Sensitivity analysis and tolerancing of Mid Wave IR metalenses

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OSA Topical Meeting on Flat Optics, June 29 2021, Virtual Event

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Who are we?

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- Start-up from Ghent, Belgium
- Dedicated provider of:
  - **Simulation** software for **metasurfaces**
  - **Designhouse** for photonic & optical applications
- 20 years of photonics R&D experience in industry and academia:
  - Simulation
  - Fabrication
  - Measurement
- Supported by:

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Founding team

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Dr. Wouter Woestenborghs

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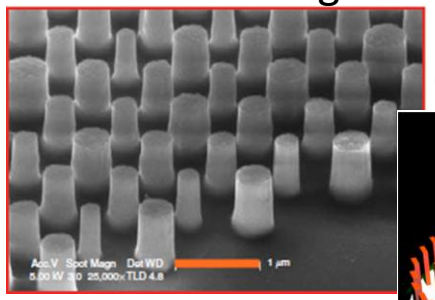
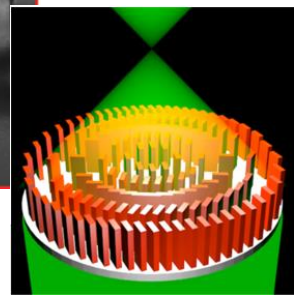
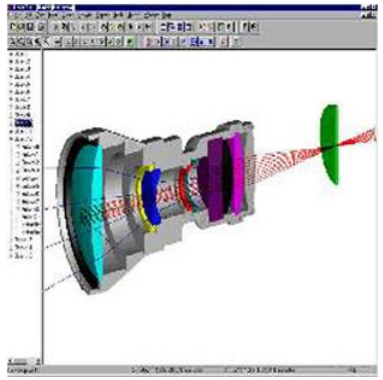
Nano-scale design



Component design



System Integration



Planopsim's mission

Planopsim supplies **R&D tools** to **engineers** & **scientists** that allow to unlock the maximum benefit of **flat optics** in a **user-friendly** way.

- Computer Aided Design **software for Planar Optics & metasurfaces**
  - All-in-one design workflow
- **Design service** for metasurfaces and photonics
  - In-house and 3d party tools

Which errors are critical?

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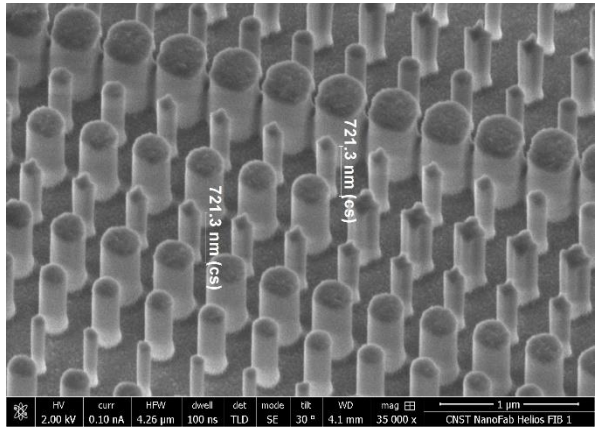
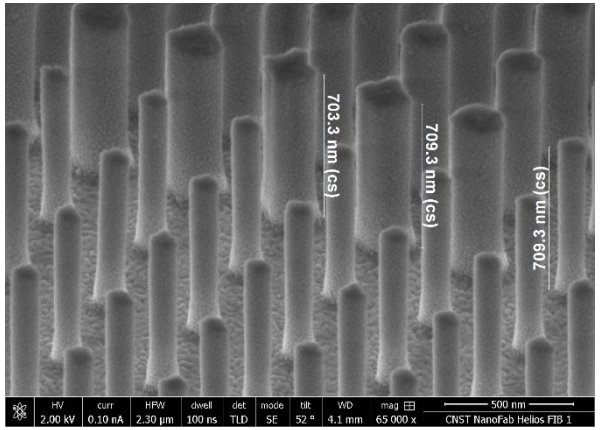
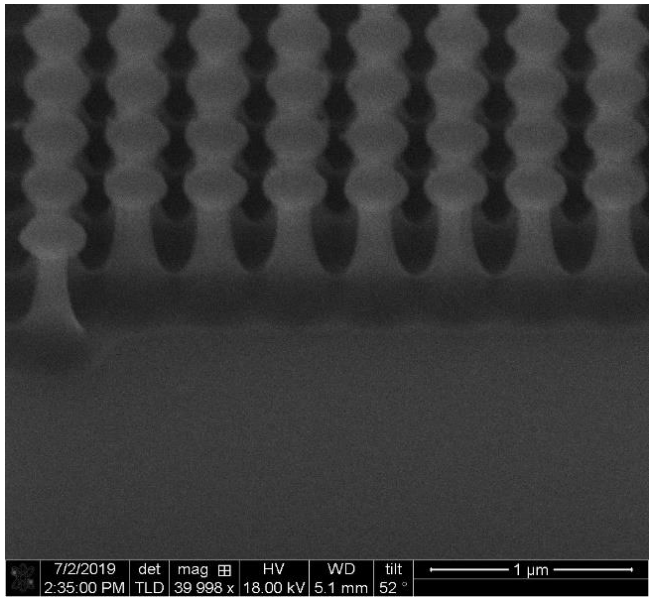
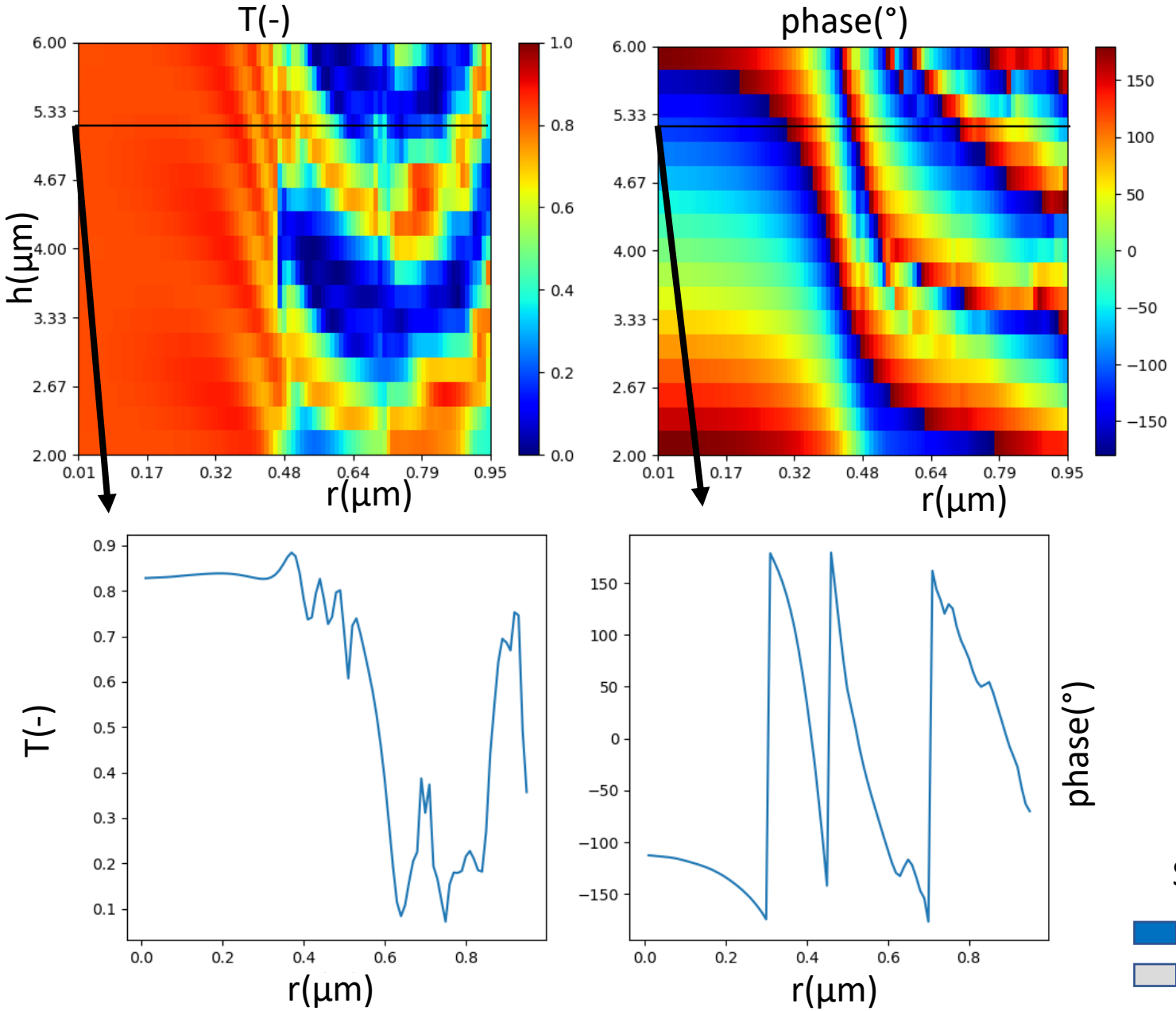
- Typical design assumption:
  - All structures are perfect
  - Optimize until specifaction is reached
- **X Million structures** in 1 meta-surface component
- There are systematic & random errors
  - This study: **systematic errors**
  - Random errors: Monte Carlo analysis
- In practice:
  - Which errors are critical-to-quality?
  - What is the effect of various error types
  - Which deviation can be tolerated of each type
- Sensitivity analysis:
  - Design using nominal structures
  - Simulation replaces nominal by perturbed structures



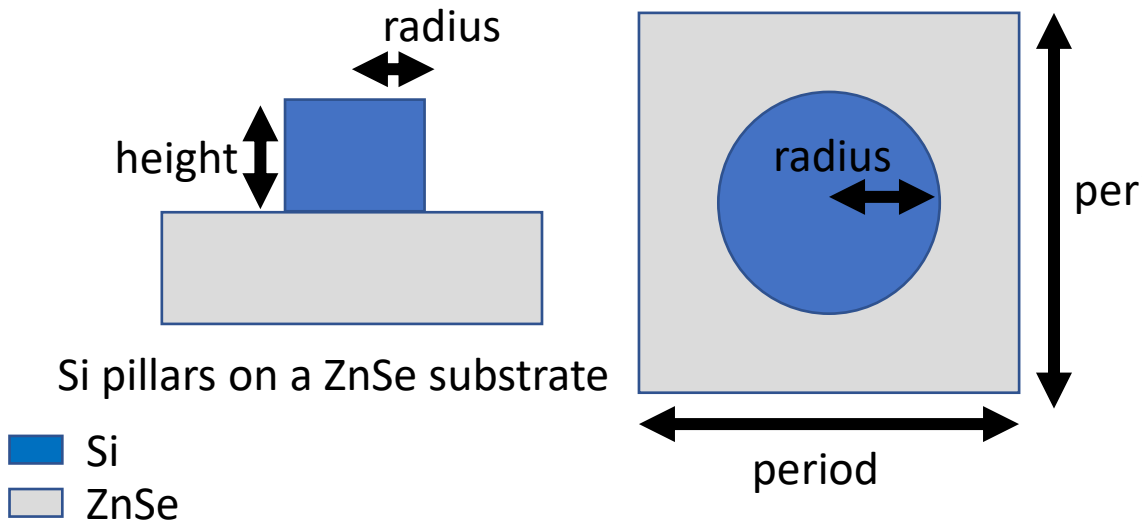




Reference meta-atom



- Meta-atom type:
  - Design λ: 4 µm
  - a-Si Cylindrical pillars on ZnSe
  - Square arrangement
- Configurations scanned with full Maxwell solver (PlanOpSim MetaCell)
- 8 meta-atoms selected for 0-360° phase coverage
  - P: 2 µm
  - H: 5,25 µm



Reference metalens

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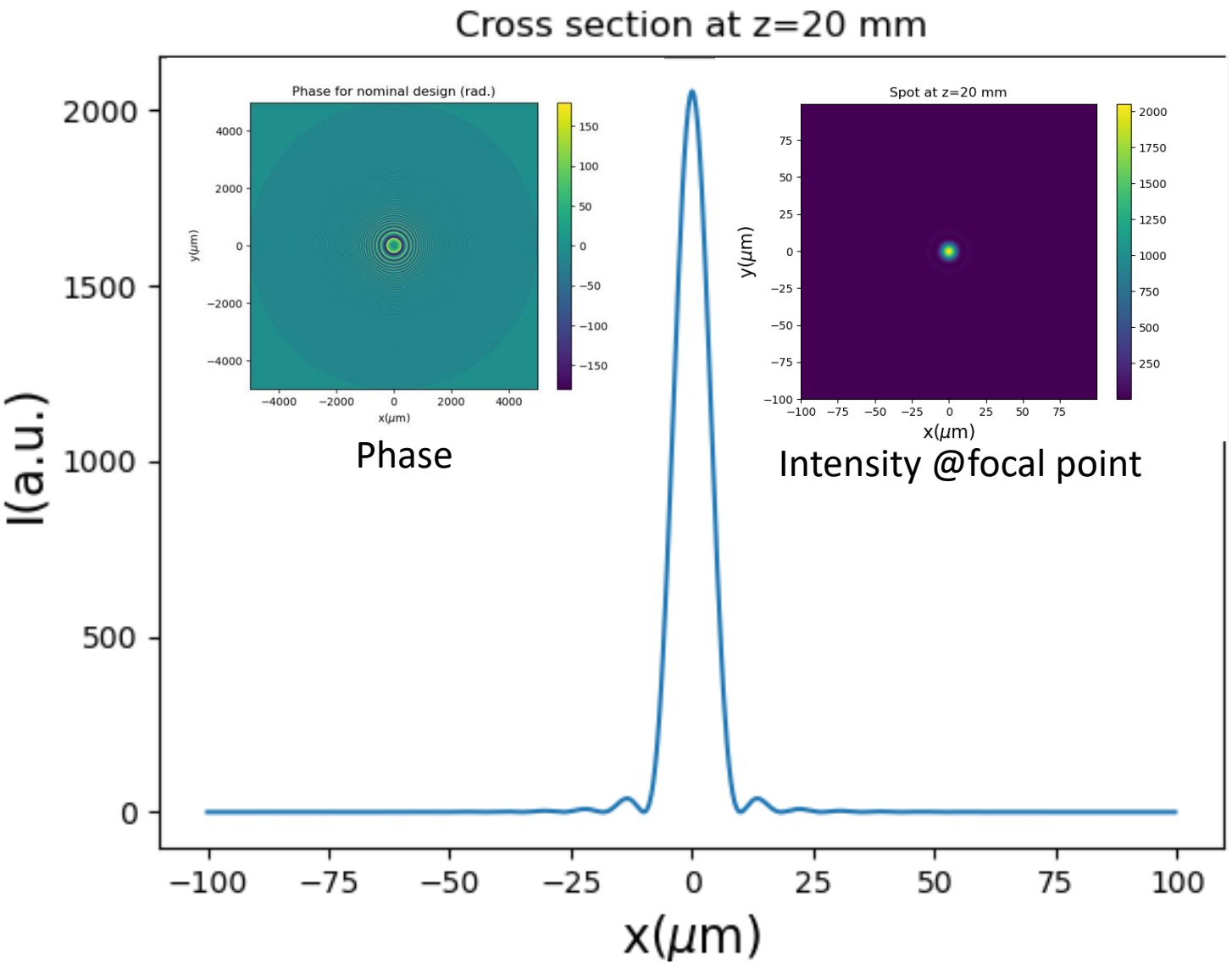
- Reference lens parameters:
  - Size: 10 x 10 mm
  - Focal distance *f:* 20 mm
  - Corresponding NA: 0.24
- Analytical spherical phasefront:

$$\varphi(\lambda) = \frac{2\pi}{\lambda}\left[\sqrt{x^2 + y^2 + f^2} - f\right]$$

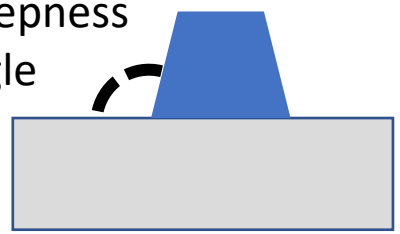
- Simulated using:
  - Fresnel propagation
  - Local periodic approximation
  - PlanOpSim Meta-Component
- Nominal spot characteristics:
  - FWHM: 8.43 µm
  - Transmission efficiency: 76.0%
  - Focussing efficiency: 59%



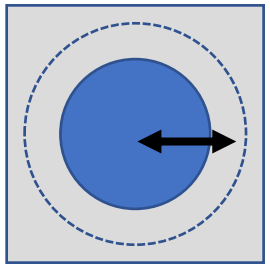
Error types

- Meta-atoms **uniformly modified from nominal** design parameters over entire meta-lens
- Sidewall angle
  - Nominally 90°
  - Varied parameter: angle
  - Assumption: cylinder -> cone
  - Over- and underetching common
- Direct radius deformation
  - Varied parameter: Δr
  - Differences in resist exposure/developing
- Height difference
  - Varied parameter: Δh
  - Variations in film evaporation
- There are many more!

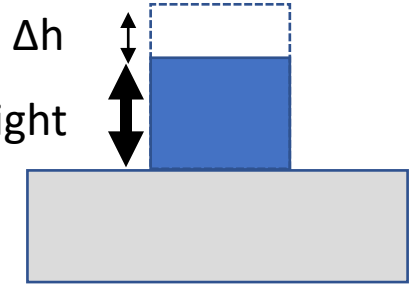
Steepness angle

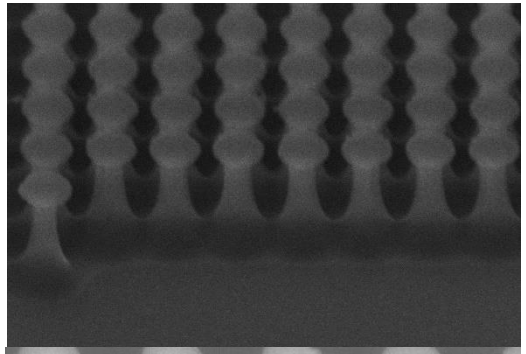


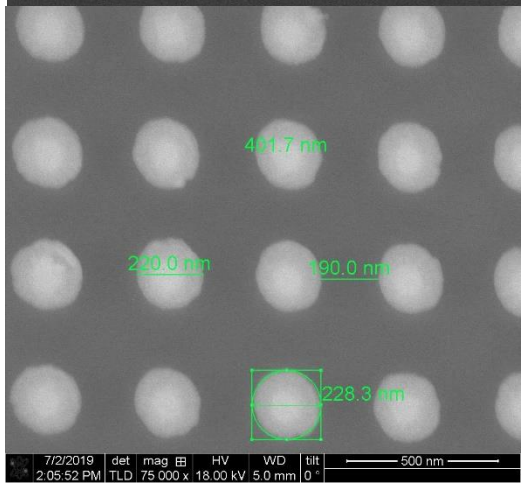
radius modified

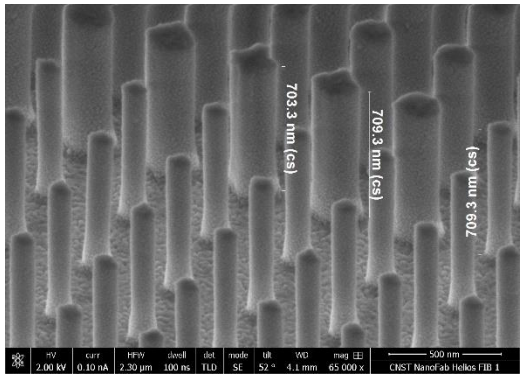


Height modified

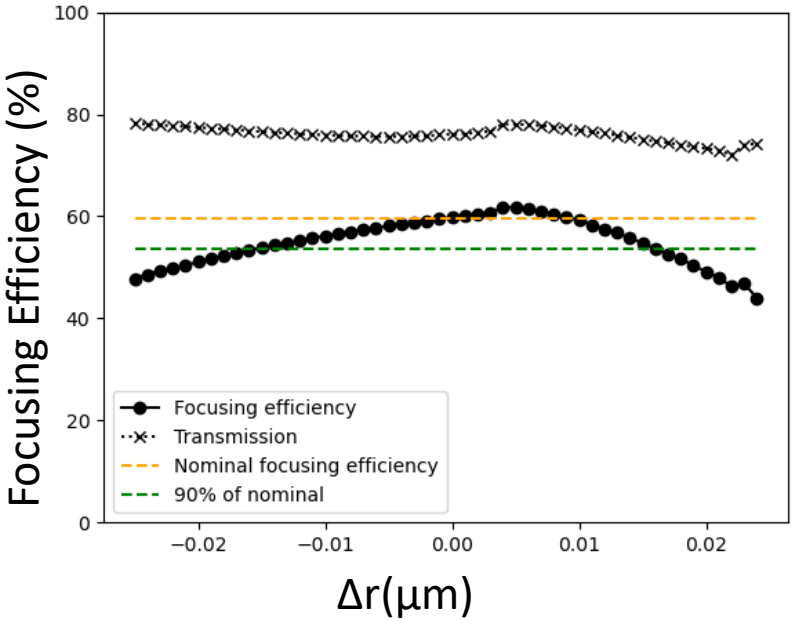


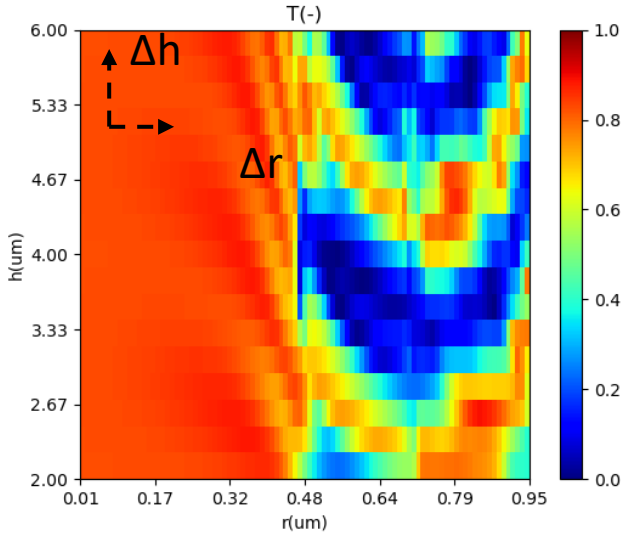


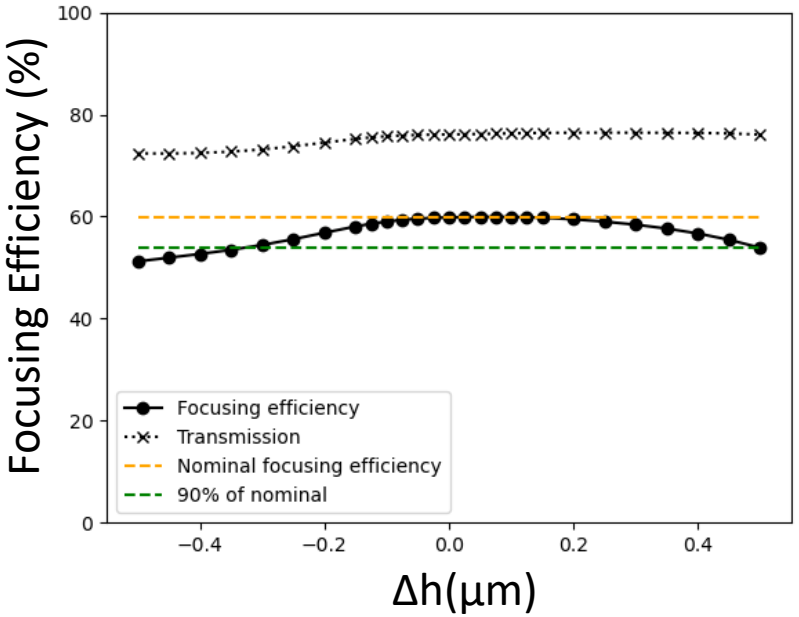




Sensitivity



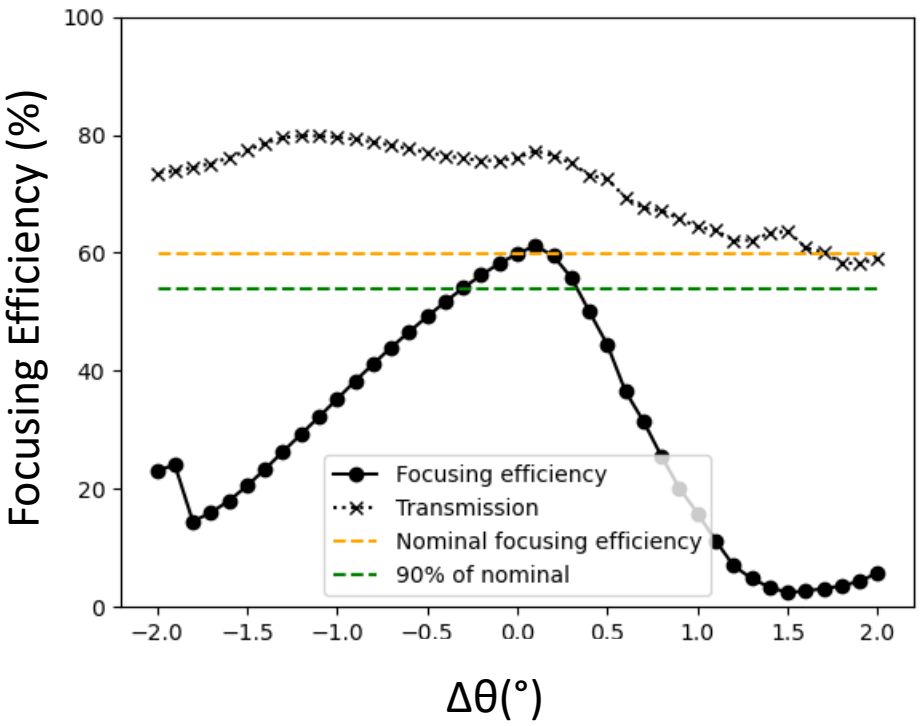




- Δr = ±0,025 μm
- Transmission 76-> 72%
- Focussing efficiency 59,9->44,0%
- Threshold 90% of nominal focussing efficiency:
  - ±15nm
  - 0,75% of pitch/ 0,375% λ

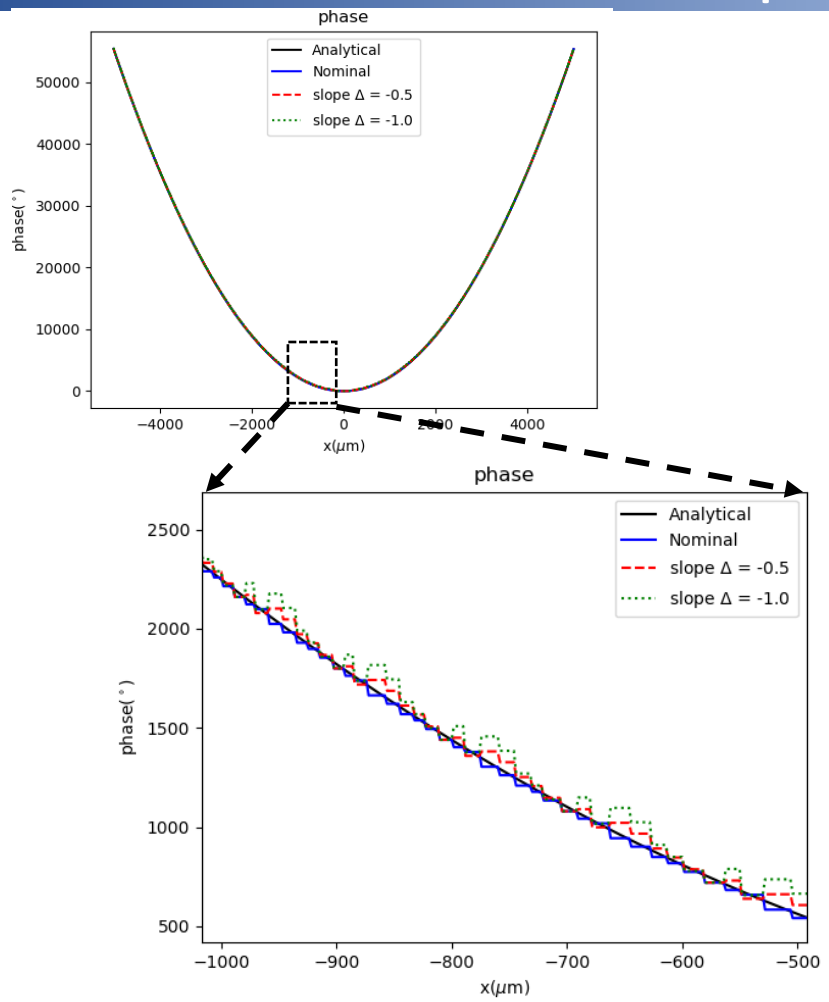
- Δh = ±0,50 μm
- Transmission 76-> 72,3%
- Focussing efficiency 59,9->51,2%
- Threshold 90% of nominal focussing efficiency:
  - -300nm+500nm
  - -5,7/+9,5% of height
  - -7,5% / 12,5% λ

Sensitivity



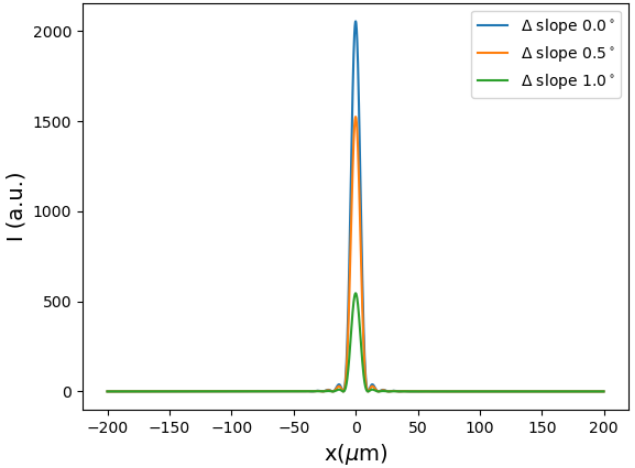
- Δθ = ±2°
- Most sensitive parameter
- Transmission 76-> 58.2%
- Focussing efficiency 59,9->2.4%
- Focussing reduces more quickly than transmission
- Threshold 90% of nominal focussing efficiency:
  - ±0,3°

What causes the performance loss



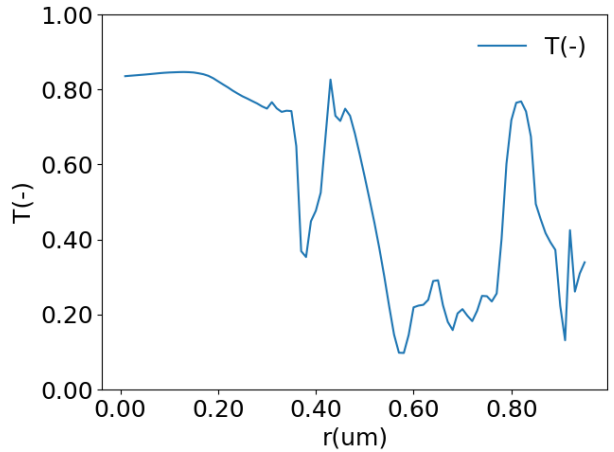
- Wavefront phase for nominal and aberrated cases
  - Example: sidewall angle
- Overall wavefront shape remains the same
- Aberrated wavefront -> perturbation on ideal wavefront
  - Focal distance remains the same
  - Spot width remains the same
  - Loss of efficiency to scattering
- Transmission: additional loss

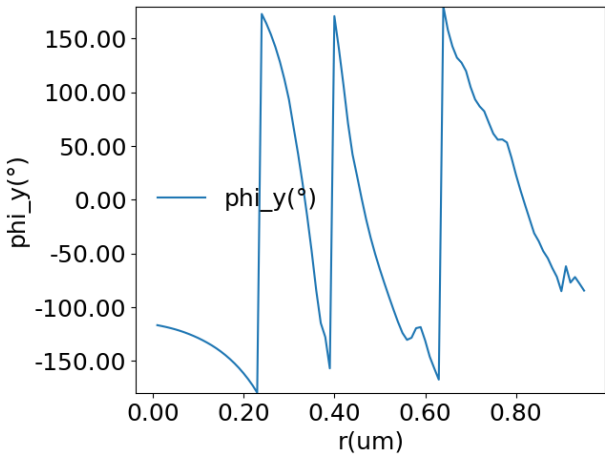
Intensity at z =20mm



Sidewall angle	Phase error (RMS)	Amplitude error (RMS)
90° (nominal)	16,2°	0,19
89,5°	34,2°	0,23
89°	68,5°	0,35

Compensating known errors





- Known sidewall steepness 88,5° (worst case)
- Meta-atoms resimulated and selected
  - P = 2µm
  - H = 5,25µm
- Meta-atoms placement repeated using new meta-atom results
- A **known and constant error can be compensated**

Sidewall angle	Transmission	Focussing efficiency	F/T
90° (nominal)	**76%**	**59.9%**	**0,76**
88,5° (uncompensated)	63,7%	2,4%	0,04
88,5° (compensated)	**76,7%**	**60,9%**	**0,79**

Multi-layer errors

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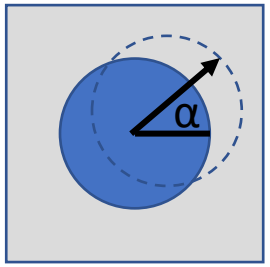
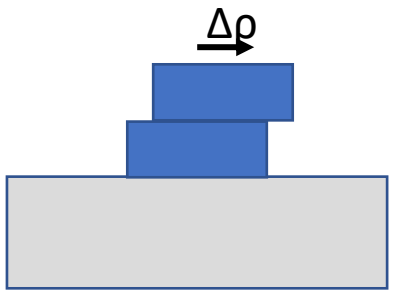
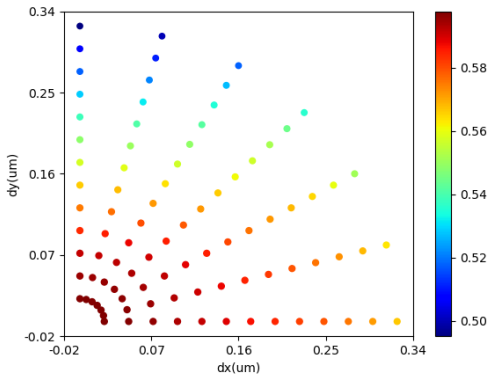
Top view



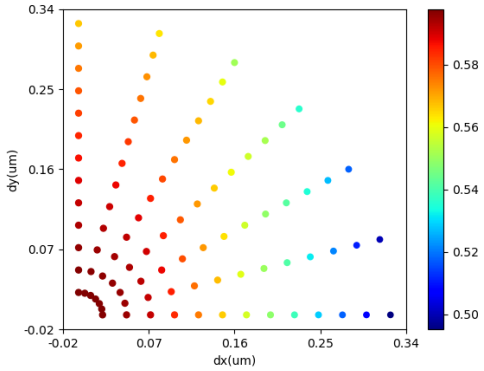
Side view



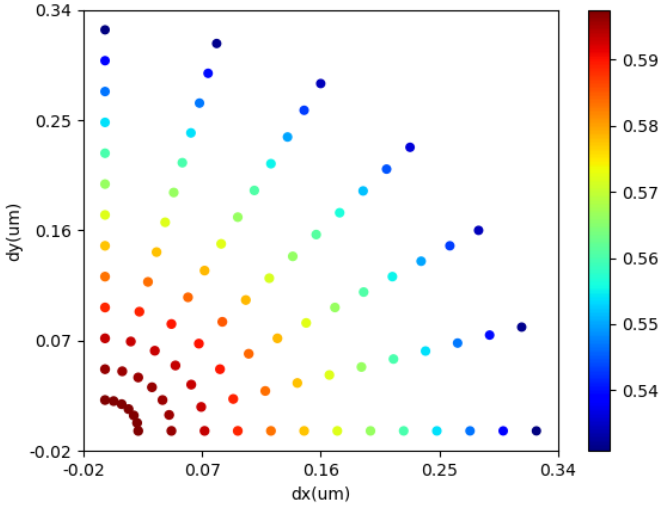
TE



TM



Focussing Efficiency



- Multi-layer structures
  - Reference case 2-layers
- Alignment error:
  - Angle α (0-90°)
  - Distance ρ (0-325nm)
- Average focussing independent of angle
  - Causes polarization sensitivity
- Focusing efficiency 59.9->53,1%
  - Transmission76% -> 70,1%
  - Efficiency mostly lost through reduced transmission

Comparison systematic to random error

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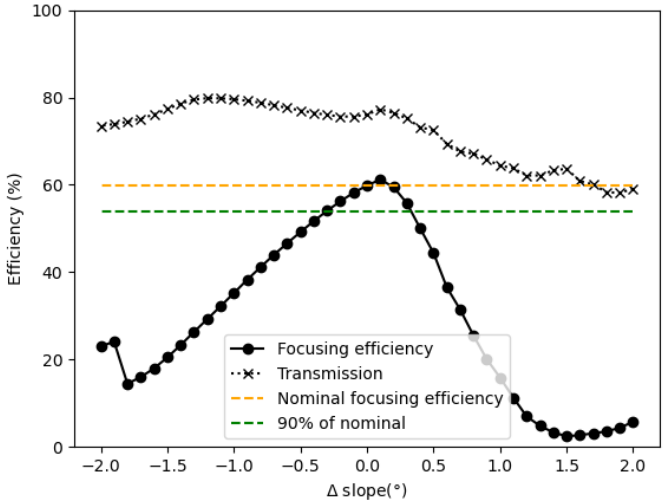
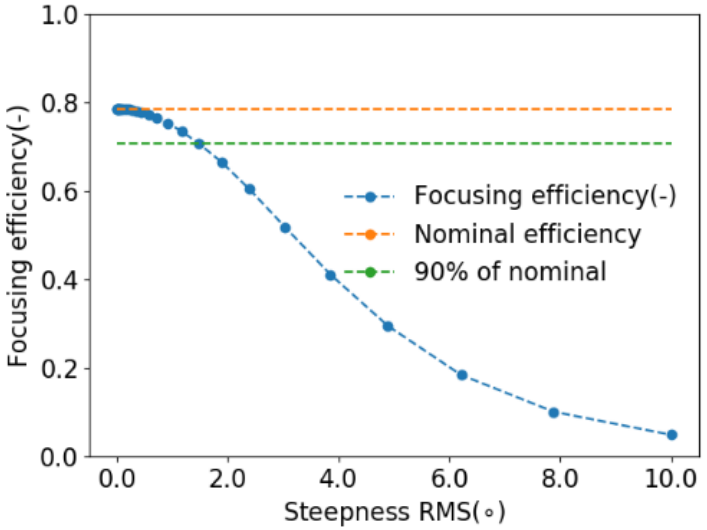
- **Systematic errors** have a **stronger impact than random errors** on focussing efficiency
- Monte carlo results for meta-lens for 532nm

Systematic errors

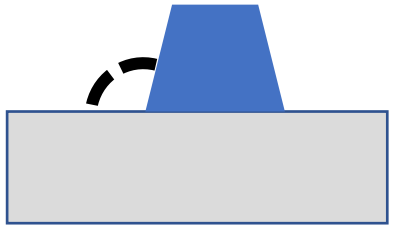


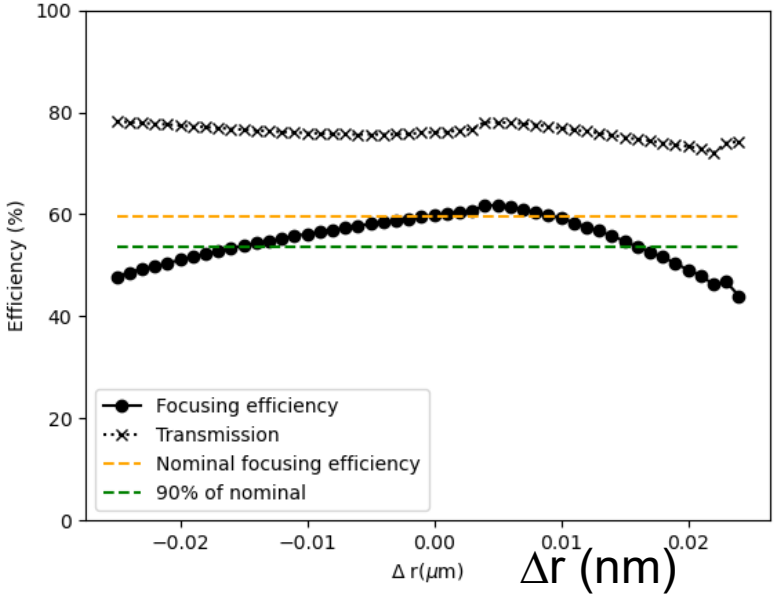
Δθ (°)

Random errors (Monte Carlo)

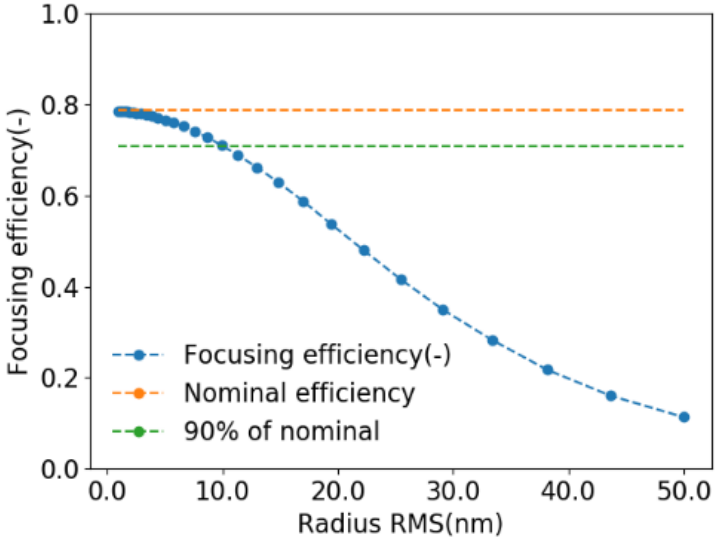


Steepness angle





Δr (nm)



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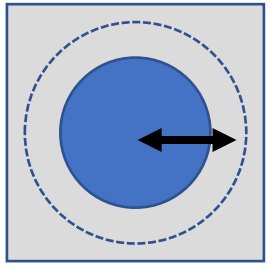

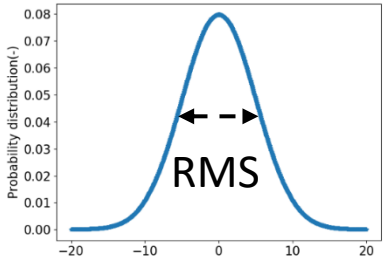

Conclusions

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- **Knowing** and **controlling critical parameters** is crucial
- **Sensitivity analysis** used to **identify** critical parameters and **quantify tolerance criteria**
- Fast integrated **simulations** provide insight to the **link** between structural **parameters** and device **performance**
- **Wavefront aberration** is the main cause of efficiency loss
- Fabrication guidelines (for reference metalens)

Parameter	Tolerance for 90% of nominal efficiency
Sidewall slope	±0,3°
Radius	±15nm (0,75% of pitch)
Height	-300nm/+500nm (5,7/9,5% og height)

Contact info

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