Tolerancing Metalenses: from a Classical Perspective

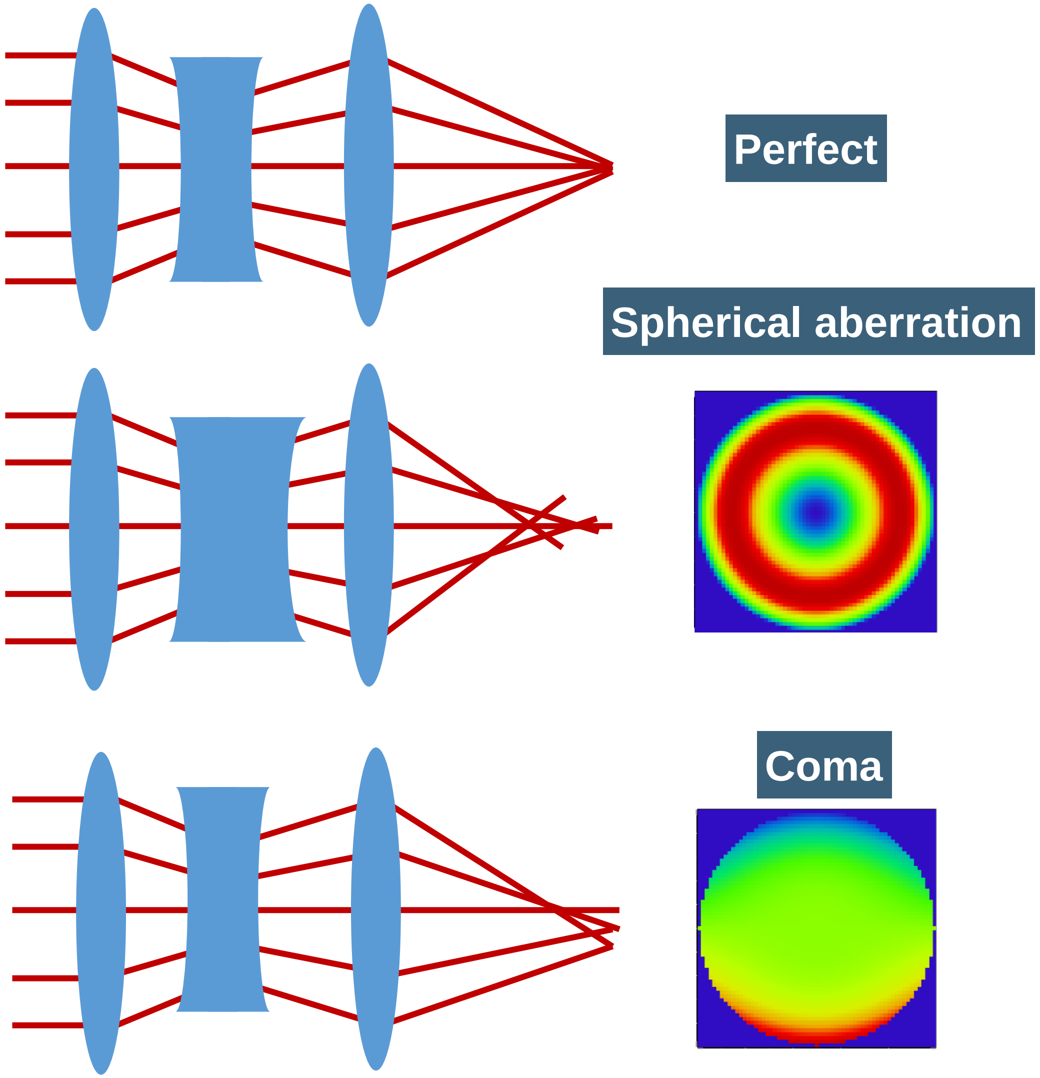
Dominik Schulz | 12.05.2023

EPIC Meeting on Photonics for AR/VR/MR

What are Metalenses and how are they different?
Review of classical tolerancing

photonics
precision engineering

- Classical optical systems have mostly spherical elements due to manufacturing reasons
- Perturbations in light interaction parameters cause small changes in the wavefront
- Deviations from spherical shape can be expressed in a polynomial expansion
- Changes in low-frequency properties lead to low-frequency changes in the wavefront
- Higher-order contributions quickly vanish when describing perturbations in ascending order of pupil coordinates
- Zernike polynomials are an appropriate choice for these polynomials



What are Metalenses and how are they different?
Does this suffice?

- Zernike polynomials identify potential origins for specific aberrations and countermeasures, e.g.:
  - on-axis spherical aberration, symmetrical off-axis astigmatism, field curvature, …

    Compensated by → airspaces
  - on-axis coma, asymmetric off-axis astigmatism, … Compensated by → lateral shifting of elements
- Perturbative description of aberrations helps choose compensators

in short

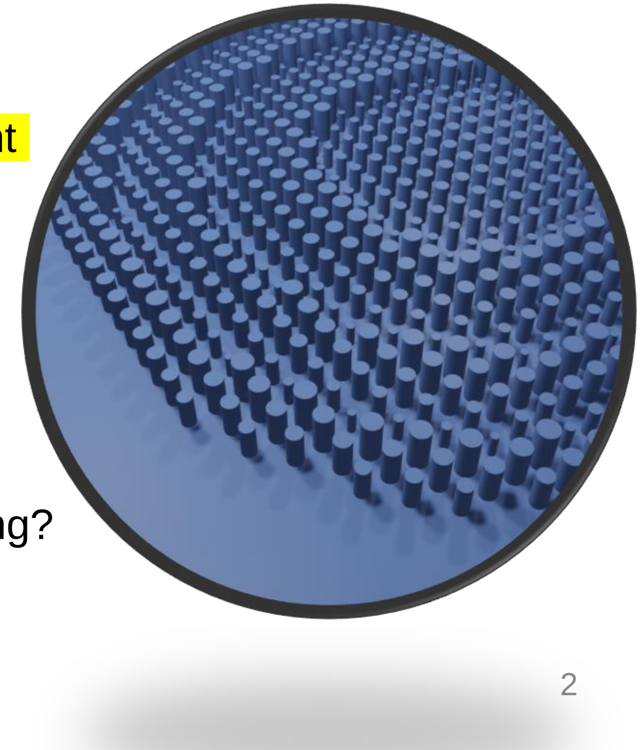
- Describing aberrations in a perturbative manner is useful due to spherical nature of surfaces
- Using Zernike polynomials allows understanding sensitivity of system and deriving adjustment strategies

what changes with metalenses?

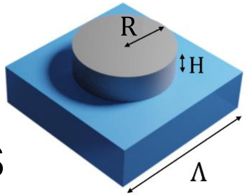
- Metalenses generate spherical wavefront by different action principles
- Manipulation of phase and amplitude by small sub-wavelength units (metaatoms)
- The question is:

  Action principle is significantly different → classical approach to tolerancing still working?

  If not, what alternatives do we have?



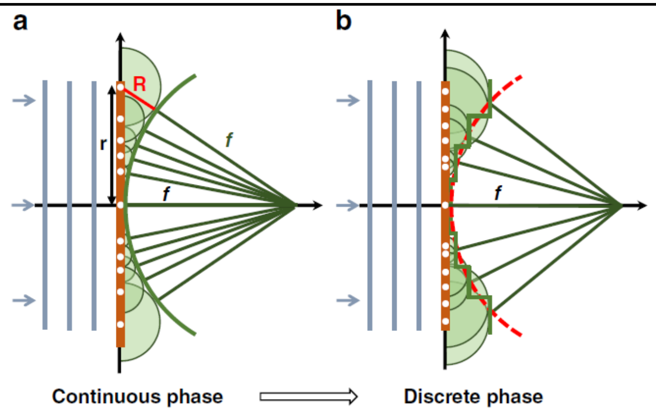
Simple example: Cylindrical metaatoms

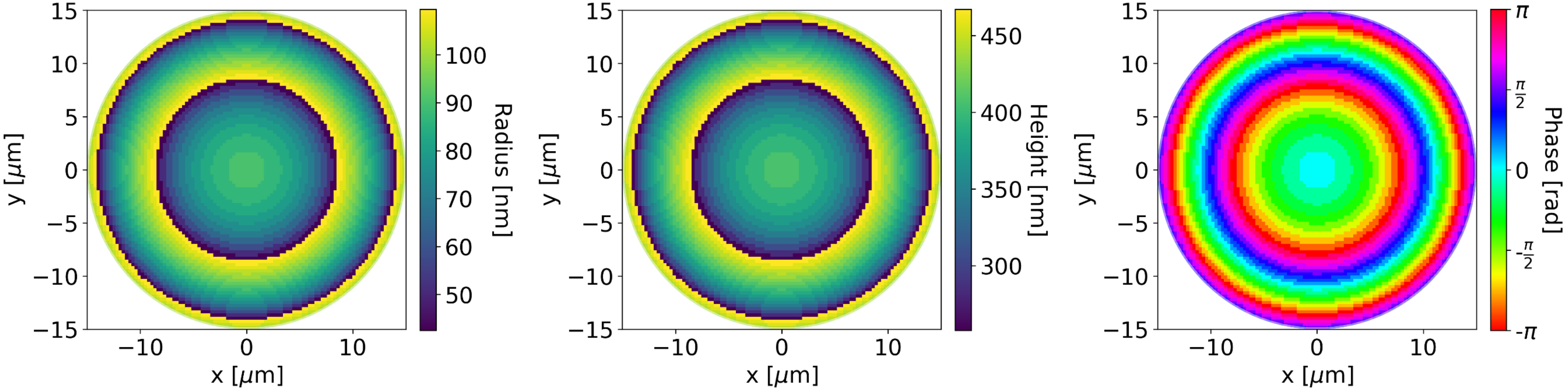


- More degrees of freedom → more possibilities for error correction
- Breaking symmetry → selectivity for polarization, enantiomeric sensing, …

Here:

- 2 degrees of freedom with axial symmetry: Radius and height
- Dielectric low-NA metalens → $\mathrm{NA} = 0.15, \lambda = 633\mathrm{nm}, \mathrm{TiO_2}$ on $\mathrm{SiO_2}$
- 16 phase levels go with radius and height

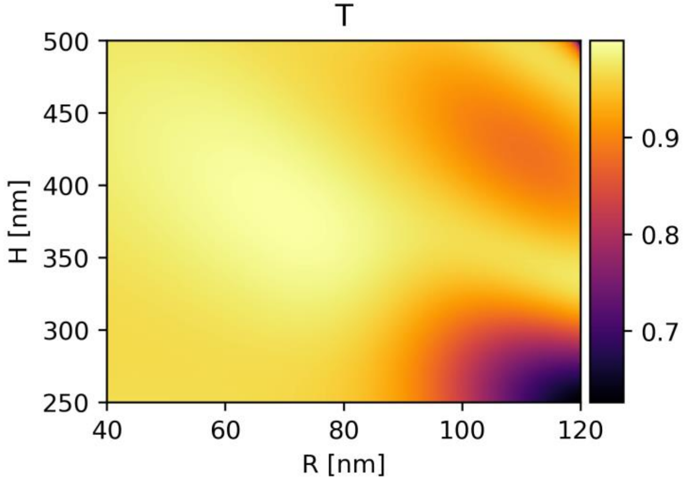


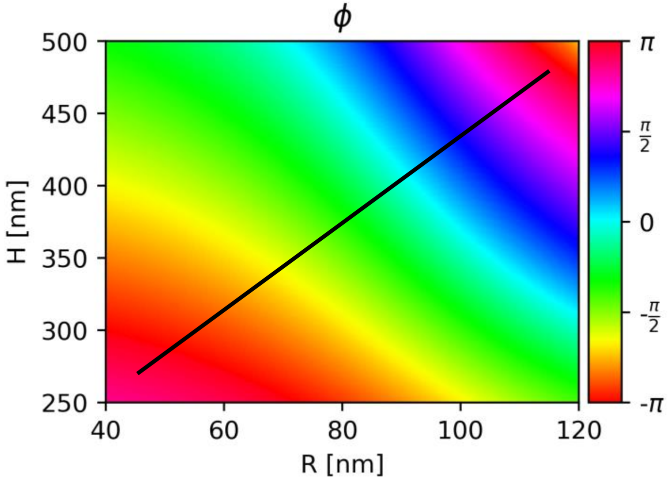


Tolerance effects (simple design):
Effect of systematic offset

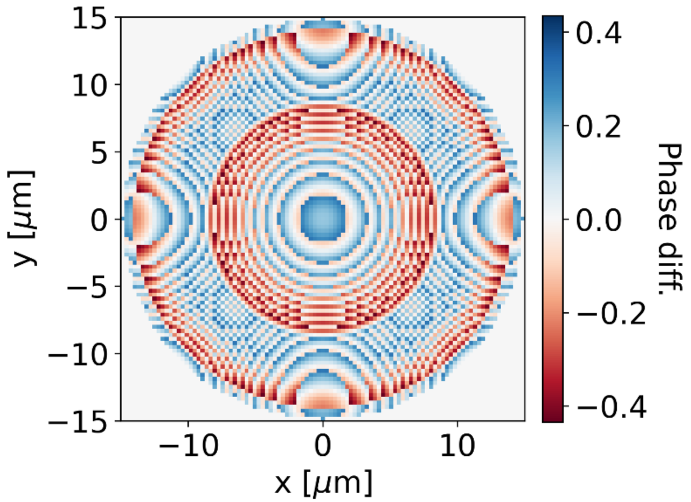
What happens including errors in fabrication?

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





RMS-WFE: $27.2\mathrm{m}\lambda$



→ **Low Zernikes not sufficient (Residuum too high)**

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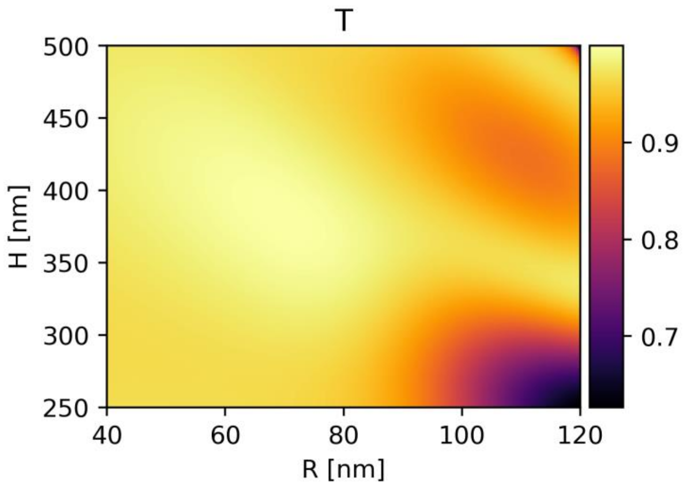

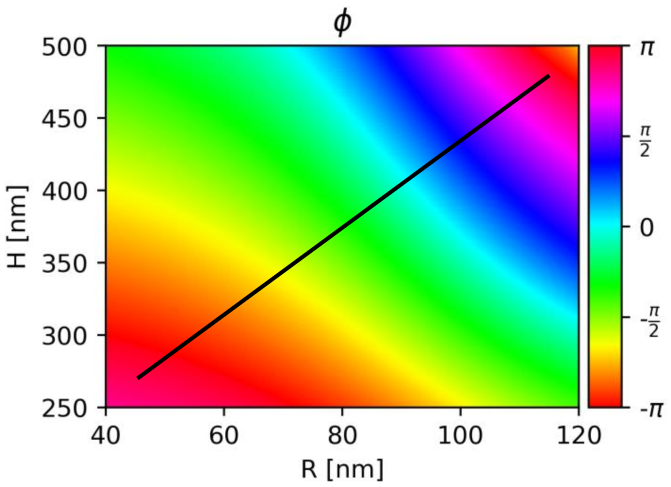

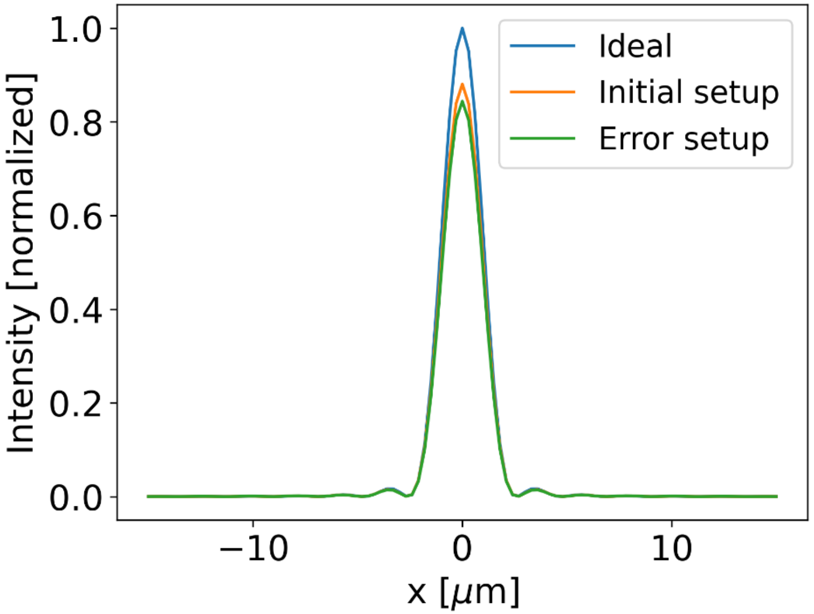

→ PSF and Strehl ratio better measure for error
→ Propagation of "full" field

Tolerance effects: Mitigation

How to improve?

- Consider tolerances already in design of metaatoms library
- Design towards insensitivity to systematic or random errors (offset, scaling, merging, …)
- Assume linear dependence on parameter in phase space
  - Small gradient → less change in amplitude and phase by parameters
- Strong change of hypersurface (resonances) → finite difference not sufficient

- Minimize loss-function with automatic differentiation for gradient

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

- Only rough measure for system performance

→ Simulation of full wavefront or supercell for resonance analysis

Tolerance effects:
Stable design

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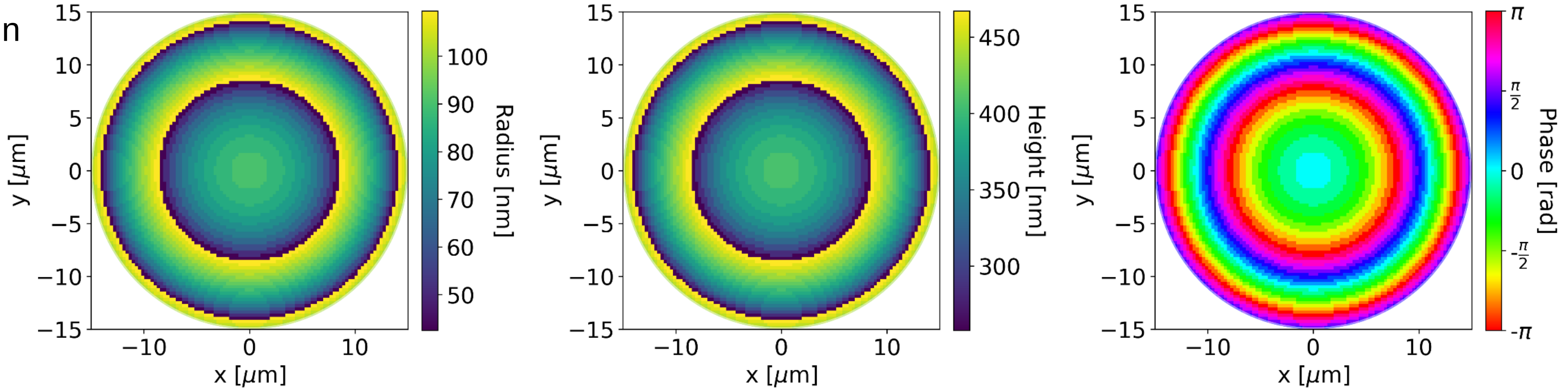
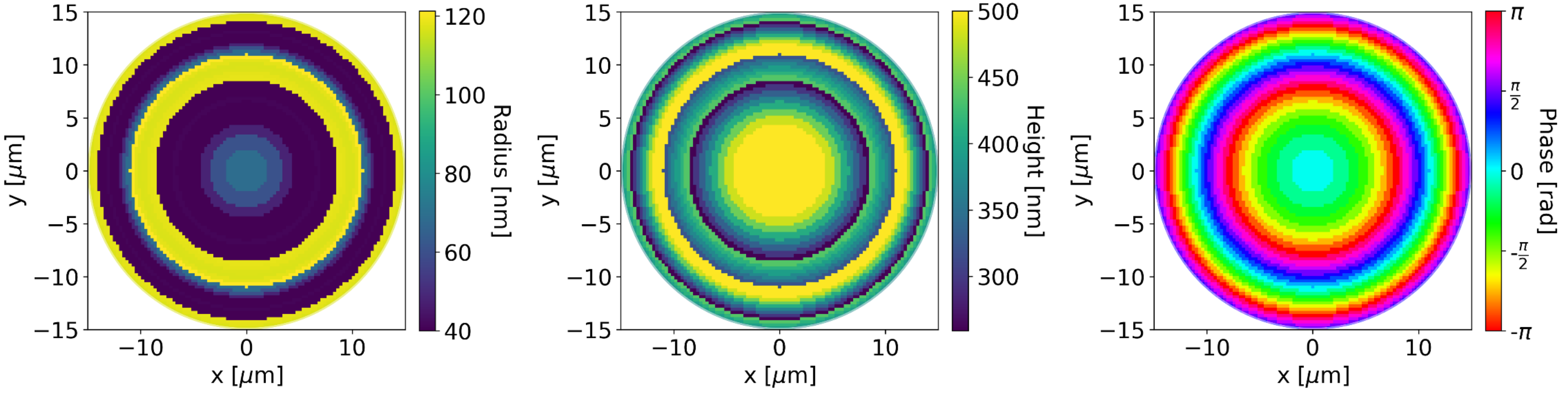
Simple design



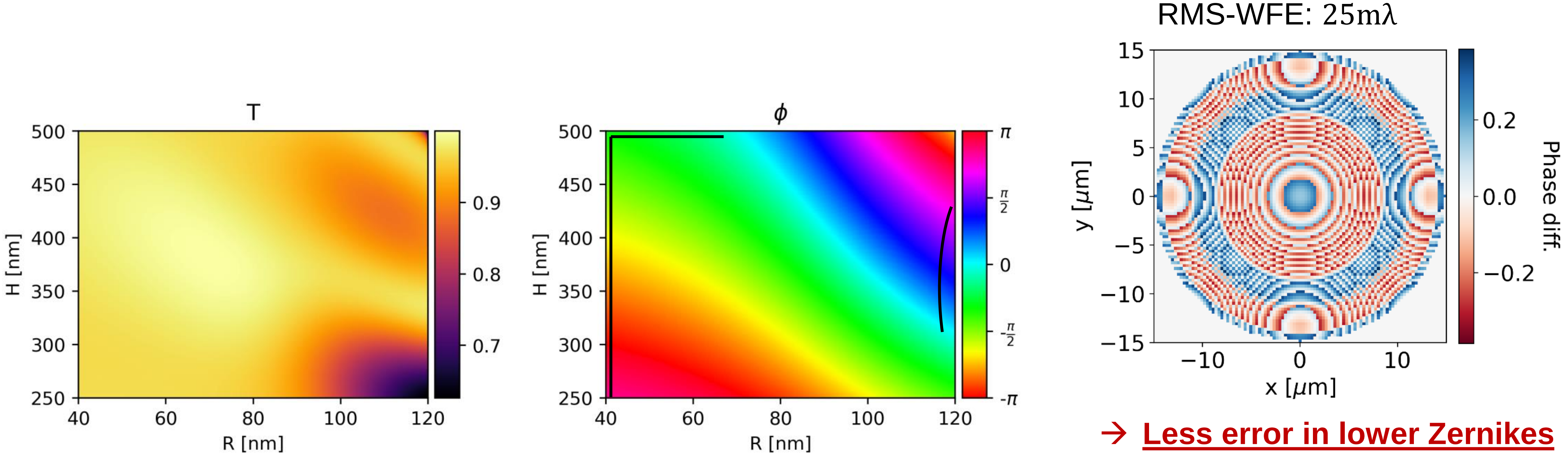
New Design after optimization



Tolerance effects:
Effect of systematic offset

What happens including errors in fabrication?

- Offset of radius and height by +5nm and +10nm homogeneously
- Optimized parameter set for metaatom library



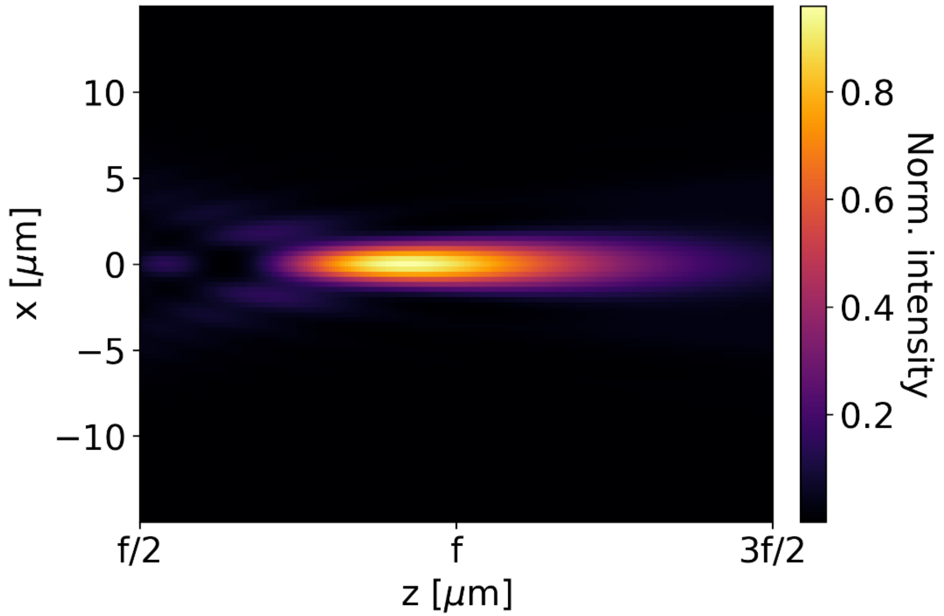
→ **Less error in lower Zernikes (Residuum smaller)**

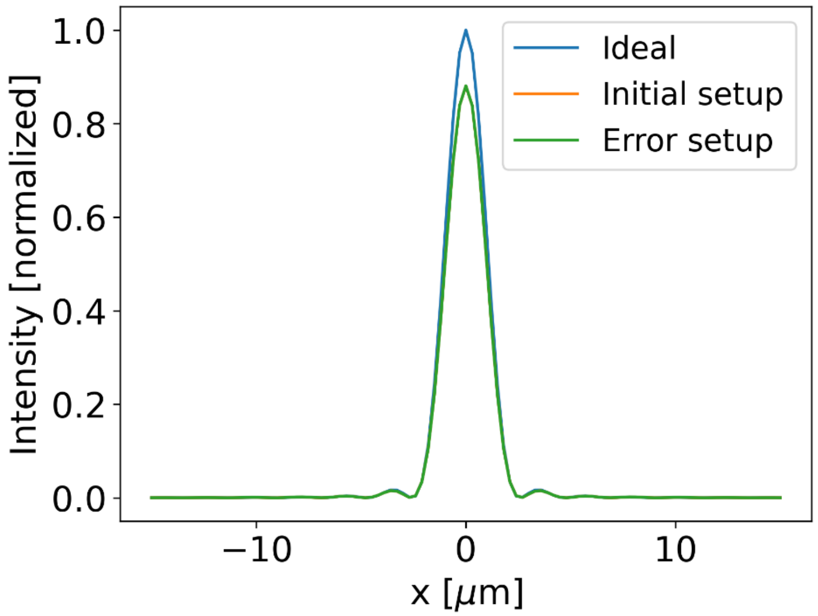
Tolerance effects:
Effect of systematic offset

What happens including errors in fabrication?

- Offset of radius and height by +5nm and +10nm homogeneously
- Optimized parameter set for metaatom library
- Gradient optimization

→ Better performance for inhomogeneous offsets



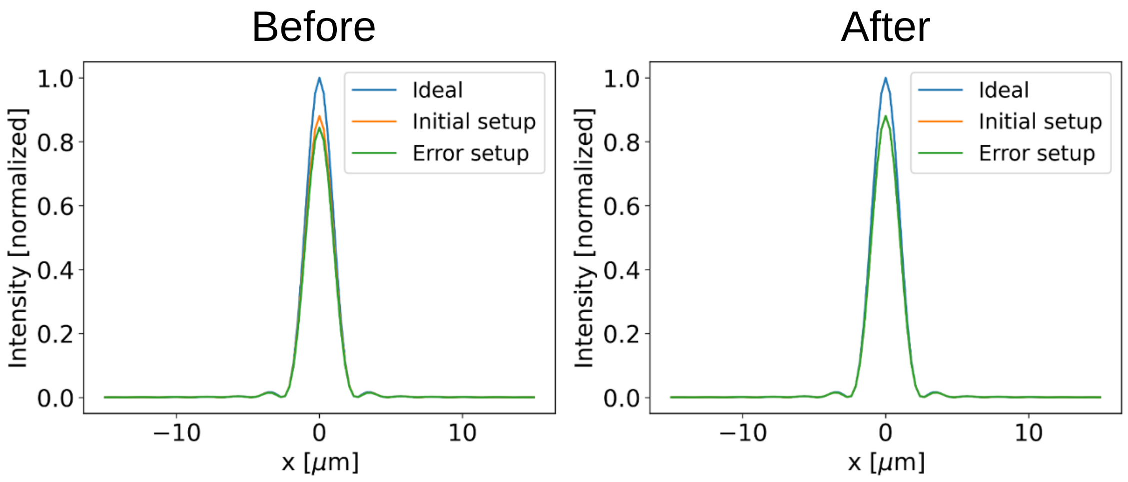


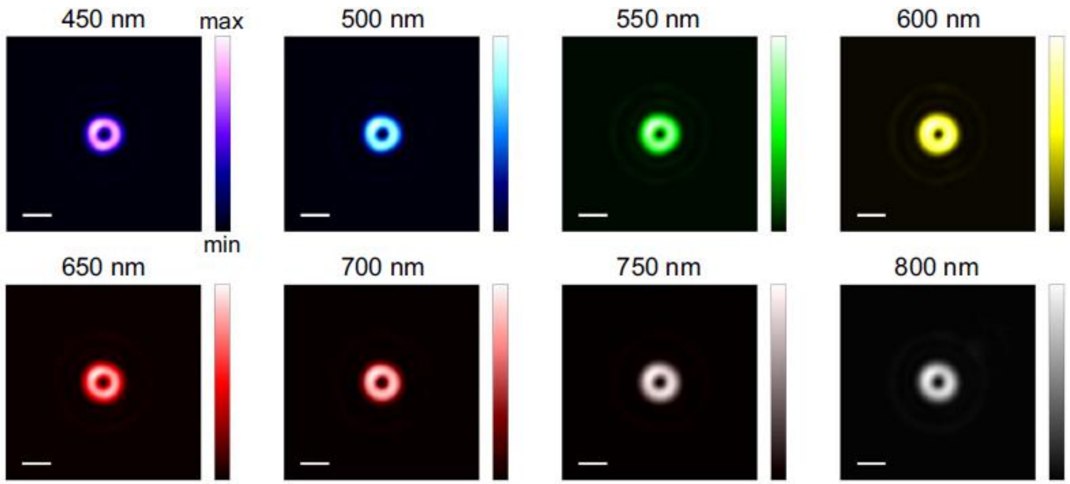
→ Better Strehl ratio

Summary and outlook

- ✓ Tolerancing fundamentally different to classical optics
- ✓ More parameters allow for more error corrections → also introduce new error sources
- ✓ We can handle homogeneous and inhomogeneous distribution of offsets due to gradient-based technique
- ✓ Define loss function for your problem

- ❑ Optimization of supercells to consider near-field couplings
- ❑ Topology optimization combined with Fourier analysis for large-area metasurfaces
- ❑ Plasmonic metalenses or multi-layers of alternating metal and dielectric layers
- ❑ Achromatic metalens-design, Multi-foci, …





Chen, W.T., Park, JS., Marchioni, J. *et al.* *Nat Commun* **14**, 2544 (2023)

Managing Directors & Founders

Jan Werschnik, PhD
jan.werschnik@ppe-jena.com

Tim Baldsiefen, PhD
tim.baldsiefen@ppe-jena.com

Carolin Muenzberg
carolin.muenzberg@ppe-jena.com

Tolerance effects:
Effect of field

What happens including errors not taken into account in optimization?

- Usually still better since WFE is smaller
- Here, up to roughly 5° better, later worse
- Adding field → cannot be included via gradient (symmetry)

  → Hessian for optimization necessary