

Hypothetical case study designed to explain concept

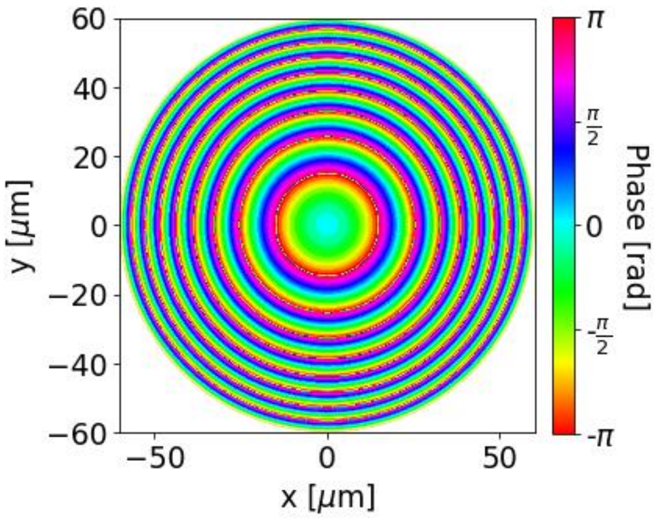



**<u>Here:</u>**

- 2 degrees of freedom with axial symmetry: Radius and height
- Dielectric low-NA metalens → $\mathrm{NA} = 0.15, \lambda = 532\mathrm{nm}, \mathrm{TiO_2}$ on $\mathrm{SiO_2}$
- 16 phase levels go with radius and height



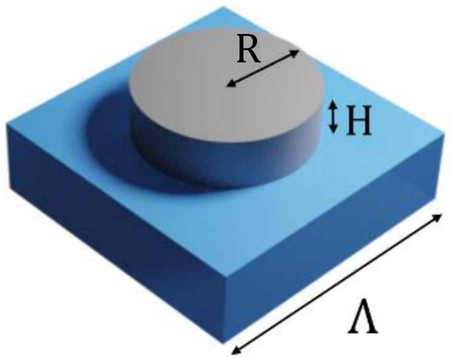



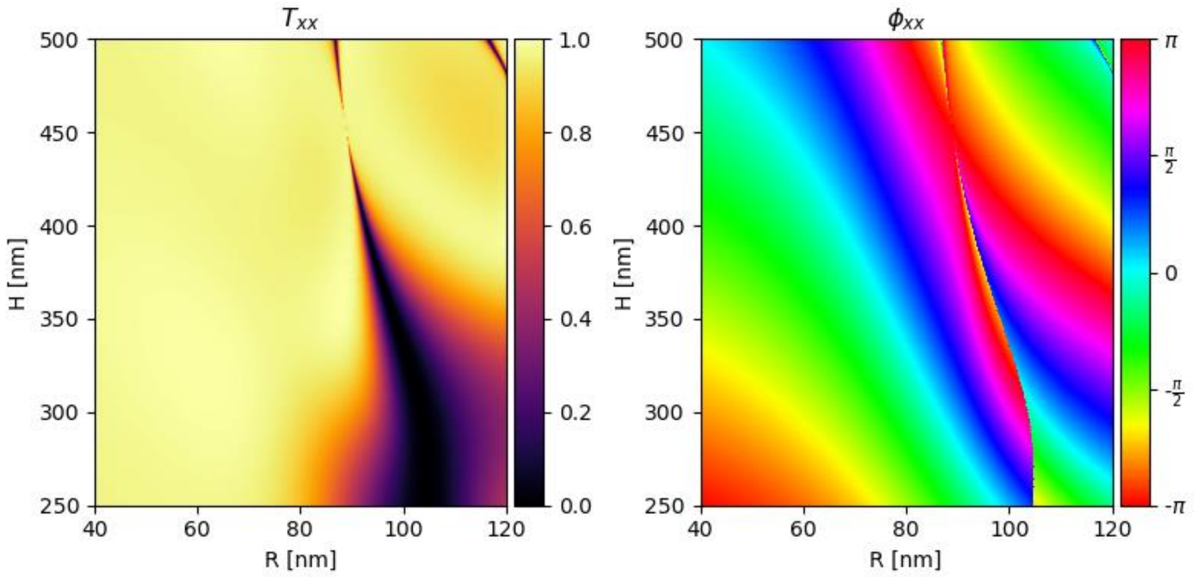



# Robust metalenses:
# (a) Retrieving the phase and transmission map

- Goal: Find the best position in phase space for fabrication

- Solution:
  - Identify the desired specifications (e.g., wavelength range, focal length, numerical aperture)
  - Define the design parameters (metaatom specifications)
  - Define boundaries/nominal values for fabrication processe (e.g., surface roughness, alignment errors)
  - Low number of parameters → sample phase space with active learning algorithms



# Robust metalenses:
# (b) Generalization via automatic differentiation

- Goal: Find the best position in phase space for fabrication

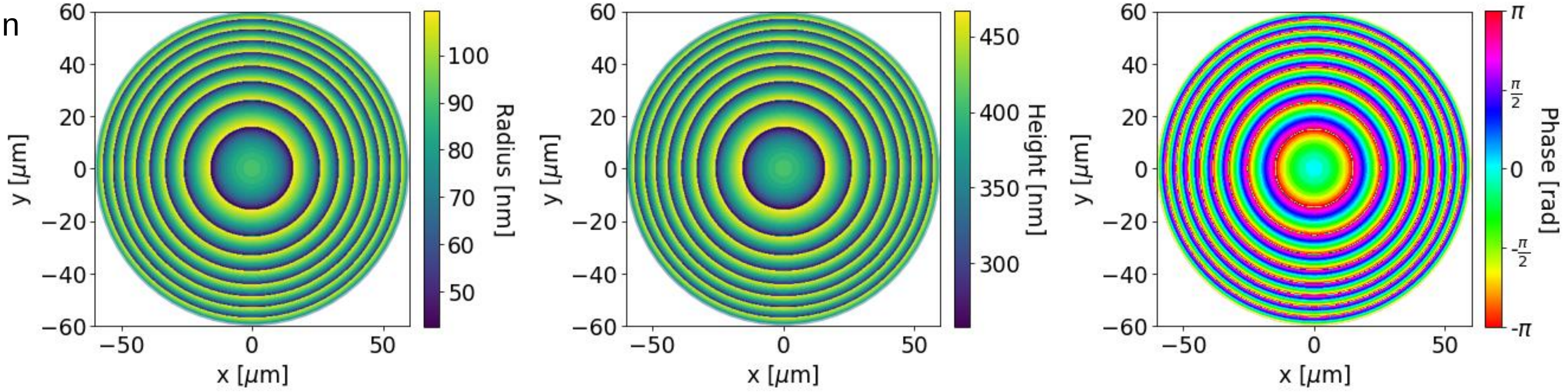
- More complex systems → more degrees of freedom
  - Problem: High dimensional space with exponential growth in resolution!

$$\mathcal{L}(\boldsymbol{\Theta}) = w_1 \left( \frac{\phi(\boldsymbol{\Theta}) - \phi_{\mathrm{t}}}{\delta\phi} \right)^2 + w_2 \left( T(\boldsymbol{\Theta}) - 1 \right)^2 + w_3 \left\| \boldsymbol{\delta\Theta} \circ \boldsymbol{\nabla}_{\boldsymbol{\Theta}} \phi(\boldsymbol{\Theta}) \right\|_2^2 + w_4 \left\| \boldsymbol{\delta\Theta} \circ \boldsymbol{\nabla}_{\boldsymbol{\Theta}} T(\boldsymbol{\Theta}) \right\|_2^2$$

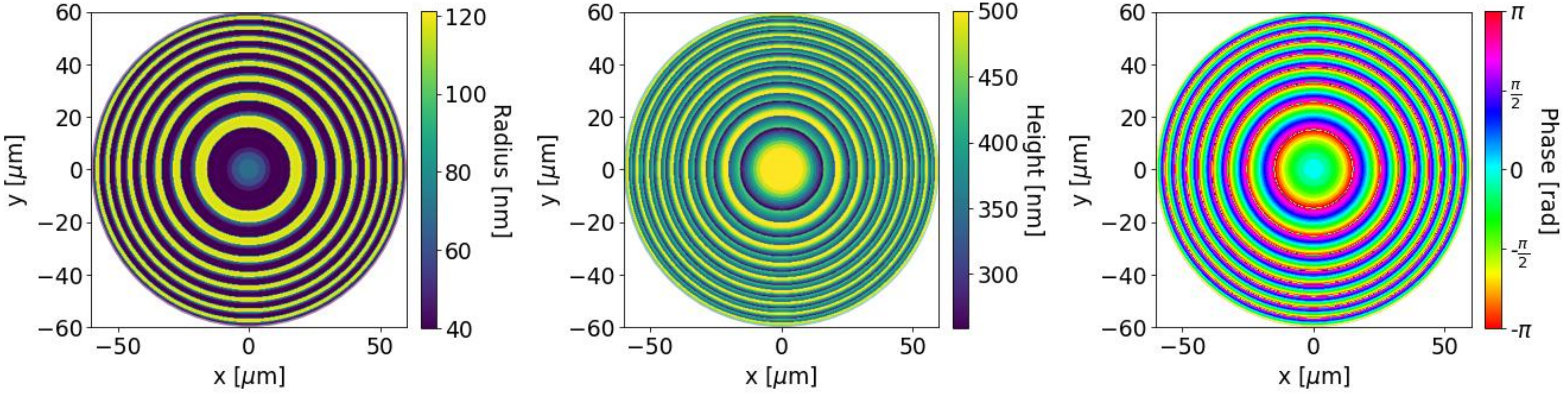
- Assume linear dependence on parameter in phase space → dependence on gradient of phase and transmission
- Nonlinear dependence on parameters → finite differences not suitable
- Gradient can be retrieved numerically exact by automatic differentiation → **Robust metaatom**
- Loss function to find robust metaatoms
- Provides only rough measure for system performance
  - Full-wave simulation or ODA for validation
  - Simulation of supercell for mode coupling analysis → **Robust metalens**

# Robust design

Simple design




New Design after optimization



# Tolerancing effects:
# Effect of systematic offset

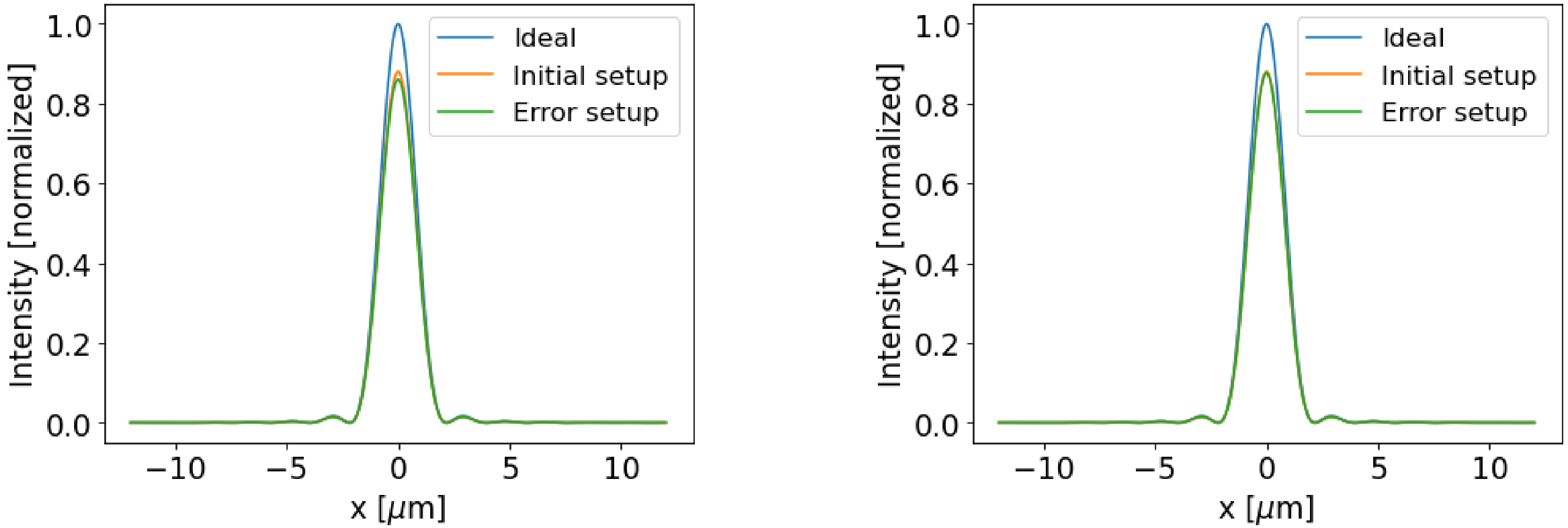
photonics
precision engineering

What happens including errors in fabrication?

- Offset of radius and height by +5nm and +10nm homogeneously
- Simple setup with linear dependence on parameters (ideal for offset)

Naïve design

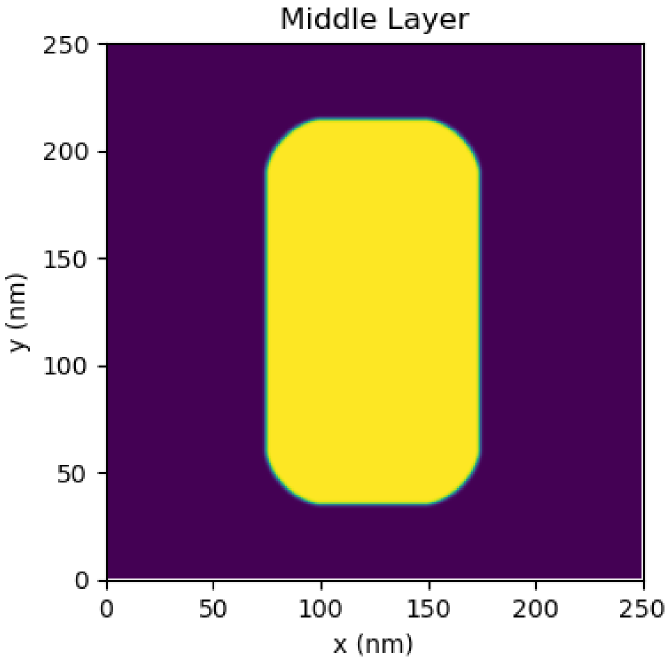
Robust design



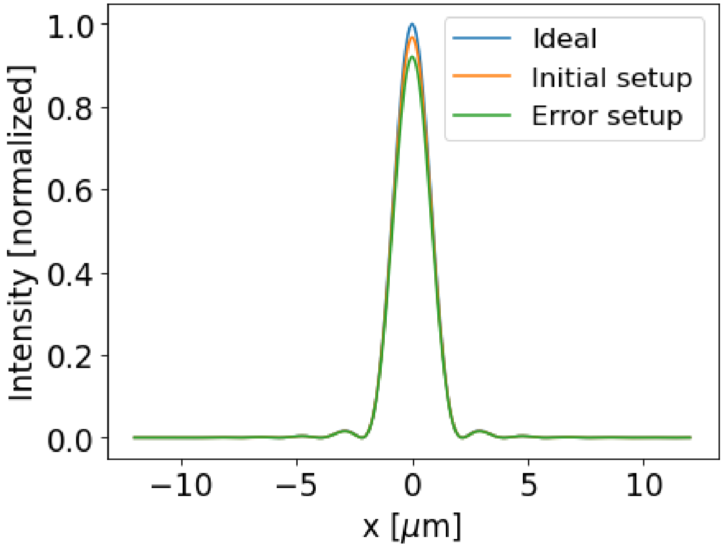

- Example just for explanation for the algorithm!
- Extension to parameter gradients that are not visible in phase/amplitude-parameter map
  - Only radius and height is sampled but also information about all gradients of input parameters
  - Enters in loss function

# Metalens: Nanofin example 532nm (Corner rounding, sidewall angle)

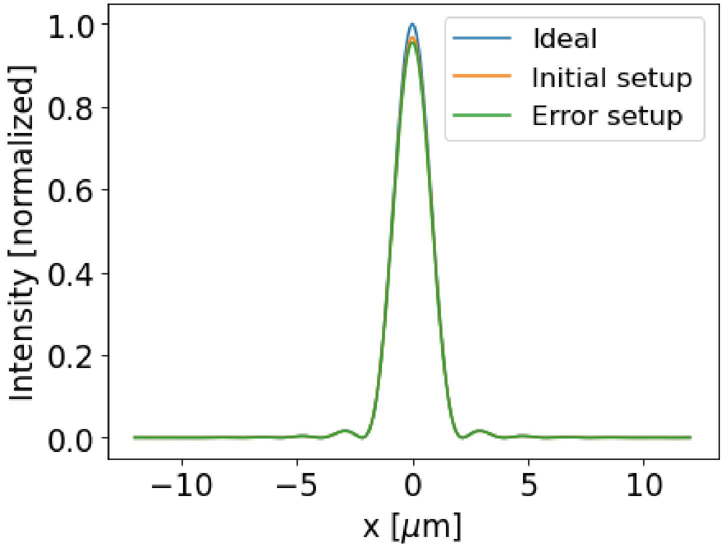
- Breaking symmetry → selectivity for polarization, enantiomeric sensing, …
- Optimize for parameters that are orthogonal to the desired parameter hyperspace
- Design parameters: $W_x$, $W_y$, $\theta$
- Nominal values for sidewall angle and corner rounding are known
- Assume variation of undesired parameter changes over metaoptic
- Nominal values for calculation: 3° side wall angle, 25nm corner rounding
- Assumption random variation by maximally 1° side wall angle and 10nm corner rounding




**Analytical design**



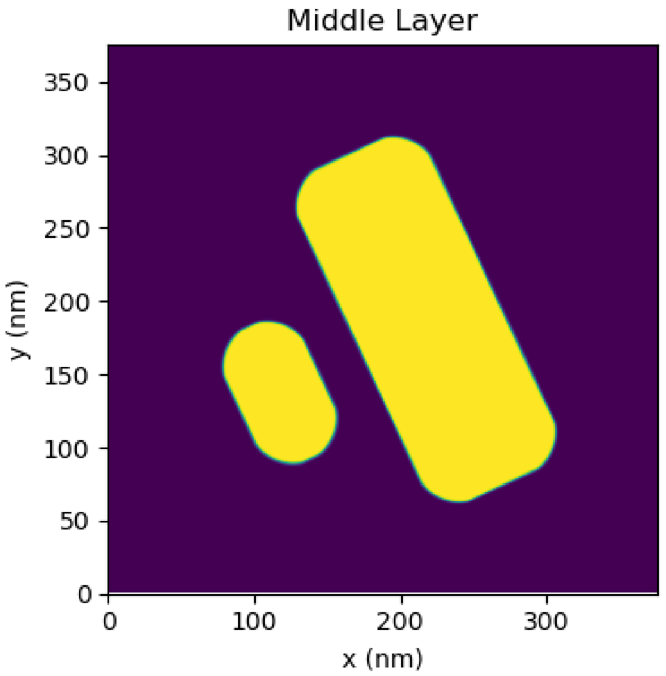

**Robust inverse design**



# 1D Metagrating: Double nanofins example 940nm (Corner rounding, sidewall angle)

- Optimize for parameters that are orthogonal to the desired parameter hyperspace
- Design parameters (complex hyperspace): $W_x$, $W_y$, $\widetilde{W}_x$, $\widetilde{W}_y$, $\theta$
- Nominal values for sidewall angle and corner rounding are known
- Assume variation of undesired parameter changes over metaoptic

- Nominal values for calculation: 3° side wall angle, 25nm corner rounding
- Assumption random variation by maximally 1° side wall angle and 10nm corner rounding




**Efficiency 1st order:**

Inverse design: 87.1% → 80.5%

Robust inverse design: 86.9% → 84.8%

# Summary and Outlook

- ✓ More parameters allow for more error corrections → also introduce new error sources
- ✓ Reduce to few important parameters that describe your system
- ✓ Handling of homogeneous and inhomogeneous distribution of manufacturing errors
- ✓ Method easy to integrate into common design methods

<u>Open points</u>

- ❑ Temperature? → working on inverse design solution
- ❑ Correct behavior for oblique incidence → loss function for inverse design → less supporting points
- ❑ Supercell optimization