OPTICA
Advancing Optics and Photonics Worldwide

Technical Groups

Practical Meta-Surface Design for Polarization Optics

Featuring Lieven Penninck, PlanOpSim NV
22 February 2022

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About Our Technical Group

Our technical group covers all aspects of polarization management and propagation in lightwave devices and systems, including theory, engineering, measurement, testing and imaging. Additionally, applications of polarization, methods of modeling and propagation will be included.

Our mission is to connect the 1200+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Special Talks at Frontiers in Optics
- Webinars on Modeling Polarization for Phase Retrieval and Optical Beams with Spatially Variable Polarization

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/FP
- On LinkedIn at www.linkedin.com/groups/7467212/
- Email us at TGactivities@optica.org

Today's Speaker

Lieven Penninck

PlanOpSim NV

Lieven Penninck is an expert on optical modelling methods focusing on meta-surfaces and nano-photonics. In 2019 he founded PlanOpSim to develop and offer numerical simulation software for the design of metasurfaces, metalenses, and planar optics. Aside from software development, PlanOpSim also provides optical design services to the photonics and optics industry. He holds a PhD in Photonics Engineering on development of simulation methods for OLED and liquid crystal devices. Outside of academia he worked on LCD display R&D and simulation and measurement of OLEDs and solar cells in various roles.

Lieven Penninck

Practical meta-surface design for polarization optics

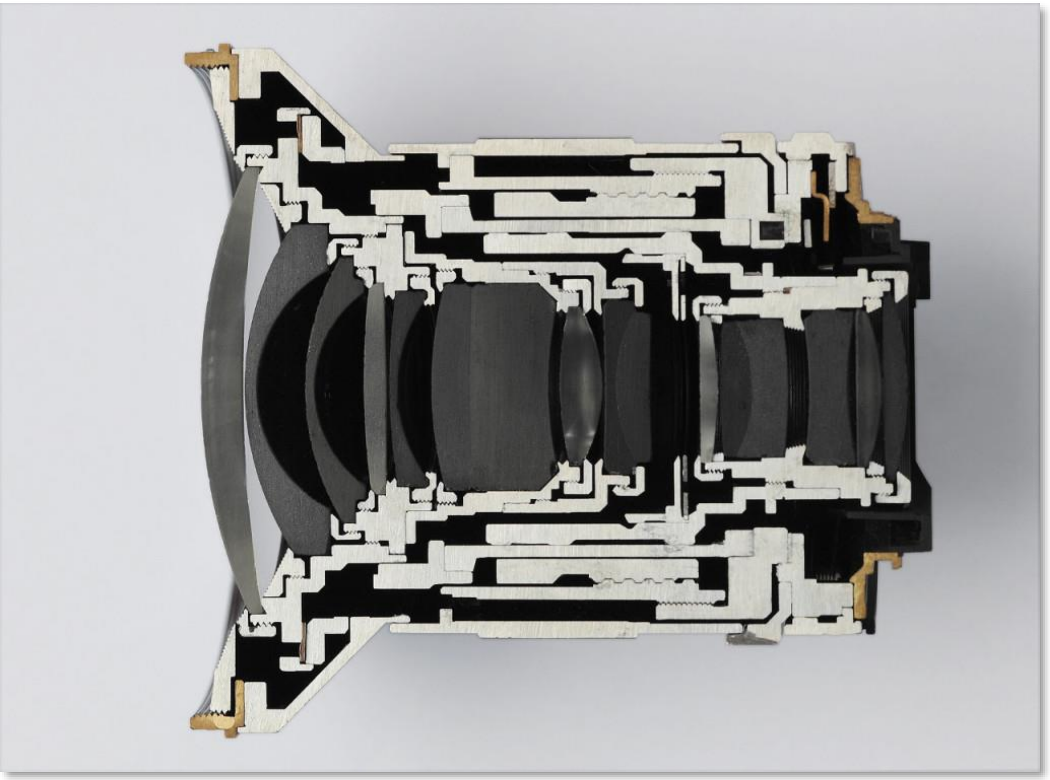
OPTICA Webinar:
Polarization Management and Propagation

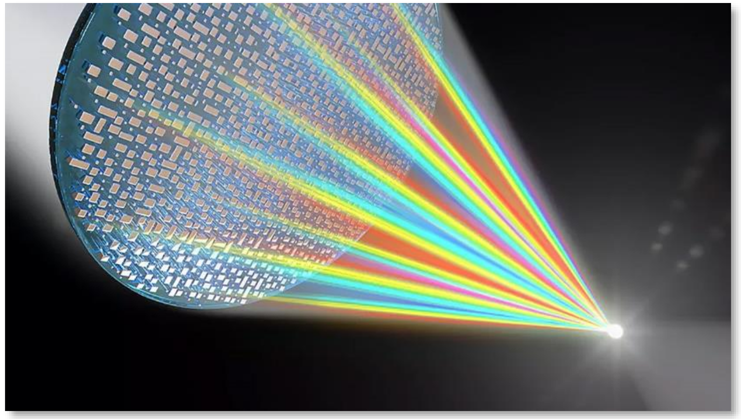
22 February 2022, 11AM EST

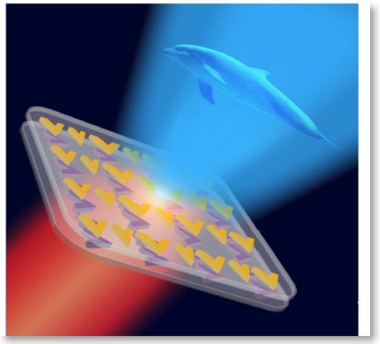
PlanOpSim
Enlightened Planar Optics

Today

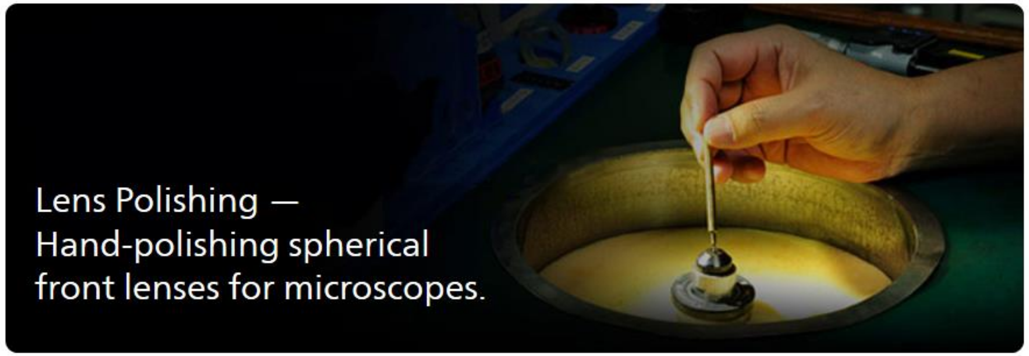
Future: Nano-enabled components

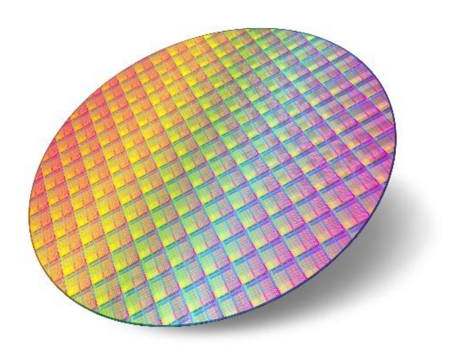






Higher Performance
Miniaturized
Simplified
New Applications

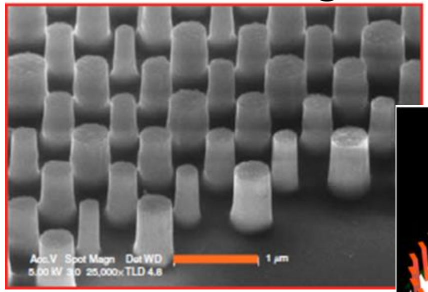




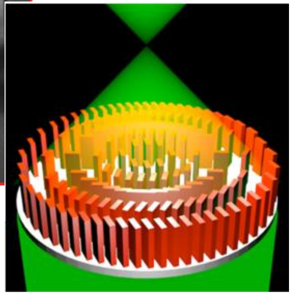
Art to Industry
Lower Cost

PlanOpSim

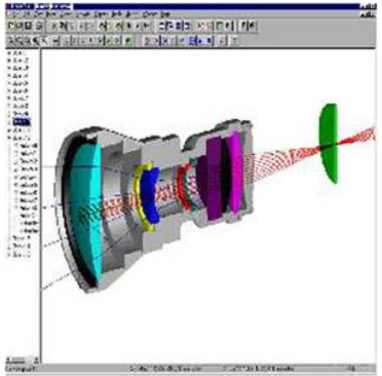
Nano-scale design



Component design



System Integration



Planopsim's mission

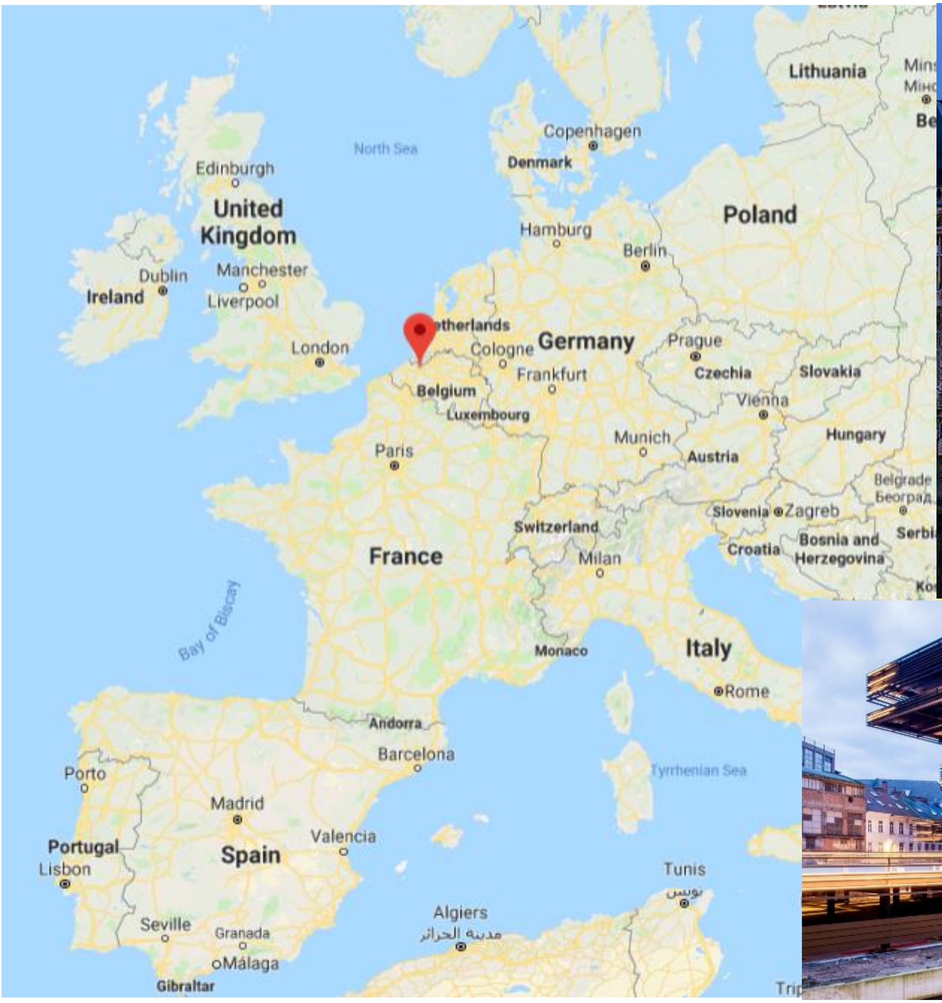
Planopsim supplies **R&D tools** to **engineers** & **scientists** that allow to unlock the maximum benefit of **flat optics** in a **user-friendly** way.

- 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

Who are we?

PlanOpSim
Enlightened Planar Optics
WWW.PLANOPSIM.COM

- Dedicated provider of:
  - **Simulation software** for **meta-surfaces**
  - **Designhouse** for photonic & optical applications
- Start-up from Ghent; Belgium
- Photonics R&D experience in industry and academia:
  - Simulation
  - Fabrication
  - Measurement
- Supported by:



imec istart

AGENTSCHAP INNOVEREN & ONDERNEMEN

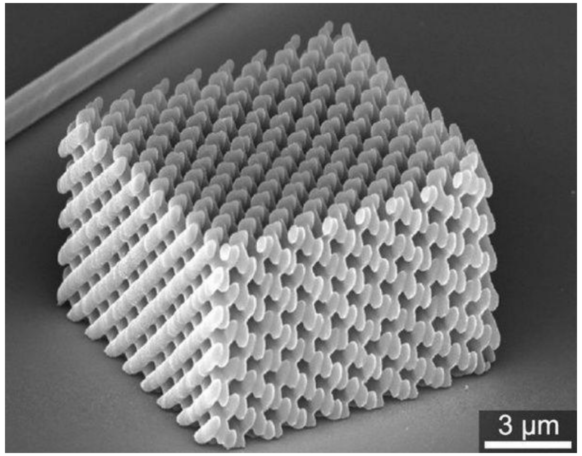
Outline

- Meta-surfaces
  - Principles
  - Nanostructures
- Practical Examples
  - Library building
  - Wide angle polarizing beamsplitters
  - Multiplexed holograms
  - Polarization splitting lenses

Meta-materials

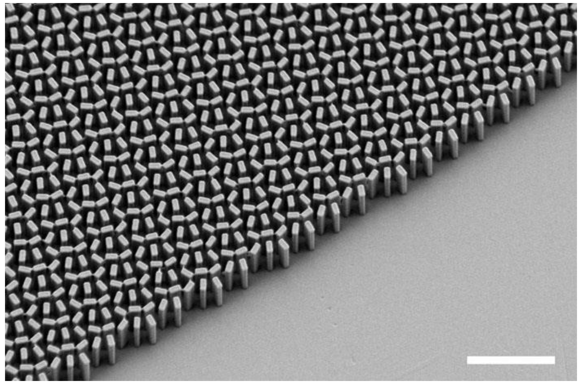
- Materials with engineered properties:
  - Design internal structures to create external properties
- EM waves: 3D sub-wavelength structuring
- 3D metamaterial
  - Very challenging to fabricate
- Let's make 2D instead
  - Meta-surface
  - Sub-wavelength structure on a substrate
  - Few nano-structuring steps
- Many elements side-by-side
  - Pseudo-periodic: regular grid but the elements are not all the same
  - Sometimes irregular

Low-Tech Metamaterial



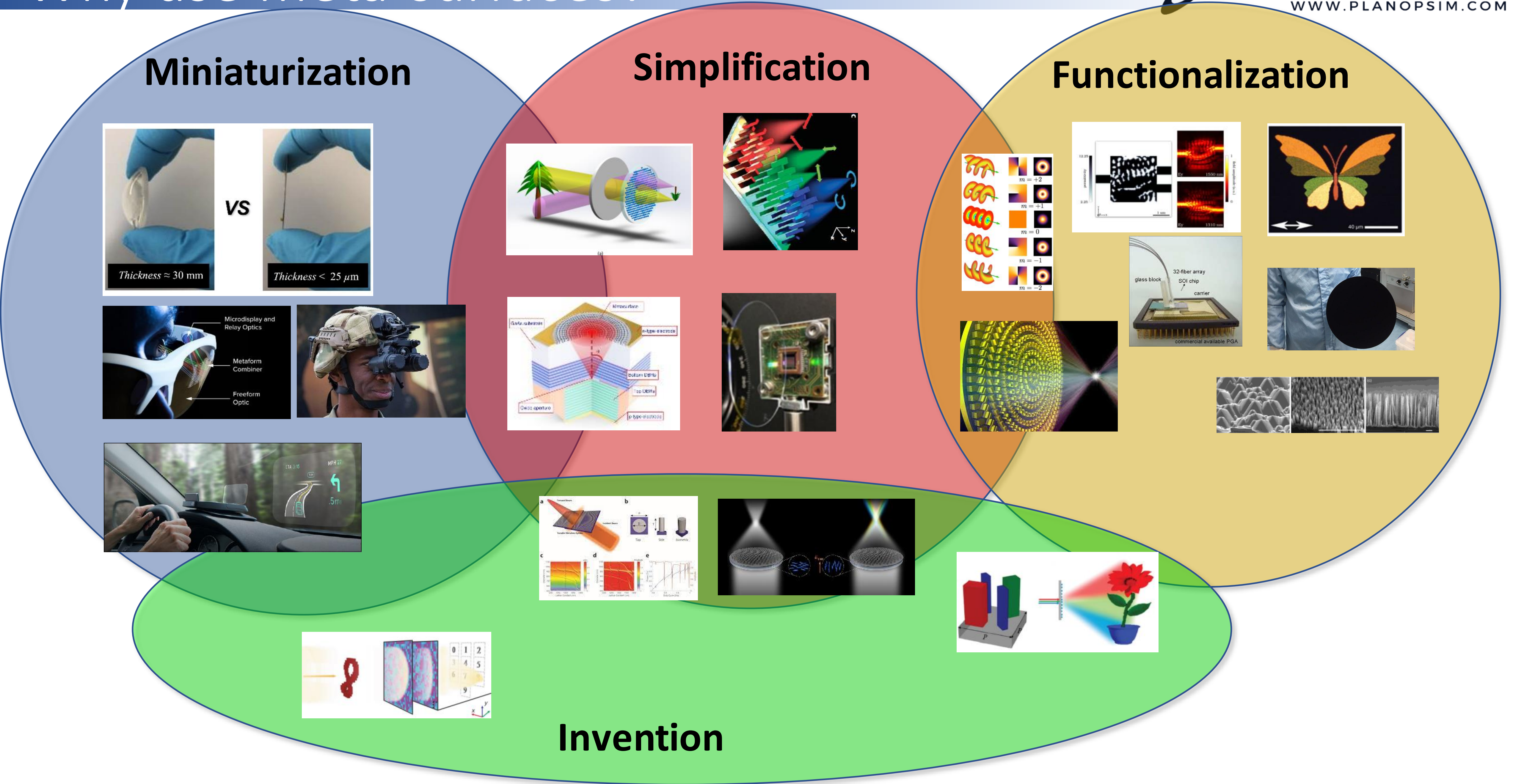
High Tech Metamaterial

λ=1.55 um (0.19 PHz)



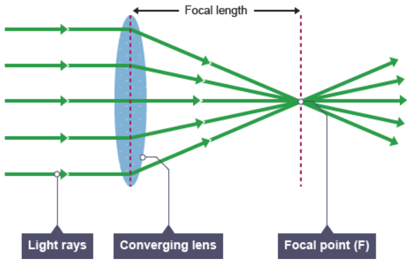
Meta-surface

Why use meta-surfaces?

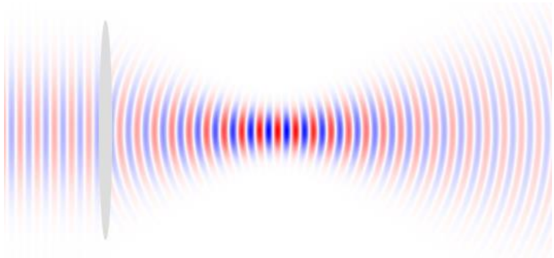


Principles of meta-surfaces

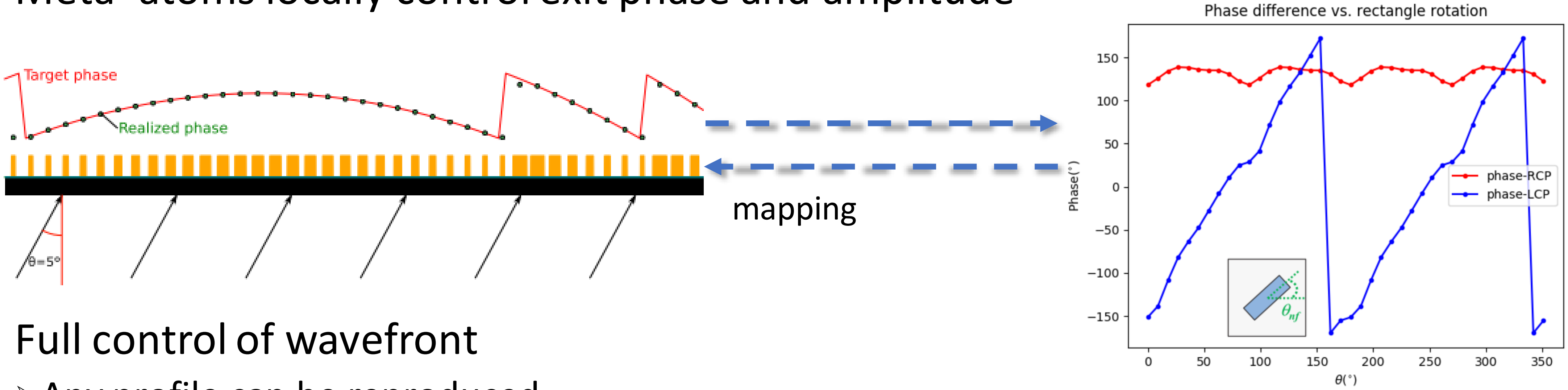
Ray picture



Wave picture



- Any component works by re-arranging the wavefront of the incoming waves
- Meta- atoms locally control exit phase and amplitude



- Full control of wavefront
  - Any profile can be reproduced
  - Including difficult shapes: aspheric lenses, arrays

Why is this new?

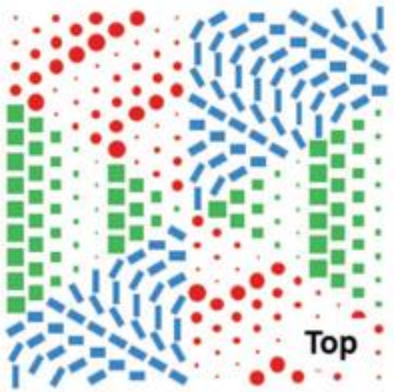
- Classical DOE:
  - Control phase by material height
- Phase sampling:
  - DOE -> greyscale or multi-layer lithography
  - Meta-surface: single lithography step
- Metasurfaces are **DOEs + extra functions**:
  - Polarization selectivity
  - Tuned spectral response: a- or hyper chromatic
  - Combined functionalities
  - Sub-λ pitch
  - Non-linear and/or topology effects

Multi-functionalization

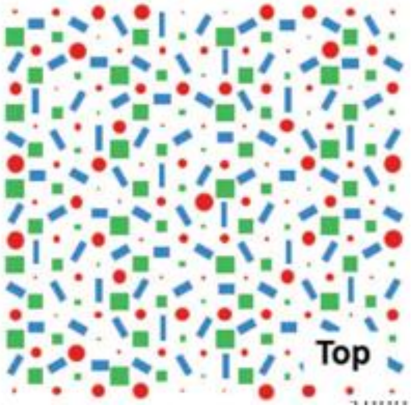
- ❖ Different functionality by area
  - ➢ Sectoring or interleaving
  - ➢ Efficiency ~ 1 /# functions

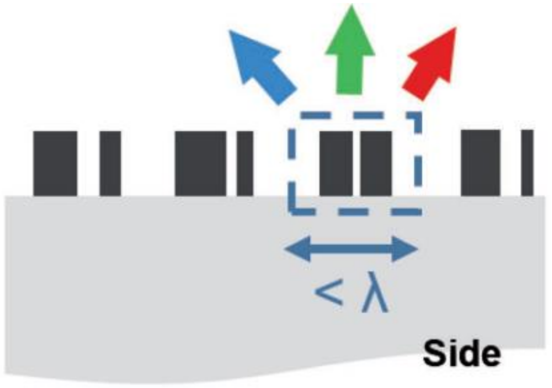
- ❖ Overloading: same structure multiple functionalities
  - ➢ Parametrized or inverse design
  - ➢ High efficiency multi-functionality is possible

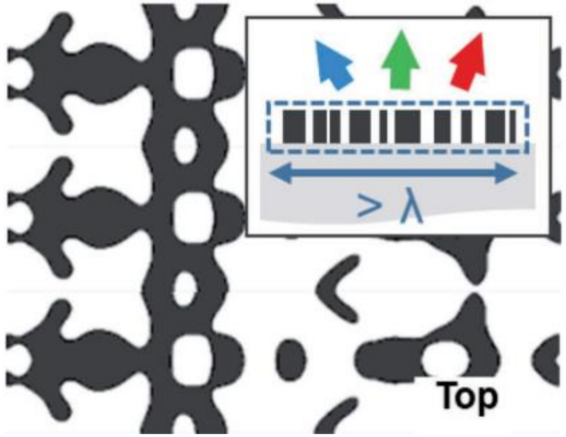
Sectoring



Interleaving







D. Sell, J. Yang, S. Doshay, and J. A. Fan, "Periodic Dielectric Metasurfaces with High-Efficiency, Multiwavelength Functionalities," Adv. Opt. Mater. **5**, 1–7 (2017).

Limits of functionalization

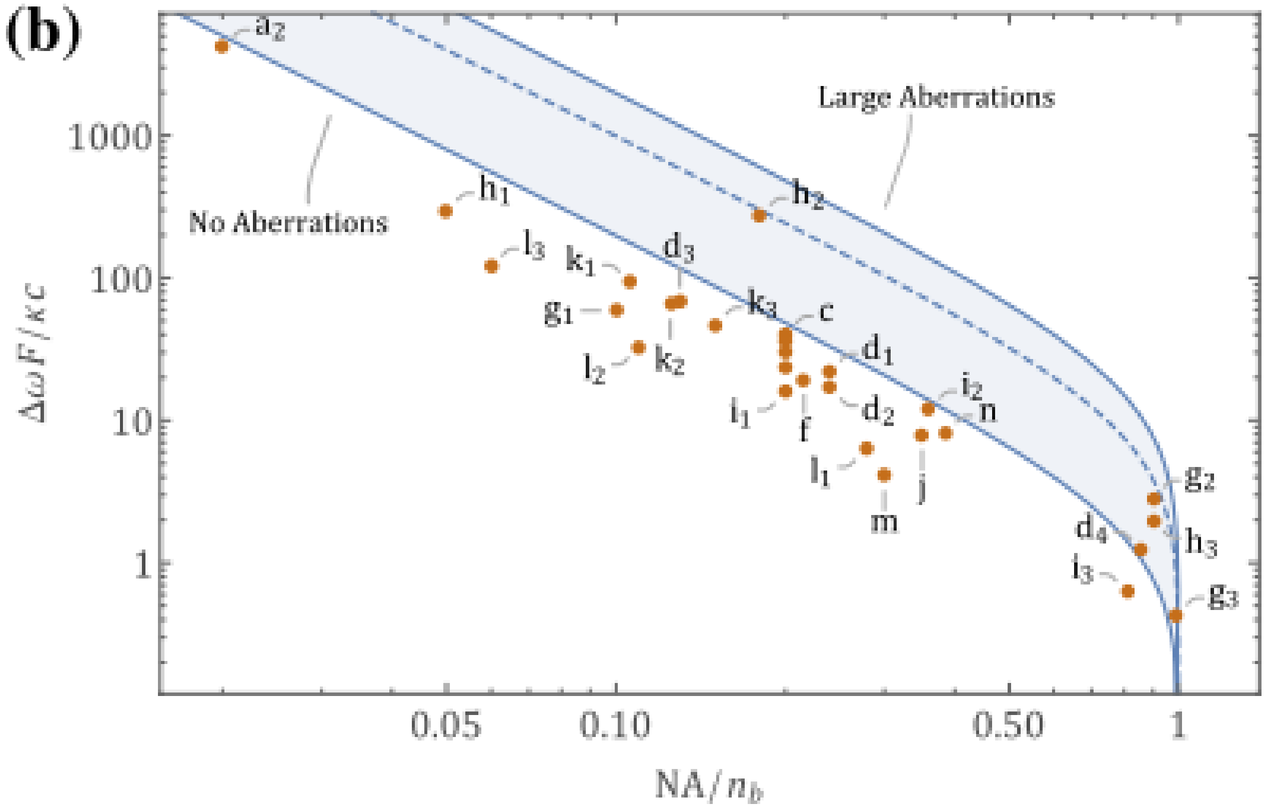
- ❖ There is no free lunch!!
- ❖ Physical limits being discovered:
  - ➢ Bandwidth, size and function are connected

$$R_{max} \leq \frac{\Delta\Phi' c}{\Delta\omega\left(\frac{1}{NA} - \sqrt{\frac{1}{NA^2} - 1}\right)}$$

Application parameters
- ➢ Bandwidth
- ➢ Diameter
- ➢ Spatial frequency, NA

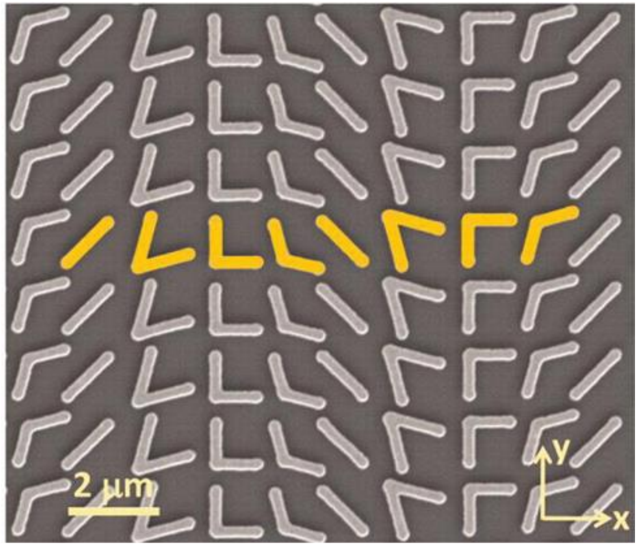
Design parameters: ΔΦ
- ➢ Materials: index contrast
- ➢ Structure: Height + aspect ratio
- ➢ Complexity: multi-layers

Literature devices within bounds of theoretical formula*

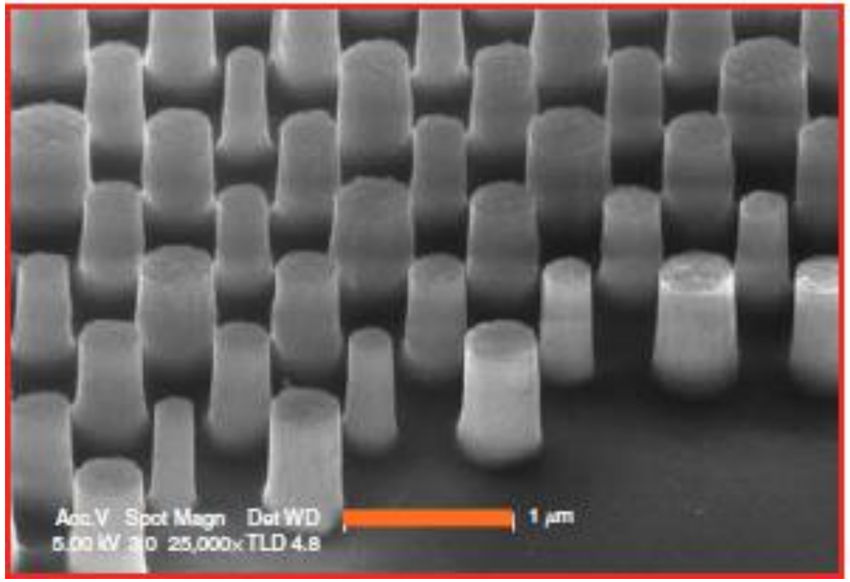


*F. Presutti and F. Monticone, "Focusing on Bandwidth: Achromatic Metalens Limits," Optica **7**, (2020).)

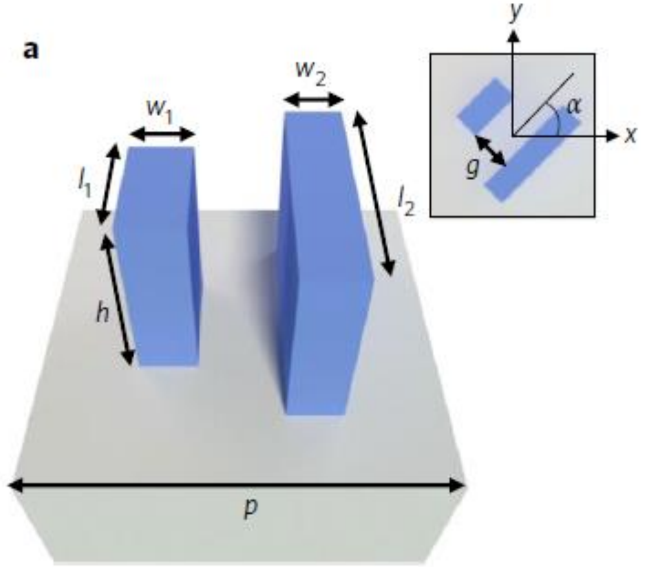
Sub-wavelength structures: 3 main types



Plasmonic structure



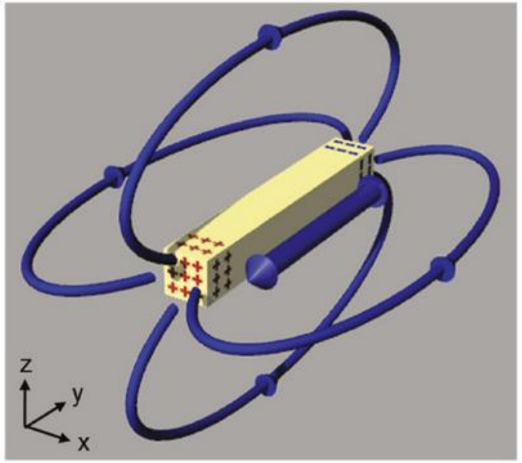
Dielectric structures



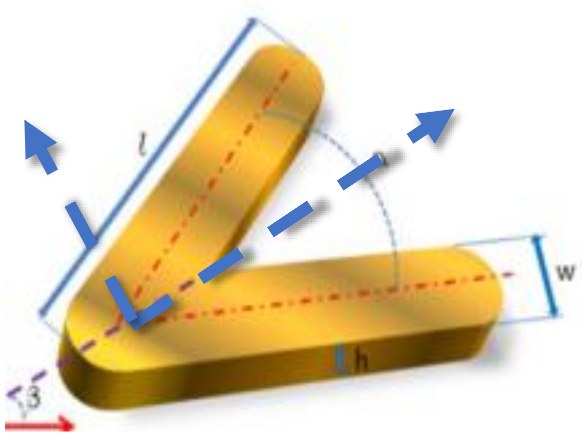
Structural birefringence

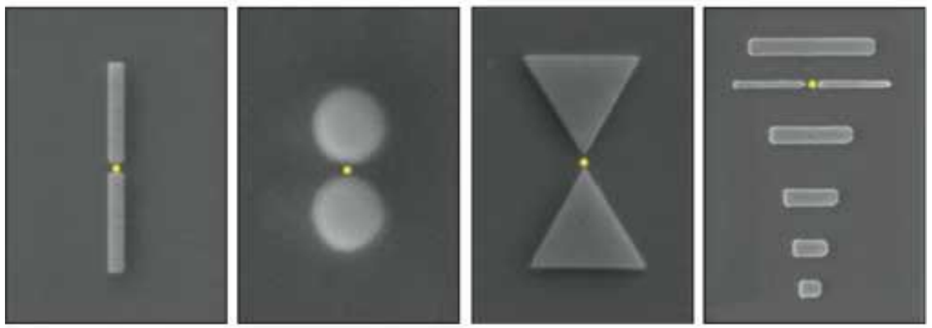
Plasmonic structures

- Ultra-thin Au, Ag, Al structures (~30nm)
  - Plasmon resonance excited by incident light
- Optical antenna principle
  - Dipole antenna
  - Phase control range 0 – 360°
  - Multipoles as well
- Antenna shapes expanded from classical antennas
- Historically first but limited in application
  - Lossy
  - Only efficient in reflection



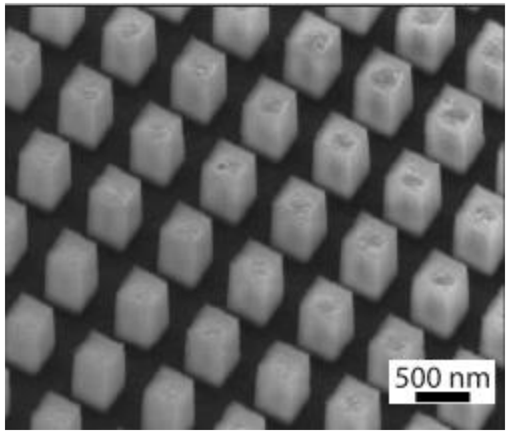
Metallic nanorod

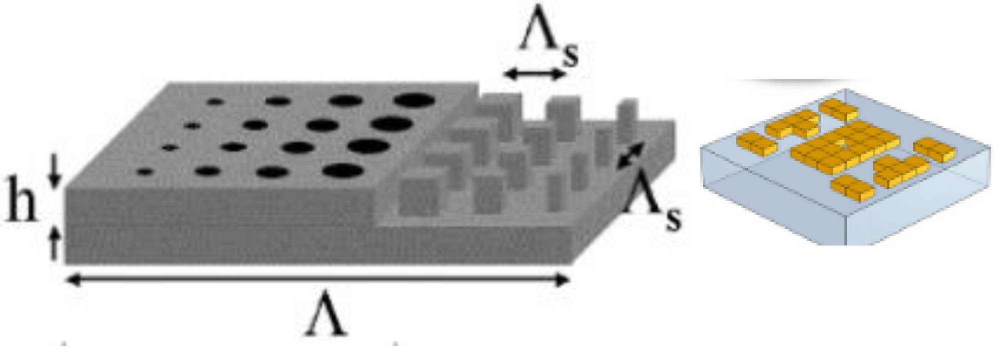


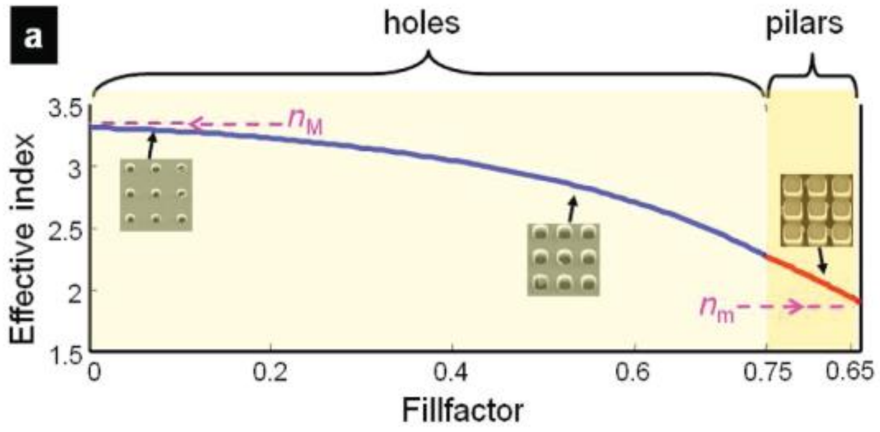


Dielectric structures

- Dielectric sub-wavelength structure
  - Act as an effective medium
  - Waveguide view
  - Resonator
- $n_{gap} < n_{effective} < n_{material}$
  - Dielectric: Si, SiN, TiO_2
  - Gap: air or low index material
- Phase & amplitude tuning:
  - Height
  - Geometry: Cylinders, Squares, Hexagon, Cross
  - Complex shapes:
    - Genetic algorithms
    - Adjoint optimization

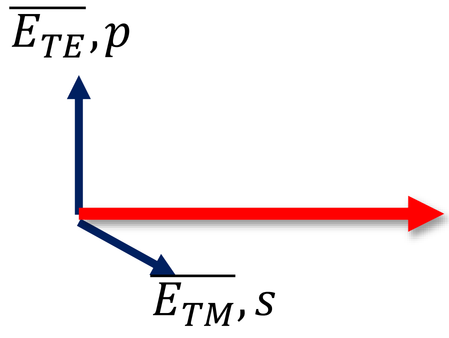


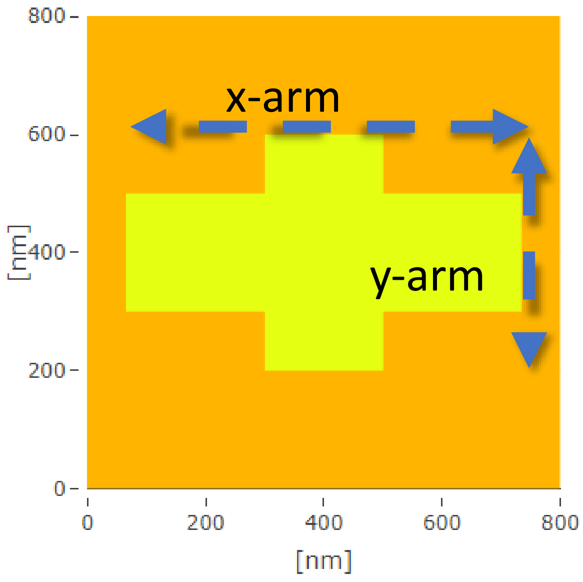




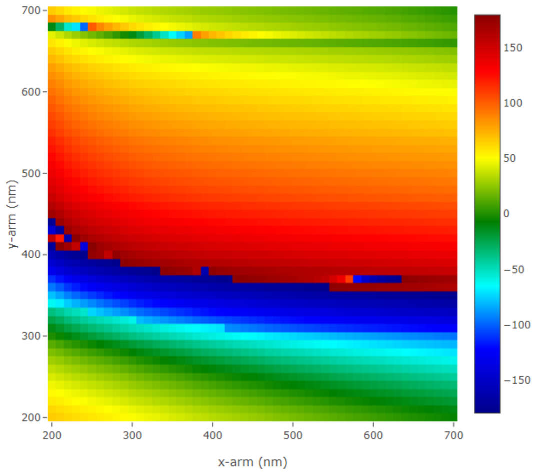
Polarization manipulation

- Symmetry:
  - 90° symmetric: no change for TE/TM
  - Non-symmetric: polarization selectivity
- Structural birefringence (form birefringence)
  - Different n_{eff} for x/y polarization
  - Acts as a an optical retarder with in plane c-axis
- Tuning the shape
  - Change Δn
  - Rotation alters phase
- Applications:
  - Polarization functionalization
  - Geometric phase



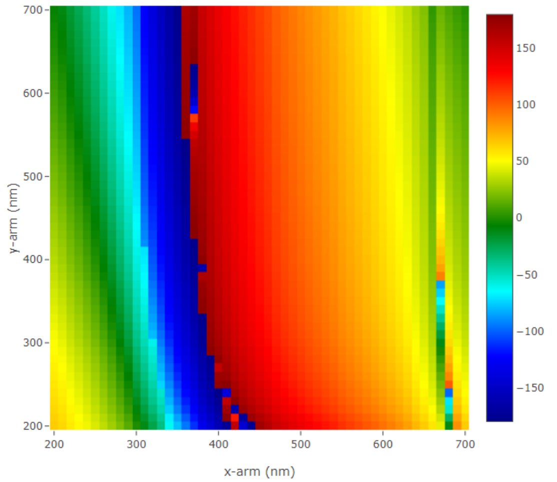


TE phase



TE, controlled by y

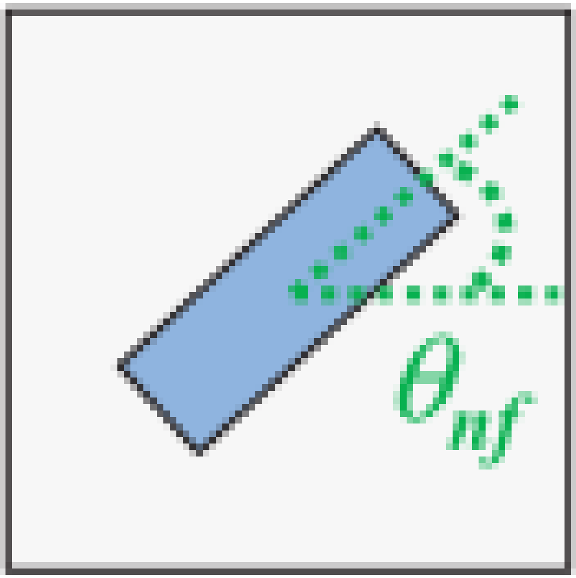
TM phase



TM, controlled by x

Geometric phase

- Incident circularly polarized light
- Jones calculus of structurally anisotropic element



Half wave retardation

$$\bar{\bar{T}}_{HWP} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix}$$

$$\bar{\bar{T}}_{HWP} = \begin{bmatrix} cos2\theta & sin2\theta \\ sin2\theta & -cos2\theta \end{bmatrix}$$

Rotation of c-axis

- Incident and Exitant Jones vector

$$J_{in} = \begin{bmatrix} 1 \\ +j \end{bmatrix} \qquad J_{out} = e^{j2\theta} \begin{bmatrix} 1 \\ -j \end{bmatrix}$$

Rotation controlled phase

Half wave retardation

$$J_{in} = \begin{bmatrix} 1 \\ -j \end{bmatrix} \qquad J_{out} = e^{-j2\theta} \begin{bmatrix} 1 \\ +j \end{bmatrix}$$

Geometric phase

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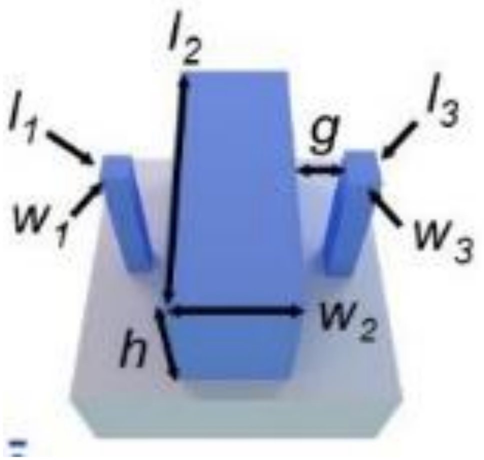
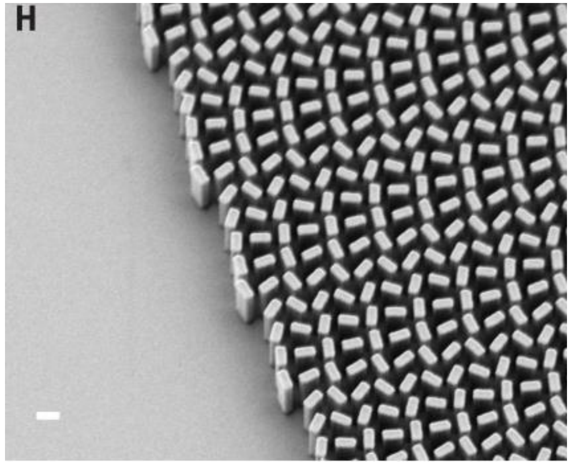
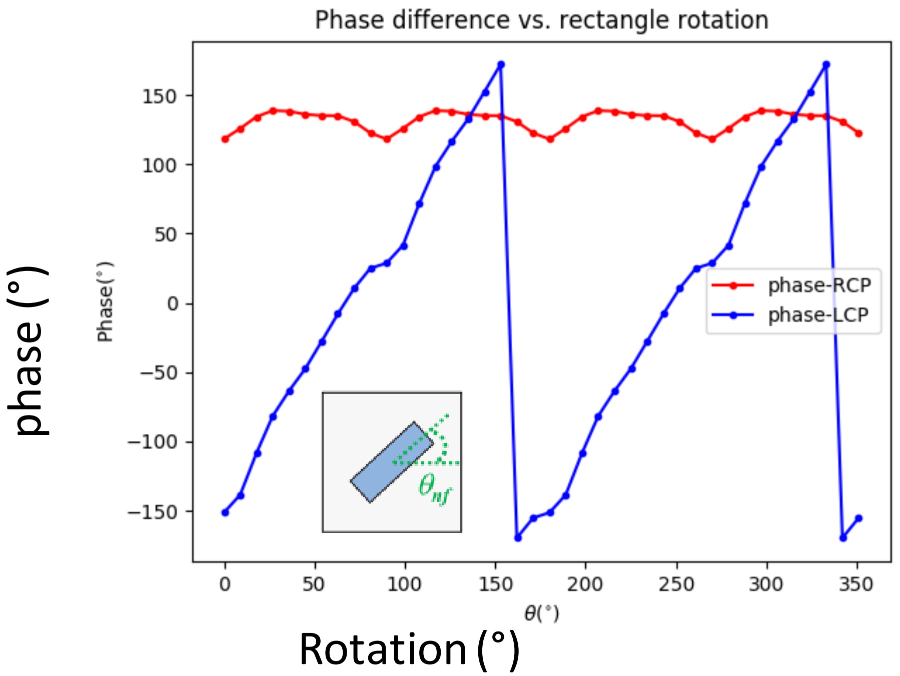
- Geometric phase structures
  - Elegant phase control
  - Not limited to shapes or nano-structures
- Tuning the shape
  - Dispersion corrections
  - Amplitude corrections (conversion efficiency)
- Applications:
  - **Polarization selective but not polarization controlling**
  - $\varphi_{LCP}(x,y) = -\varphi_{RCP}(x,y)$







Principles of meta-surfaces

- Why sub-wavelength?
- Suppress diffraction:

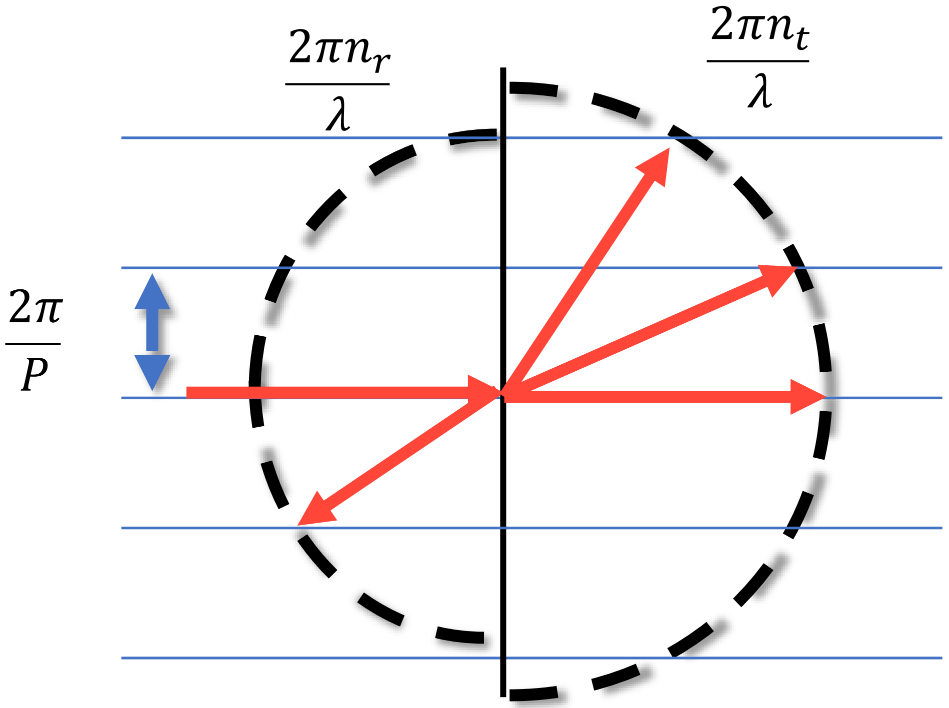
$$\frac{2\pi n_t}{\lambda} < \frac{-2\pi\, n_r \sin(\theta_{in})}{\lambda} + 1\,\frac{2\pi}{P}$$

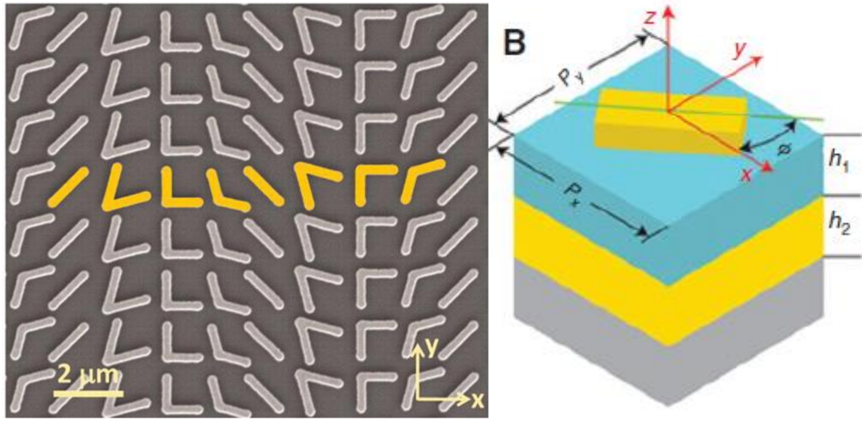
- P < λ/n only 0-order diffraction possible

$$P < \frac{\lambda}{n_{r/t} + n_r \sin(\theta_{in})}$$

- Normal incidence into air:

$$P < \frac{\lambda}{n_r}$$





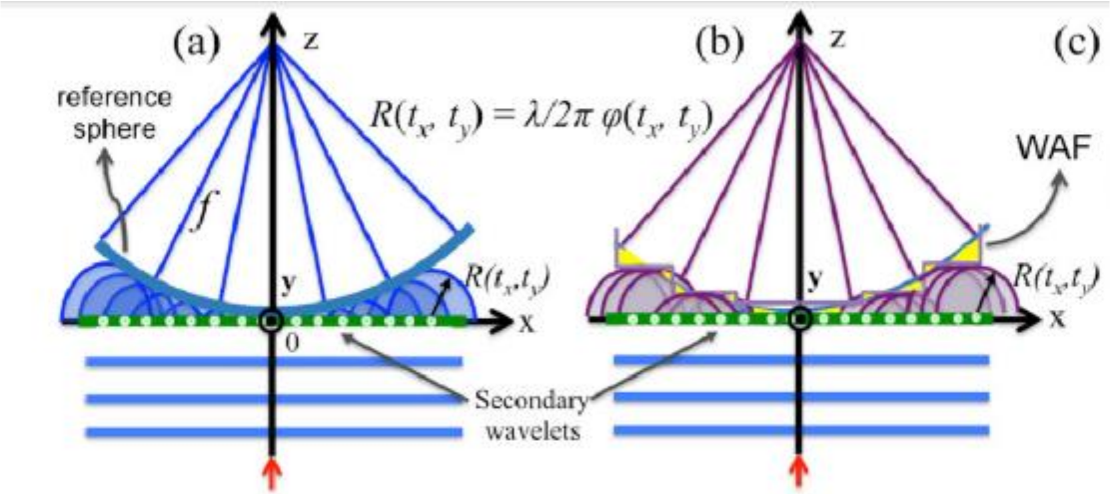
Sampling

Spatial sampling

- Nyquist theorem: 2 samples per period
- $\frac{2\pi}{P} > 2\frac{\delta\varphi}{\delta x}$ → $P < \frac{\lambda}{2n\frac{\delta f}{\delta x}}$ ← Normalized gradient
- Implications:
  - Focal distance: short is more difficult
  - Beam steering: large deflection angle is more difficult

Phase sampling

- In reality phase is continuous
- In a metasurface we sample the phase
- Wavefront aberration function
  $WAF_{RMS} < \lambda/14$

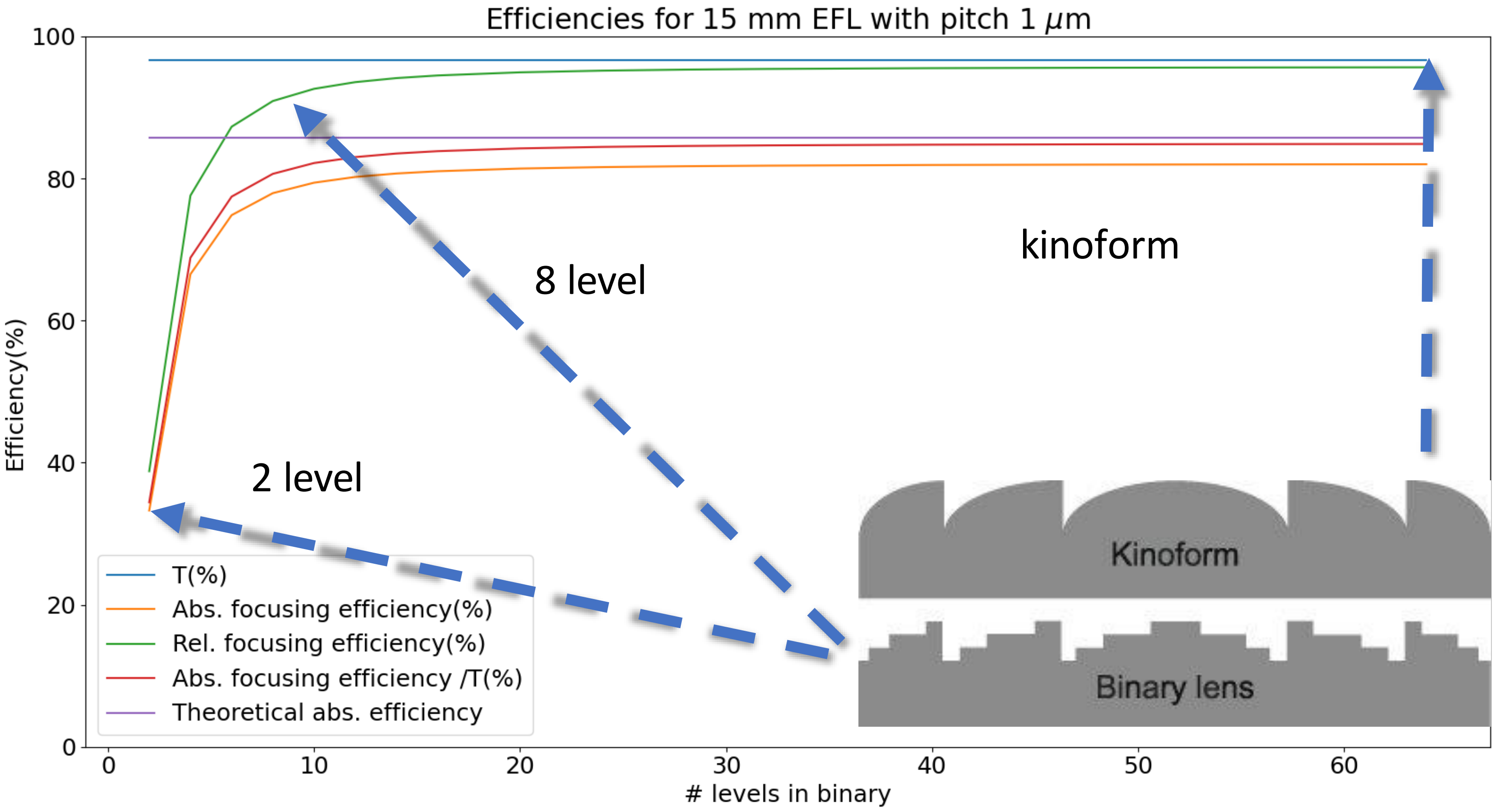


1) US 2018 / 0246262 A1, low – contrast Silicon Nitride based metasurtaces
2) F. Aieta, et. al, "Aberrations of flat lenses and aplanatic metasurfaces," *Opt. Express*, vol. 21, no. 25, p. 31530, 2013.
3) Huang, K. *et al.* Planar Diffractive Lenses: Fundamentals, Functionalities, and Applications. *Adv. Mater.* **30,** 1–22 (2018).

Practical effect

- Equal wavefront, changed phase sampling
- Diffraction limited lens for 1064nm

  NA= 0.164
- Better sampling = higher efficiency
- Saturation from 16 levels

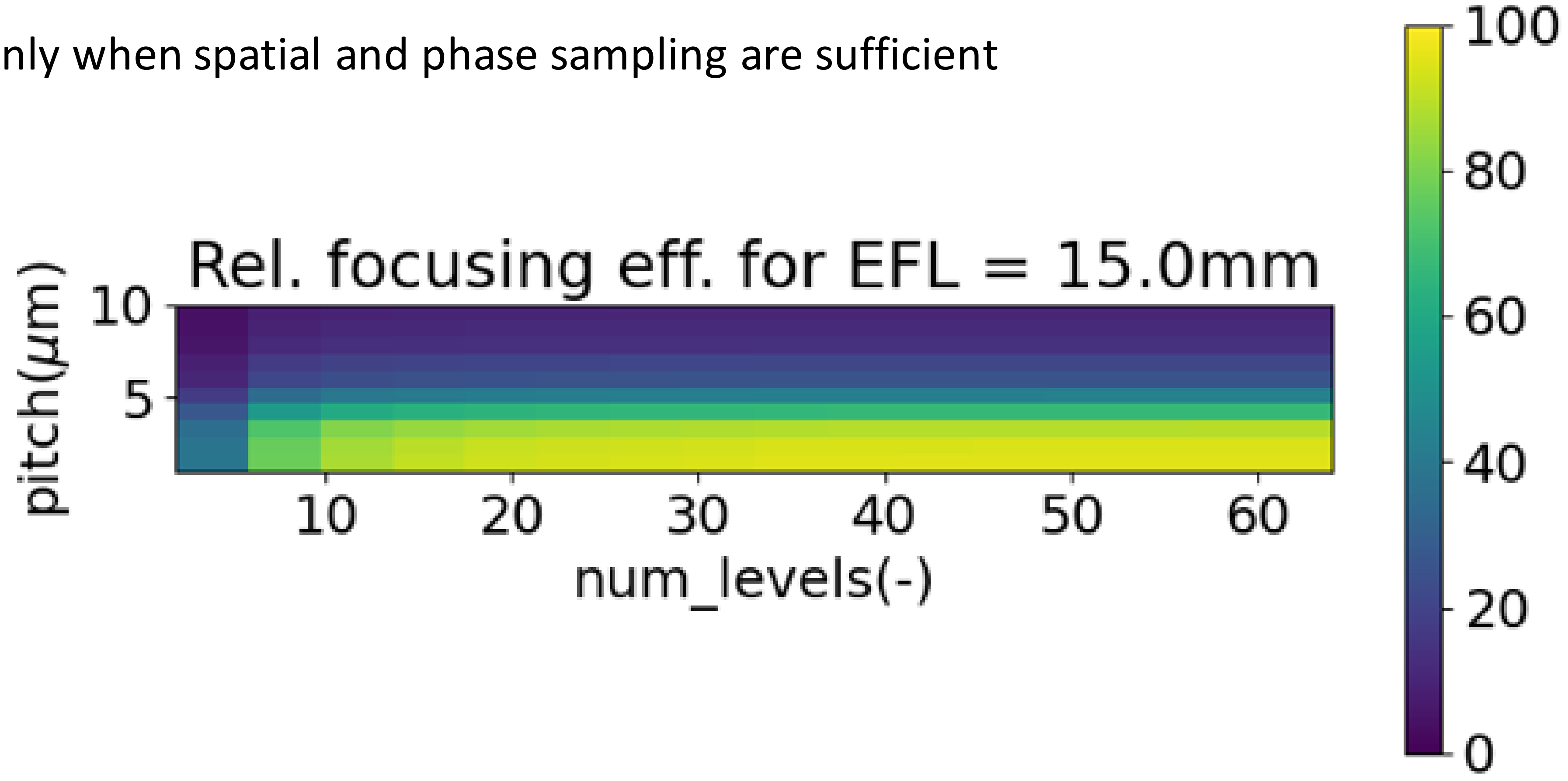


Spatial and phase sampling combined

- Diffraction limited lens for 1064nm (NA= 0.164)
- Spatial sampling often a stronger requirment than sub-diffraction requirement

$$P < \frac{\lambda}{2NA} = \frac{\lambda}{2\sin(\theta_{out})n_t}$$

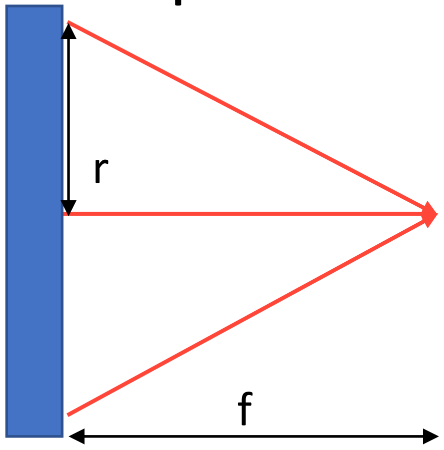
- High efficiency reached only when spatial and phase sampling are sufficient



Which profile

- Which wavefront do we need?
- Analytical:
  - Aspheric lens: all rays constructively interfering
  - Orbital angular momentum beam
  - Bessel beam: axicon

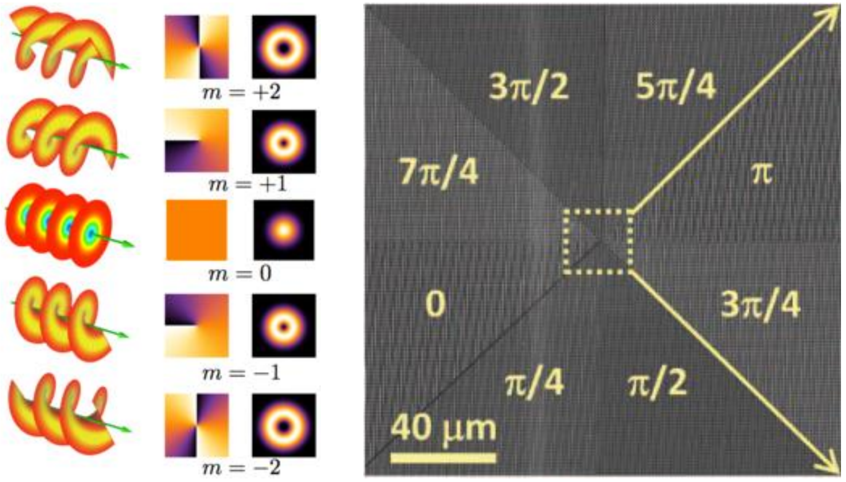
Aspheric lens



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

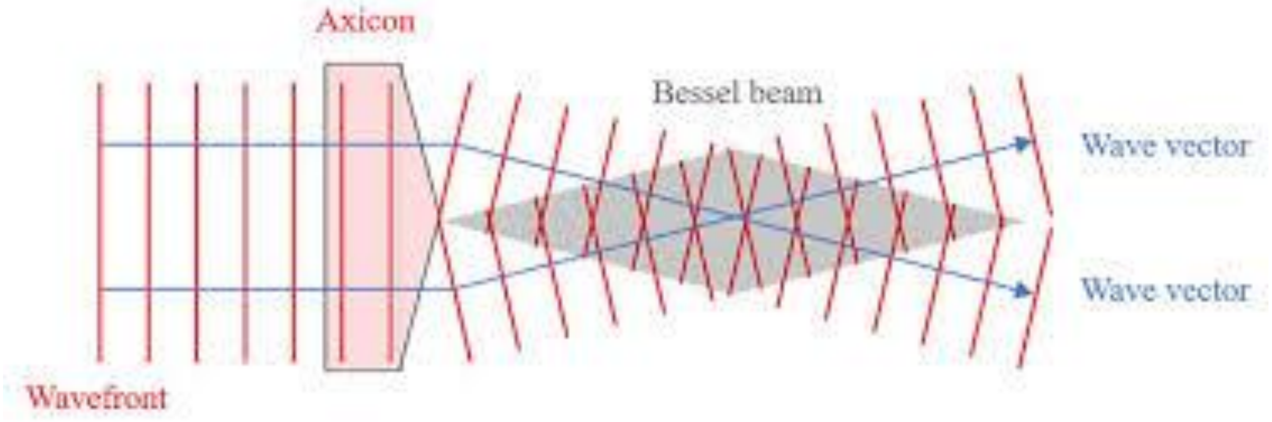
Orbital angular momentum

$$\tan 2\varphi = \frac{y}{x}$$



Bessel beam

$$\varphi(\lambda) = -\frac{2\pi}{\lambda} sin(\theta)r$$



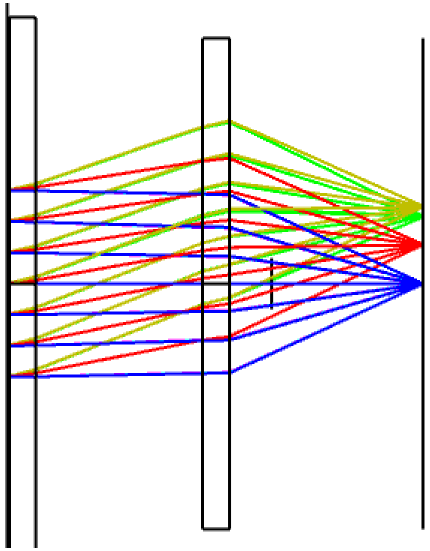
Ray tracing

- Analytical calculation only possible in simple systems
- Realistic situations:
  - Multiple specifications
  - Multiple components
- Optimize wavefront in ray tracing
  - Parametrized wavefront description
  - E.g. ZEMAX binary surface

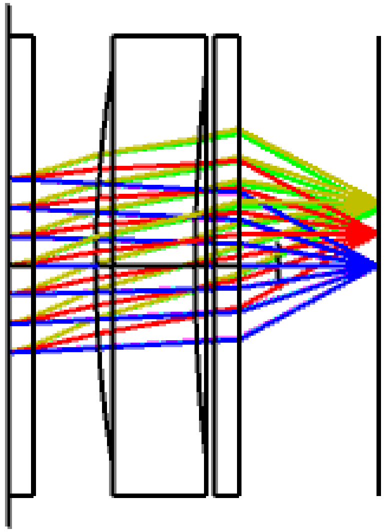
$$\Phi = M \sum_{i=1}^{N} A_i \rho^{2i}$$

- Advantages:
  - Co-optimization of multiple metasurfaces
  - Investigate complex performance trade-offs
- Disadvantage:
  - Idealized wavefront

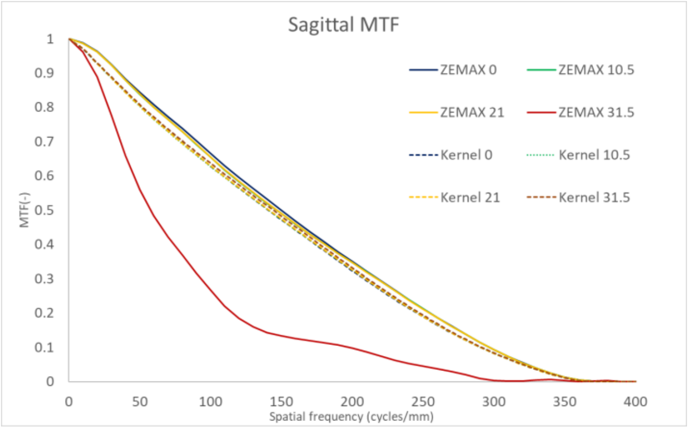
2 meta-surface system



Hybrid meta-surface + refractivesystem



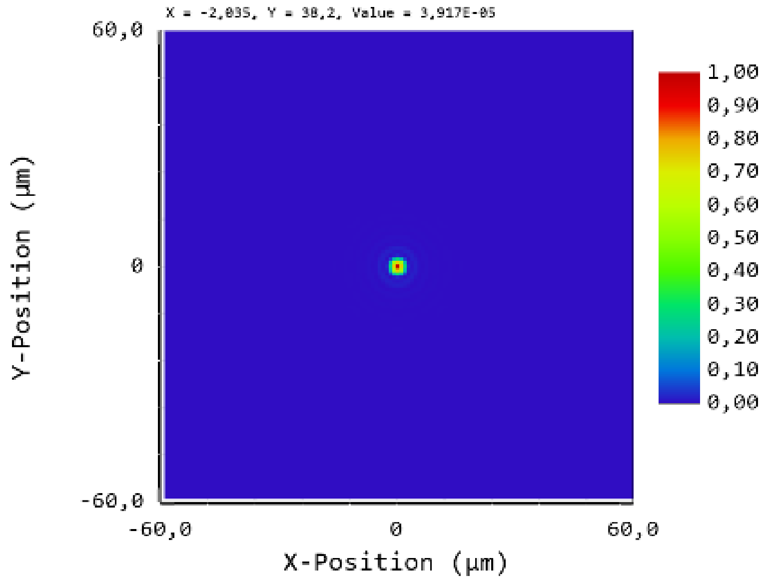
System MTF vs. field angle



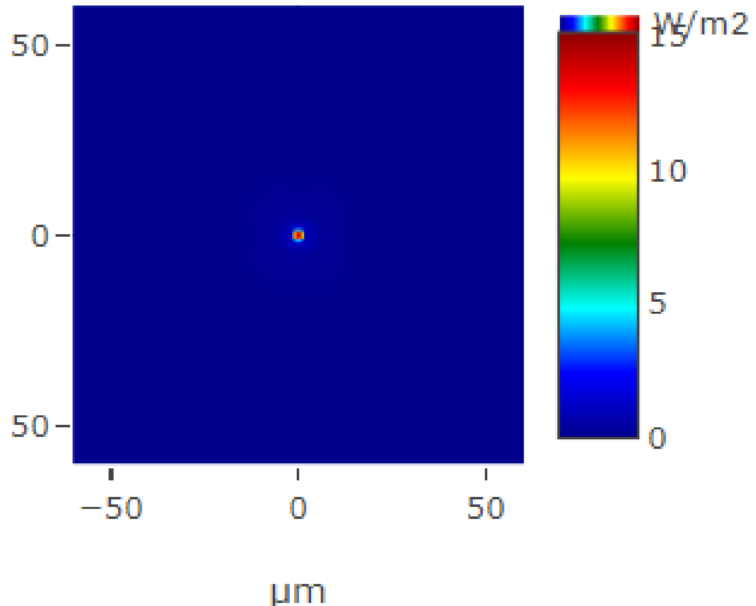
From wavefront to meta-surface

- Wavefront optimized in ray-tracing
- Reproduce as meta-surface
- Example for Si pillars @940nm
  - Nanostructure Transmission efficiency 76% (NFWF efficiency)
  - Focusing Efficiency 57% (FFWF Efficiency)

Ray tracing



Meta-component simulation



Computer Generated Holography

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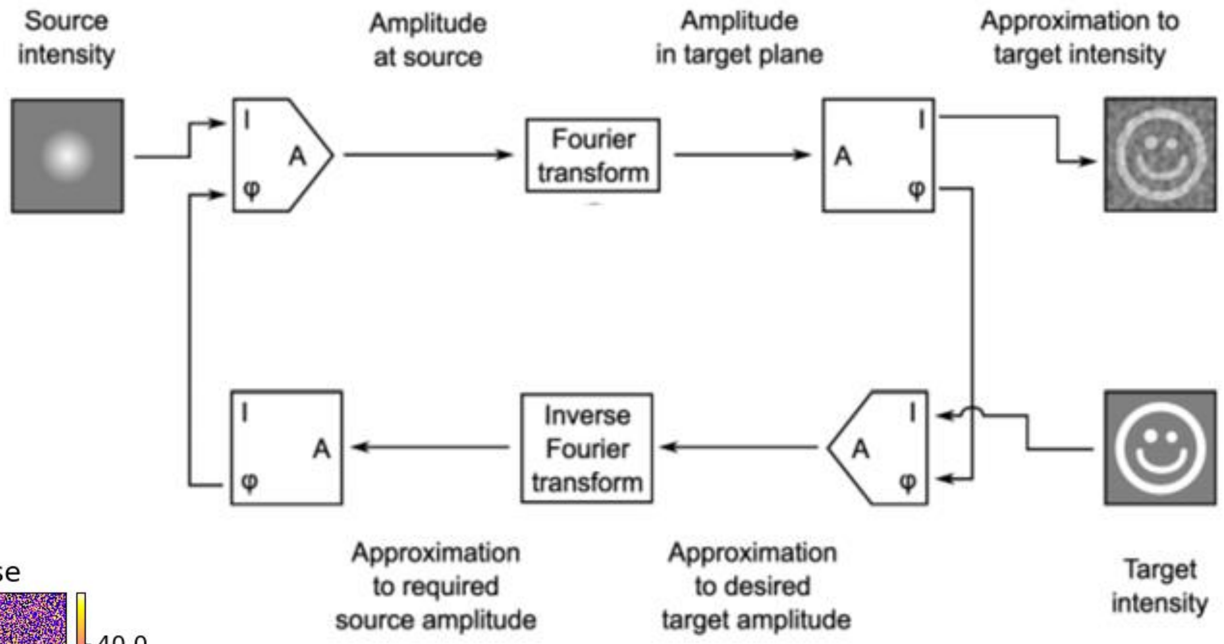
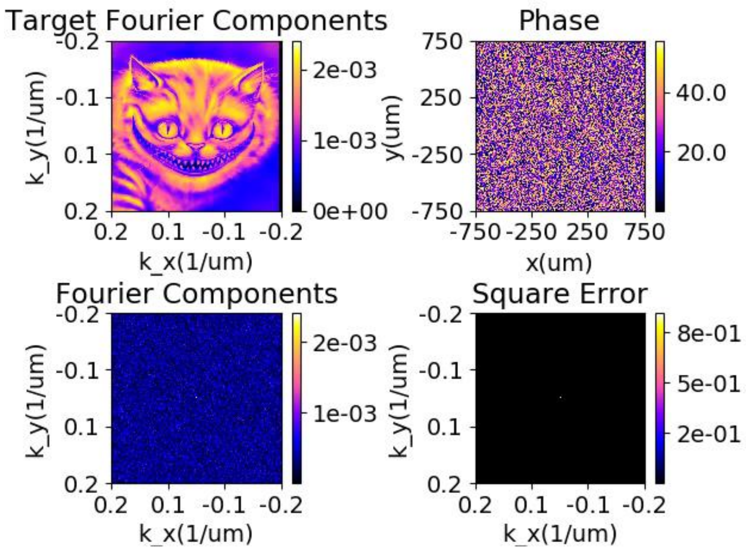
- Computer Generated Holography:
  - Most general ~ least performant
  - Iterative Fourier Transform Algorithm
  - Phase- only or phase amplitude
- Meta-surface vs. other holograms:
  - Polarization multiplexing
  - Wide angle due to small pitch
  - Phase sampling levels

IFTA flow



Example

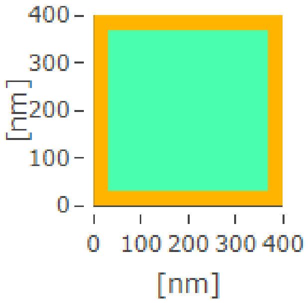


Outline

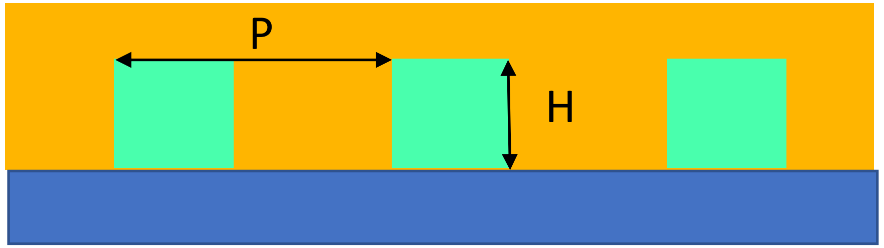
- Meta-surfaces
  - Principles
  - Nanostructures
- Practical Examples
  - Library building
  - Wide angle polarizing beamsplitters
  - Multiplexed holograms
  - Polarization splitting lenses

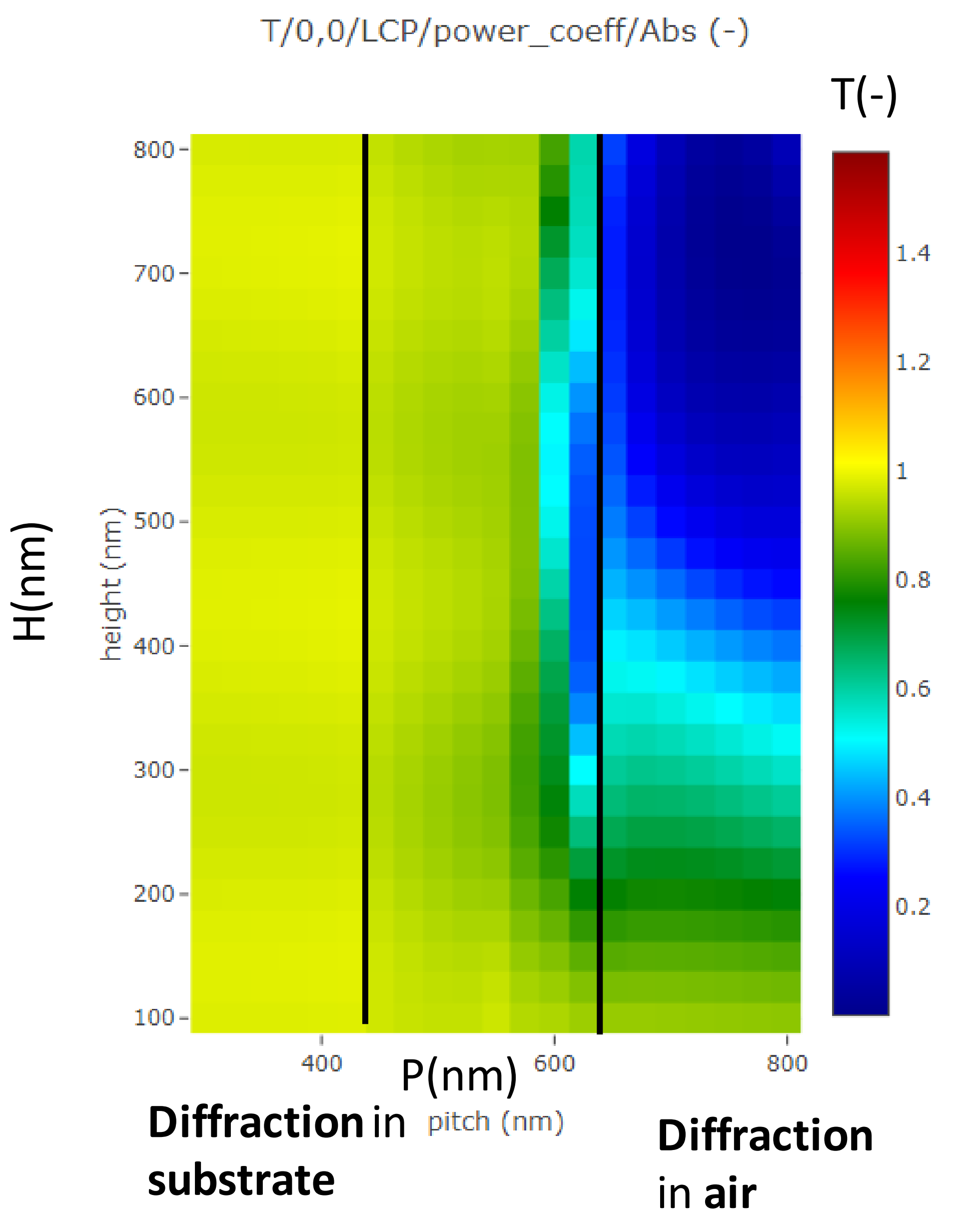
Beamsplitter: library building

- Library:
  - 1 litho step: height and unit cell same
  - Design wavelength: 633nm
  - Material platform:
    - TiO2 on SiO2
- Determine working point:
  - Fixed structure modify height (H) and pitch (P)
  - Pitch = 400nm sufficient to avoid diffraction



Material	Color
Air	
TiO2	





Beamsplitter: library building

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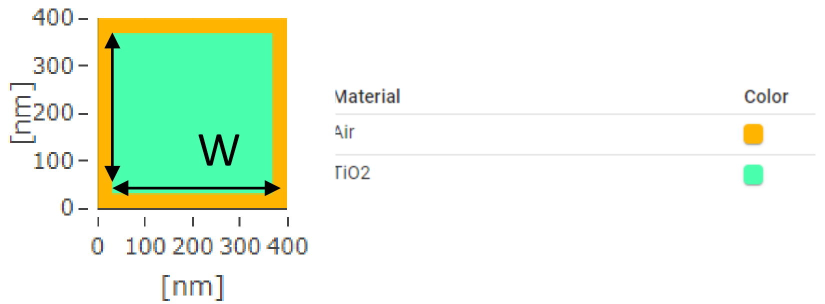
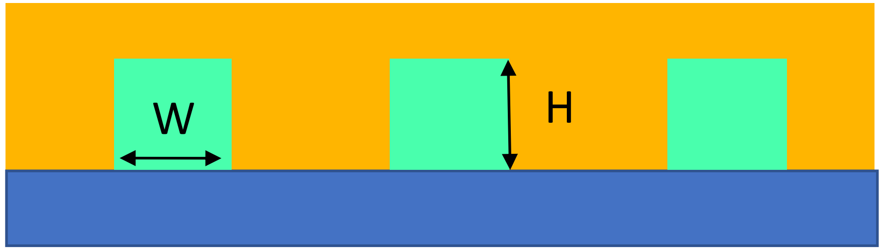
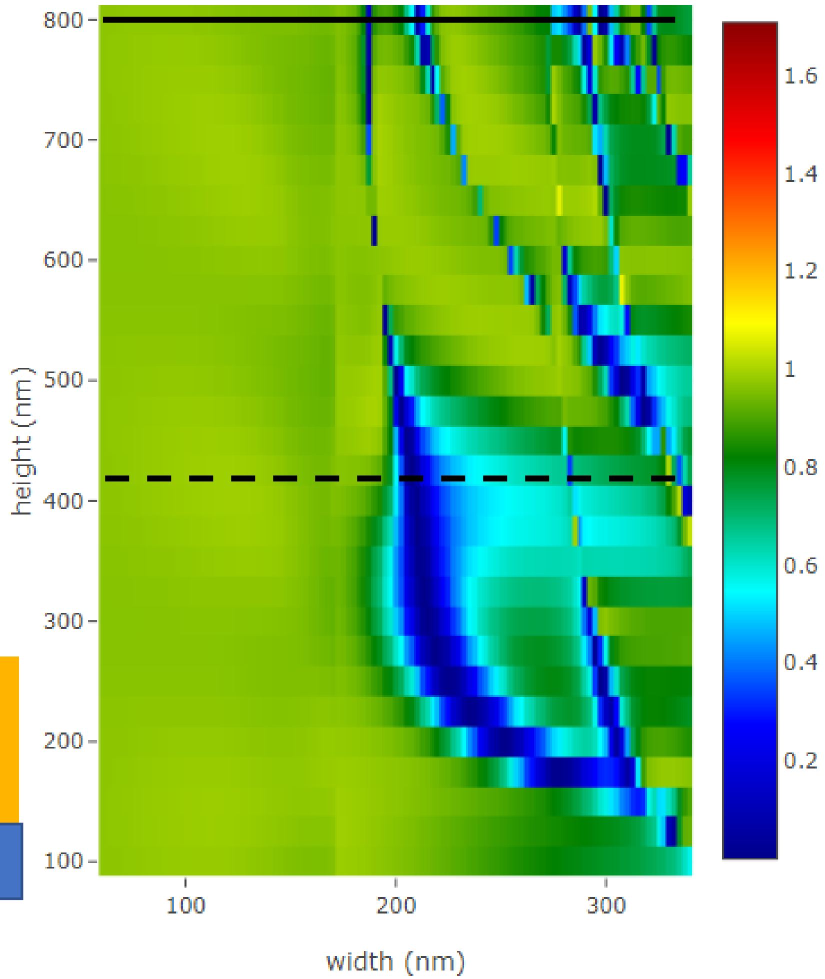
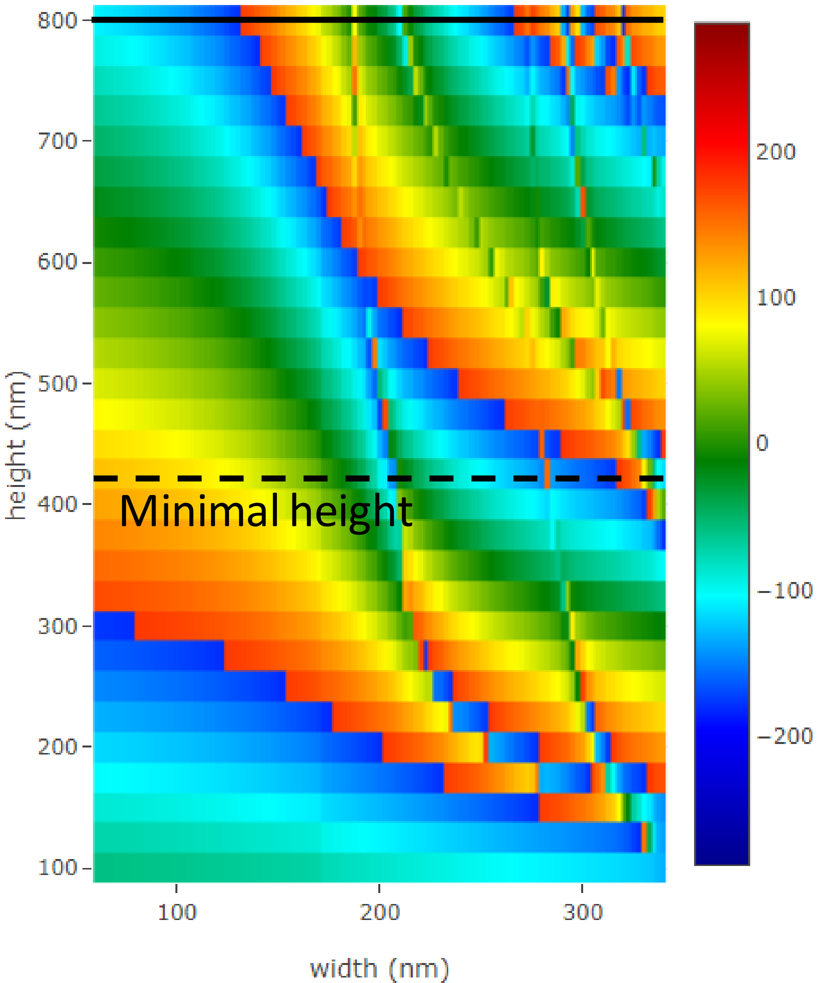
- Multiple structures: width varied
  - Fixed pitch: 400nm
- Max. T, 360° phase coverage
- Selected height:
  - >425 nm to cover phase for non-polarizing meta-surface
  - Following examples: 800nm





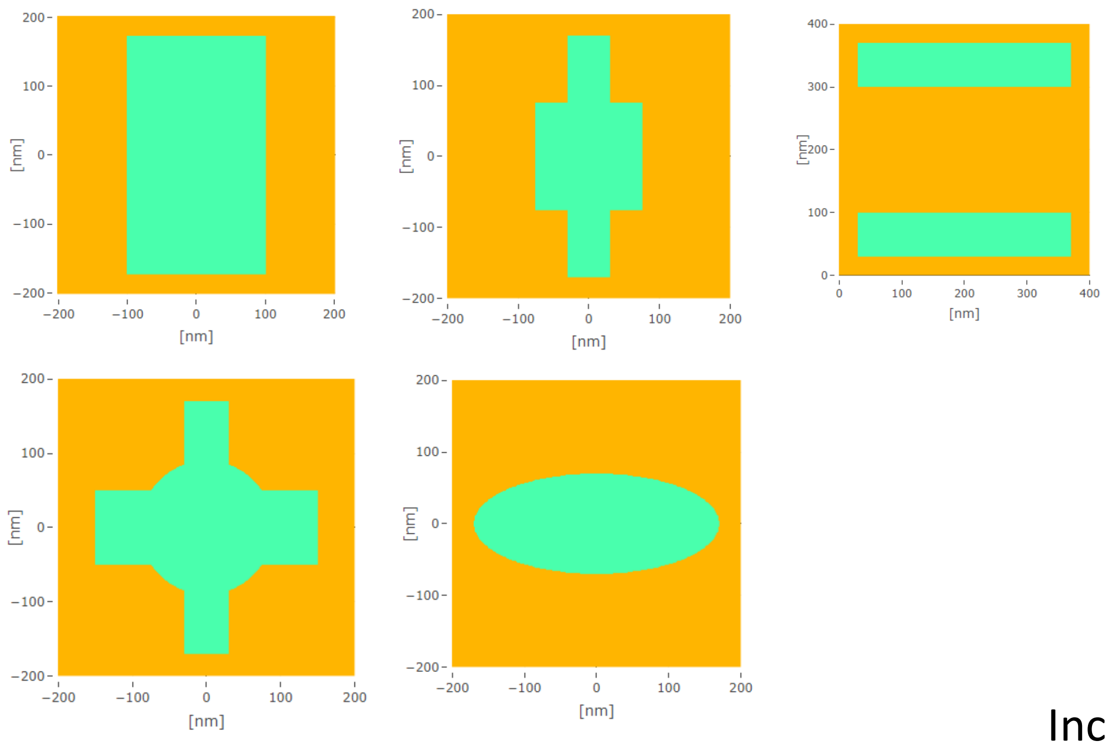
Selected height



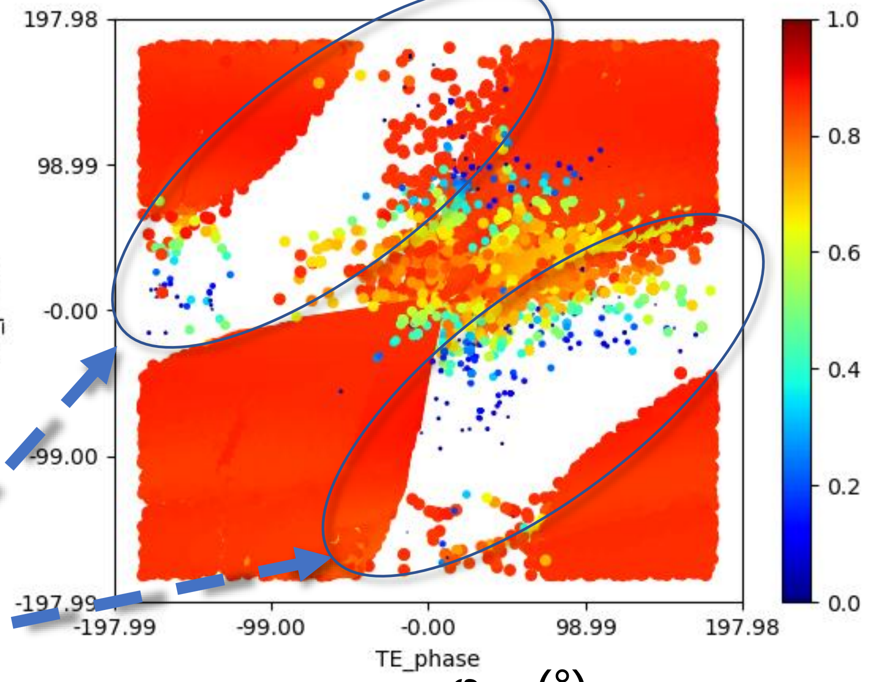


Beamsplitter: library building

- Polarization effect-> symmetry breaking
- Cover all pairs : $\varphi_{TE}, \varphi_{TM}$
- 1 dot = 1 structure



H= 600nm - > 38 k structures

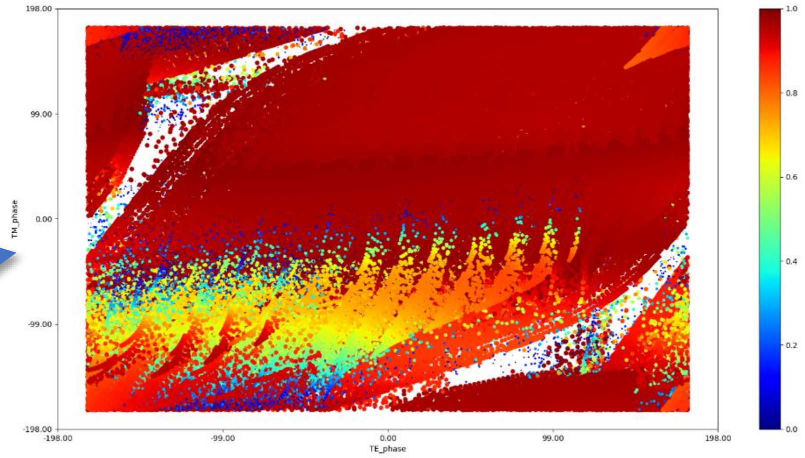


$\varphi_{TM}(°)$

Insufficient Δφ

φ_{TE} (°)

H=800nm -> 58 k structures

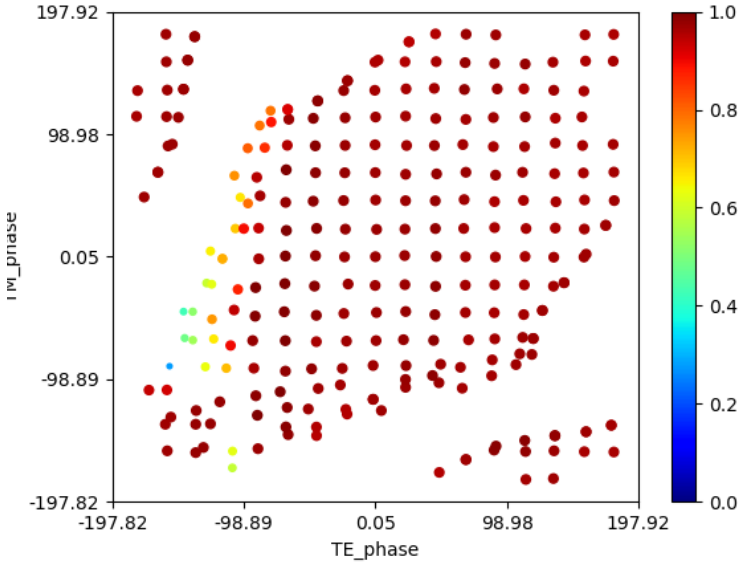


$\varphi_{TM}(°)$

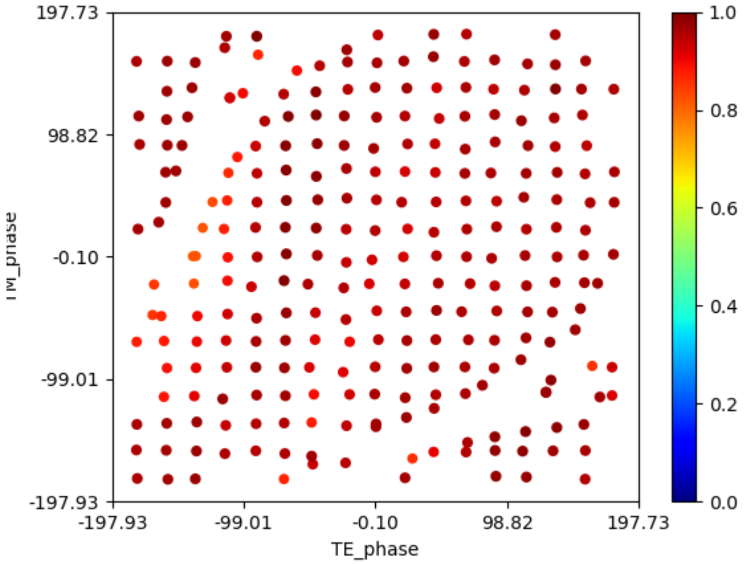
Increased H,
smaller dead zone

φ_{TE} (°)

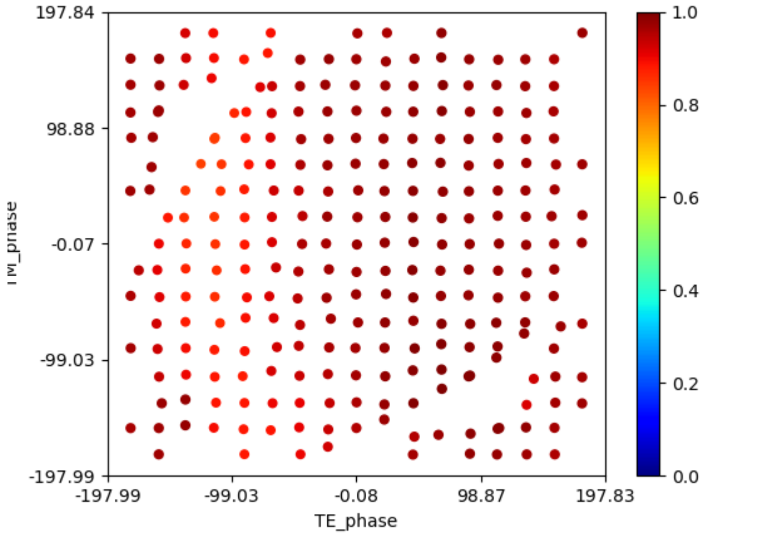
Selection: 16x16 elements



P=300nm



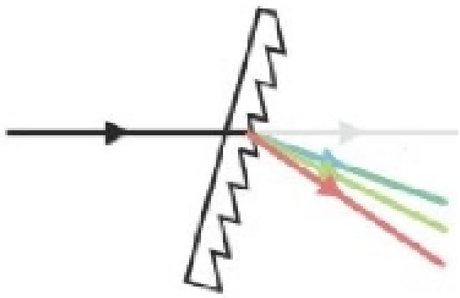
P=350nm



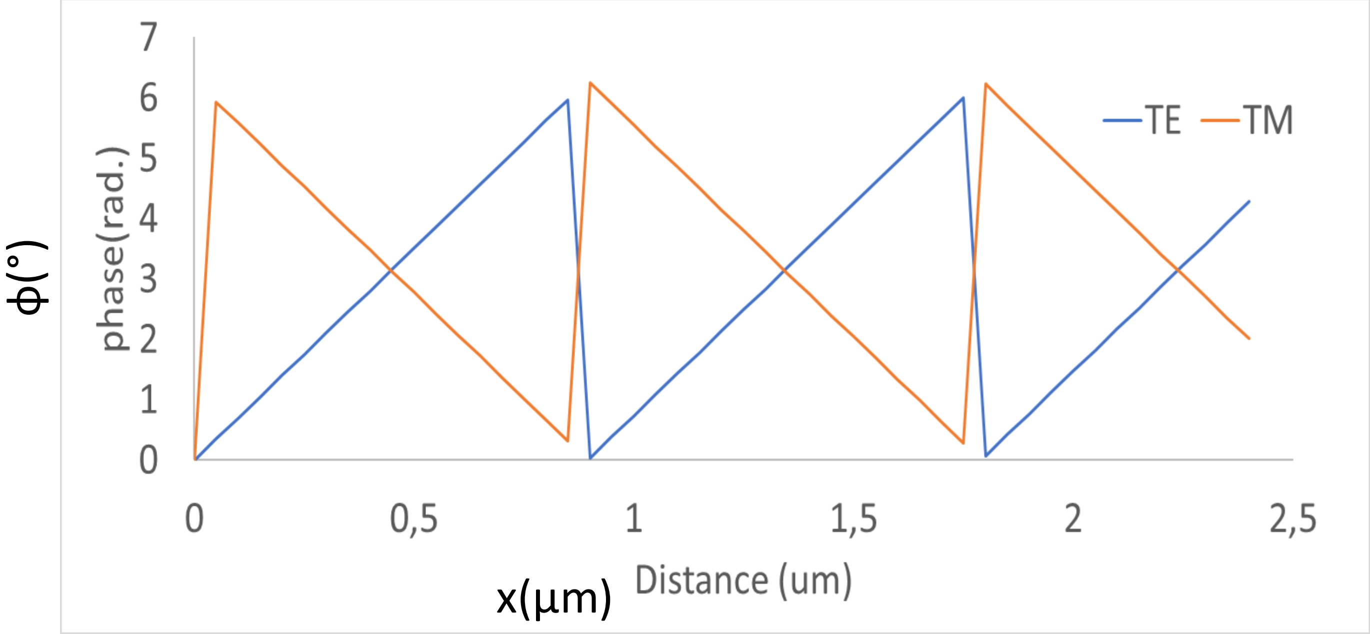
P=400nm

- Library selection: 16x16 structures
- 3 different pitches: 300, 350 and 400nm
- 1 dot = 1 structure

First application beamsplitter



- Classical beamsplitter:
  - Separates TE and TM polarization
  - 90° split angle
- Blazed grating: 1 deflection direction
- Combined functionality
  - Custom: narrow or wide splitting angle
  - Arbitrary splitting direction of TE and TM



- Convert parallel to oblique wavefront:

$$\varphi_{TE/TM} = -\frac{2\pi}{\lambda} * \sin(\theta_{TE/TM}) * x + C$$

Beam splitter:

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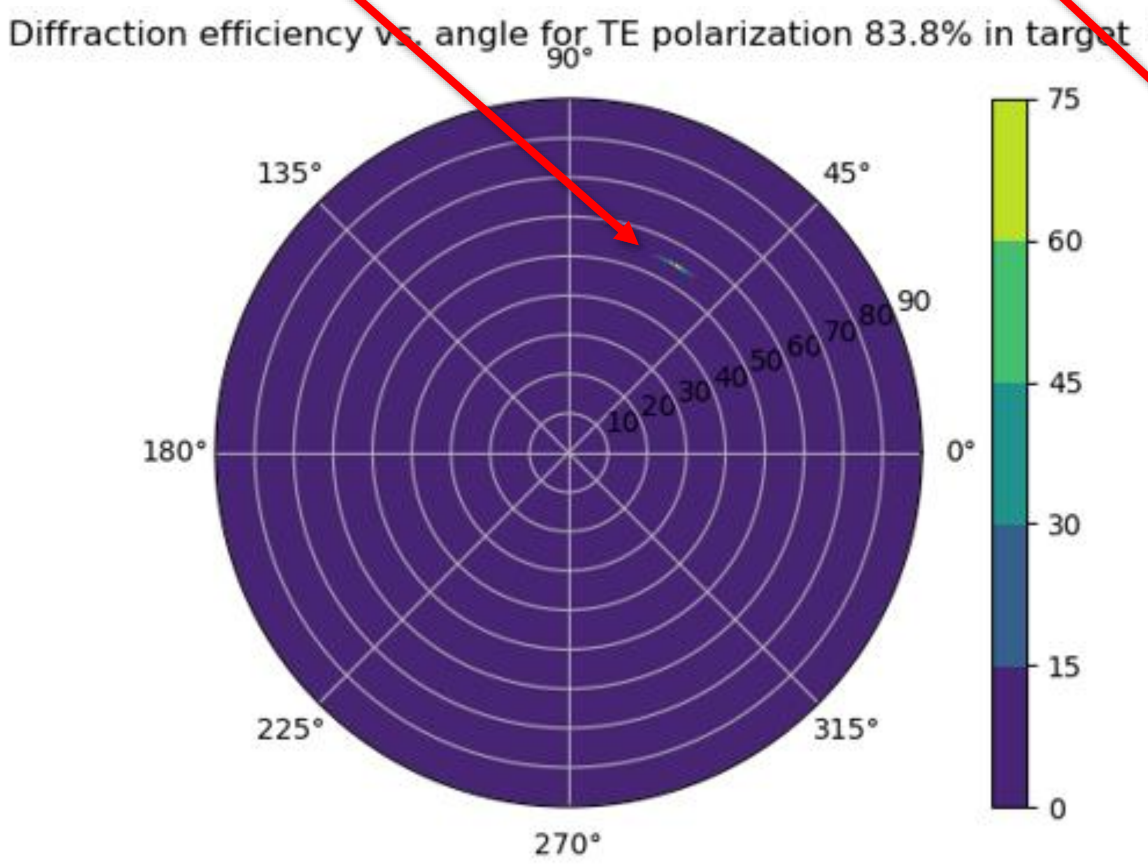
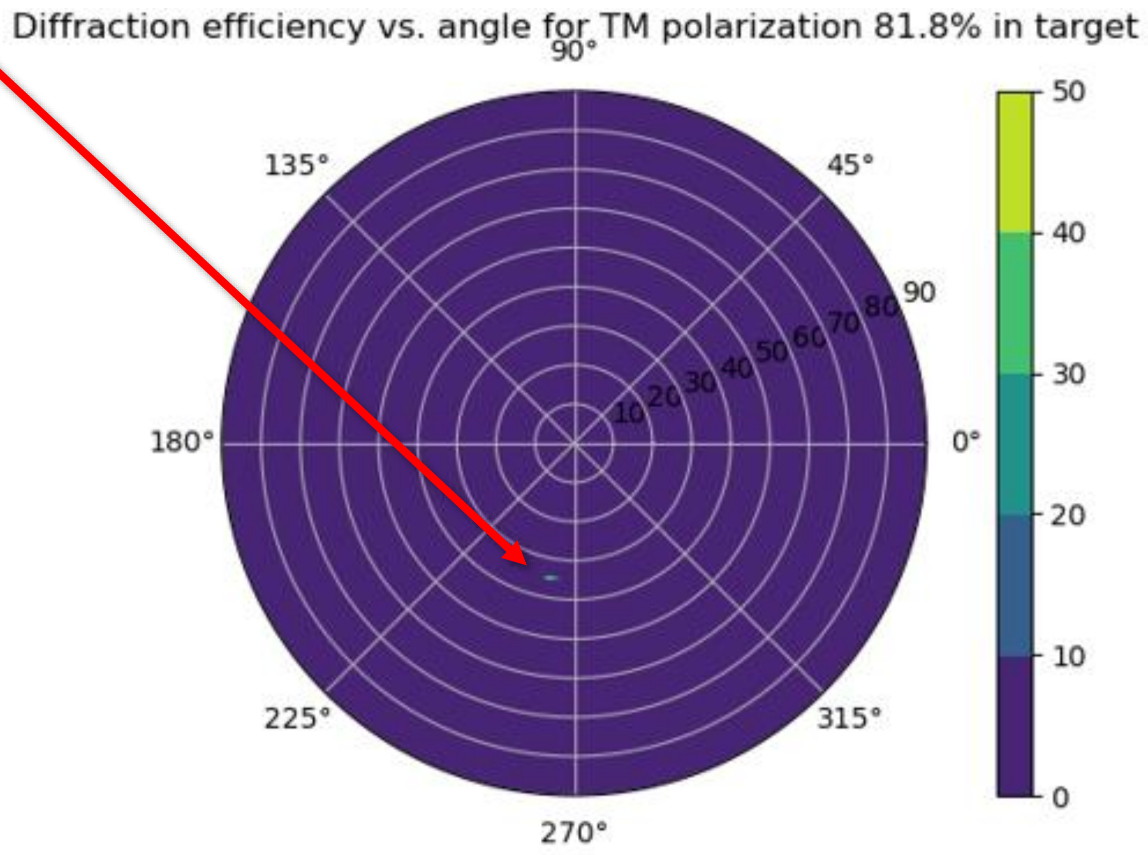
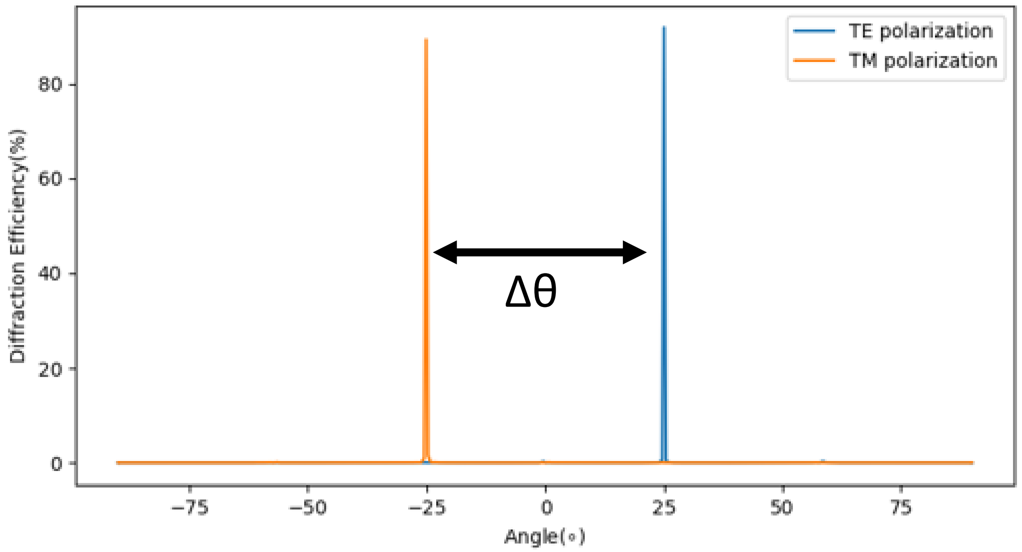
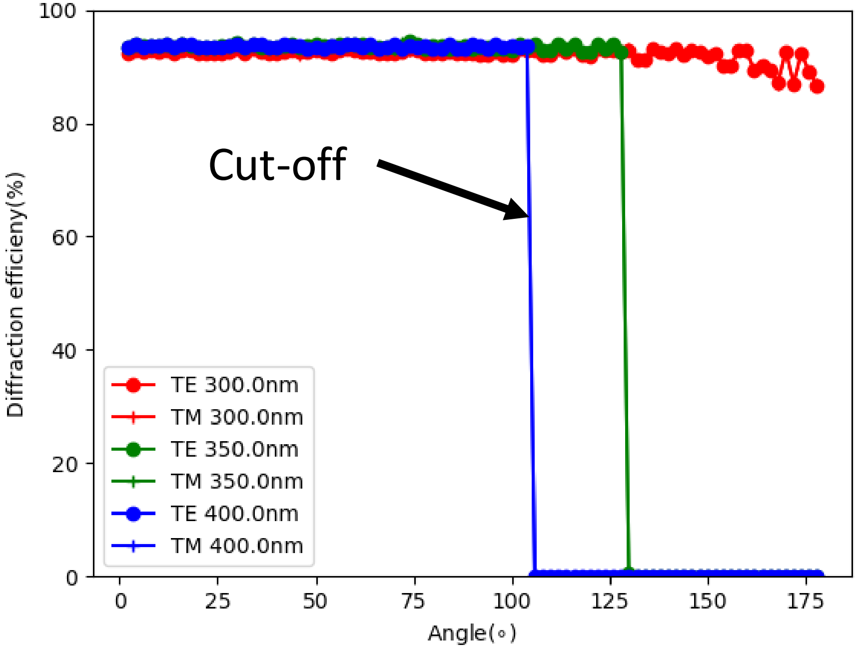
- Diffraction efficiency: >80% in 1° around target
- Angles not in same plane
- Custom angle
  - TE (55,60) TM (35,-100)





Beam splitter:





- ❖ With sufficiently small pitch, splitting angle up to 175°
- ❖ Target phase reproduced with some deviation

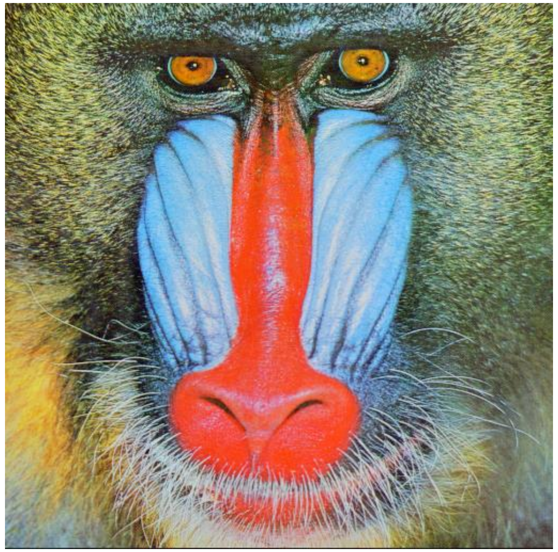
Pitch(nm)	Theoretical cut off	Simulated cut-off
400	104,6°	104°
350	129,5°	127°
300	None	None

Multiplexed hologram

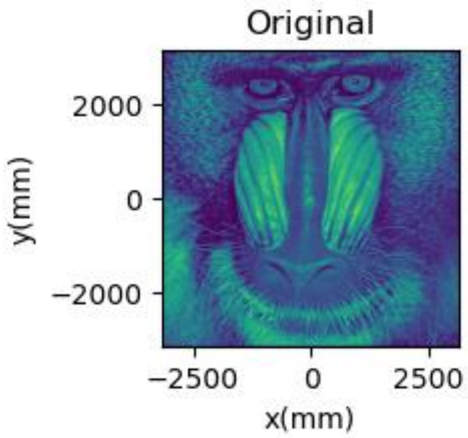
- Hologram images
  - Wide angle: 18°
- Design wavelength 633nm
  - TiO_2 on SiO_2 structures
  - Library from previous example
- Meta surface:
  - Size: 2x2 mm (25M meta-atoms)
  - Projection distance: 1m

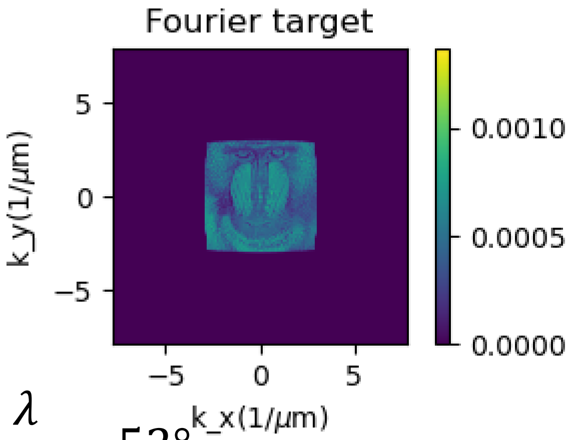
TE image

TM image

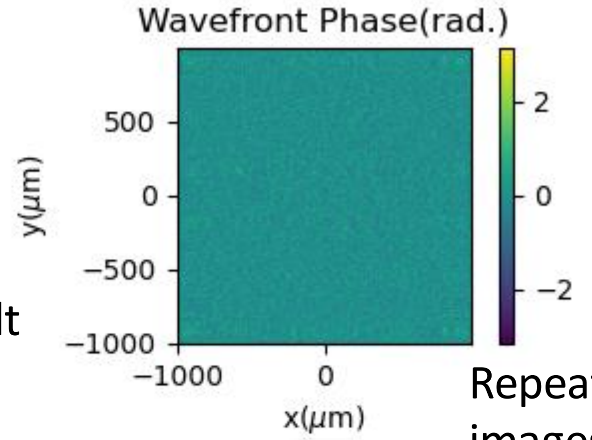


Multiplexed hologram: step by step





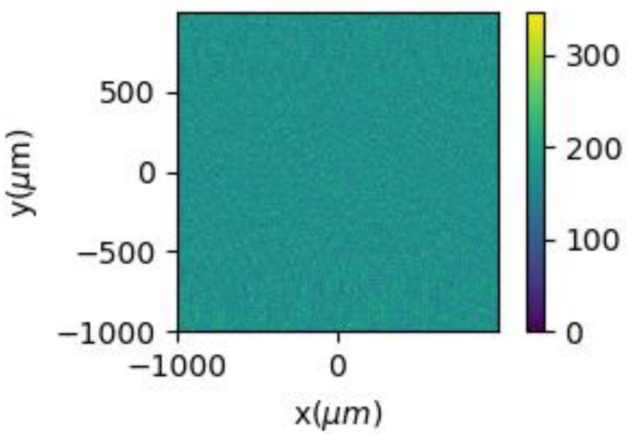
IFTA result



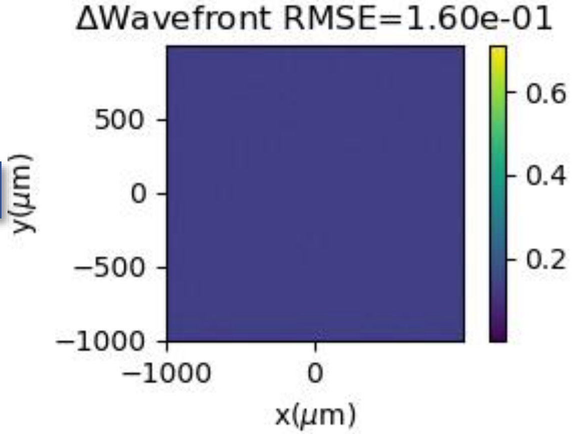
$$\sin(\theta) = \frac{\lambda}{2P} = 52°$$

Repeat for both images

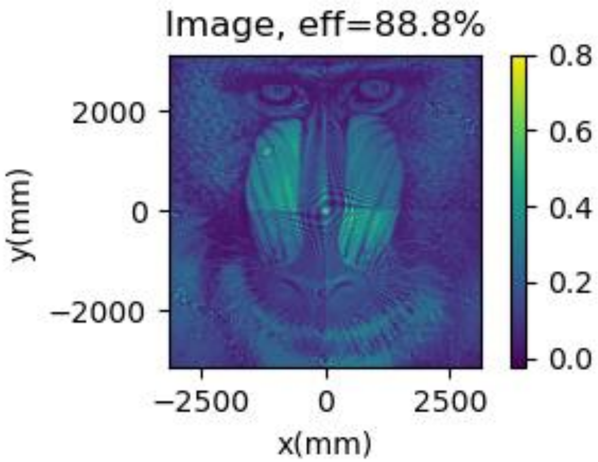
Meta atom approximation



Co-optimized for 2 wavefronts



Resulting image

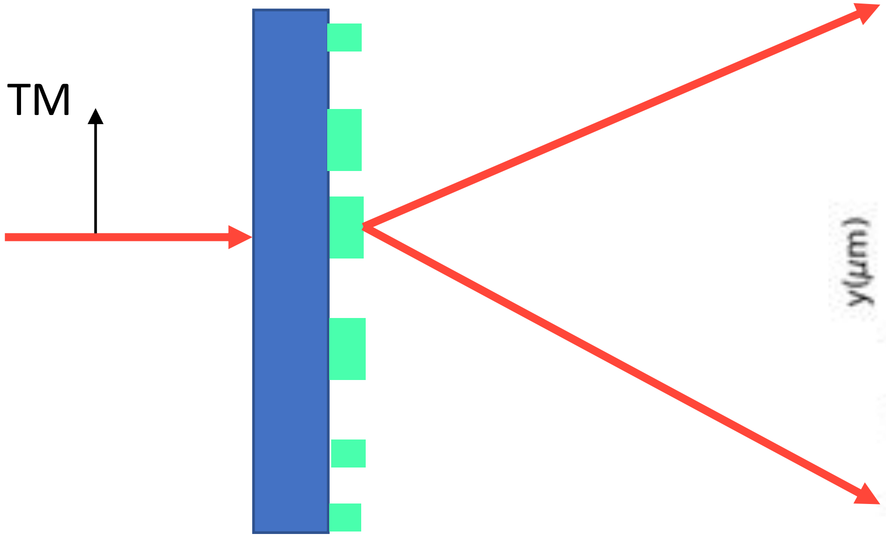


Multiplexed hologram: results

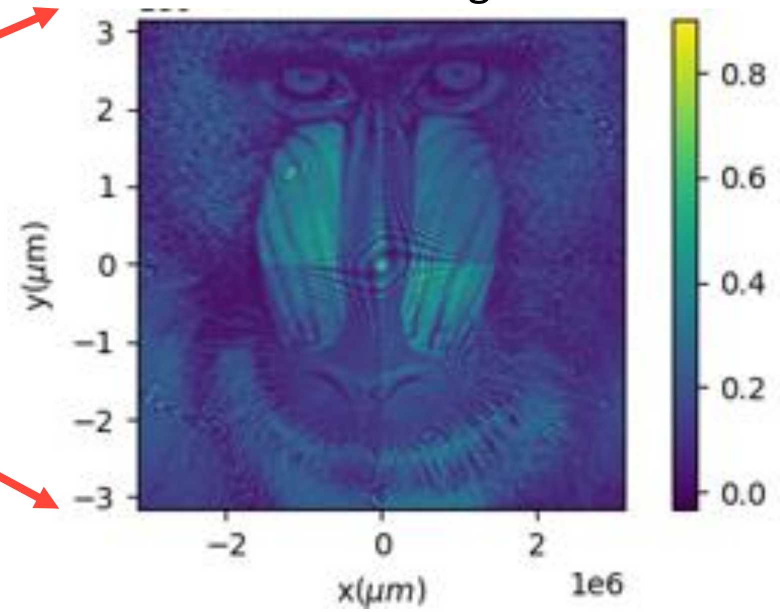
- High efficiency:
  - 16 level phase only

	Image RMSE	Wavefront error (RMSE)	Efficiency
TE	3.3 e-8	0.1	91%
TM	2.5 e-8	0.1	89%

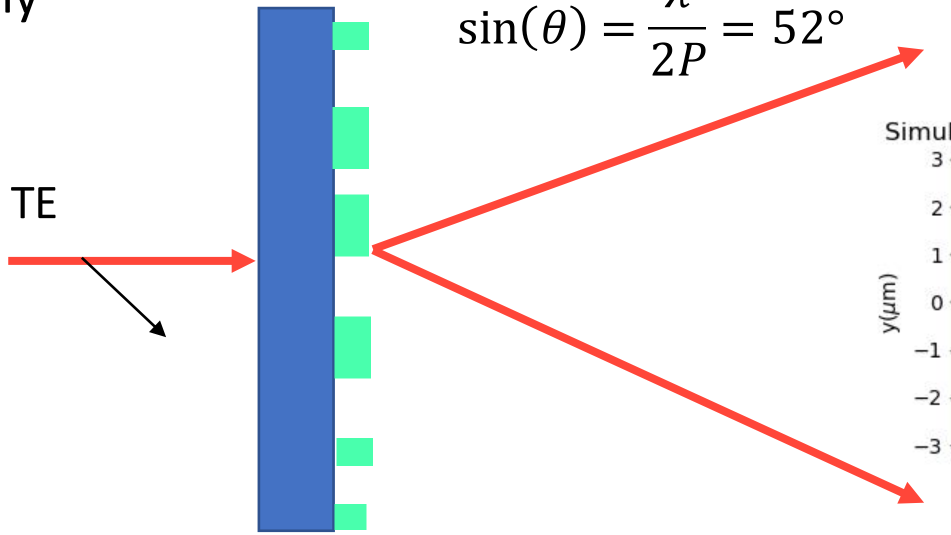
- Both images produced simultaneously



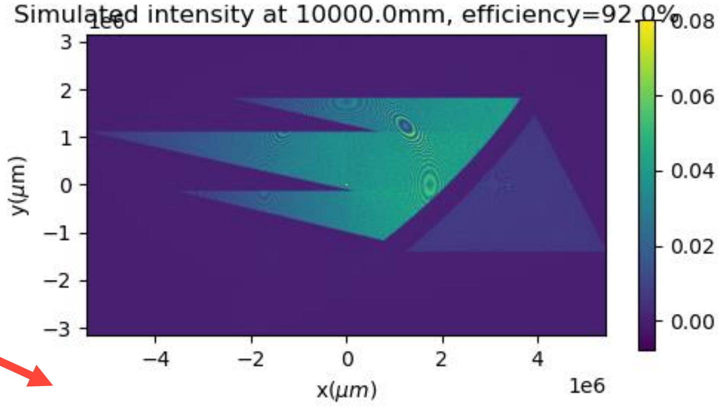
Simulated image TM



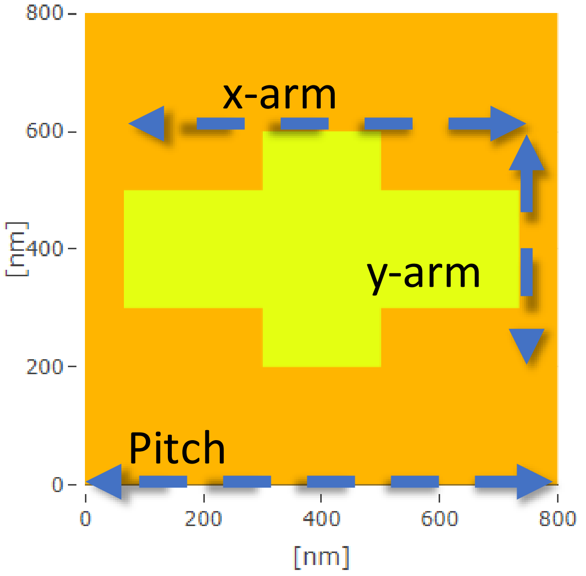
$$\sin(\theta) = \frac{\lambda}{2P} = 52°$$

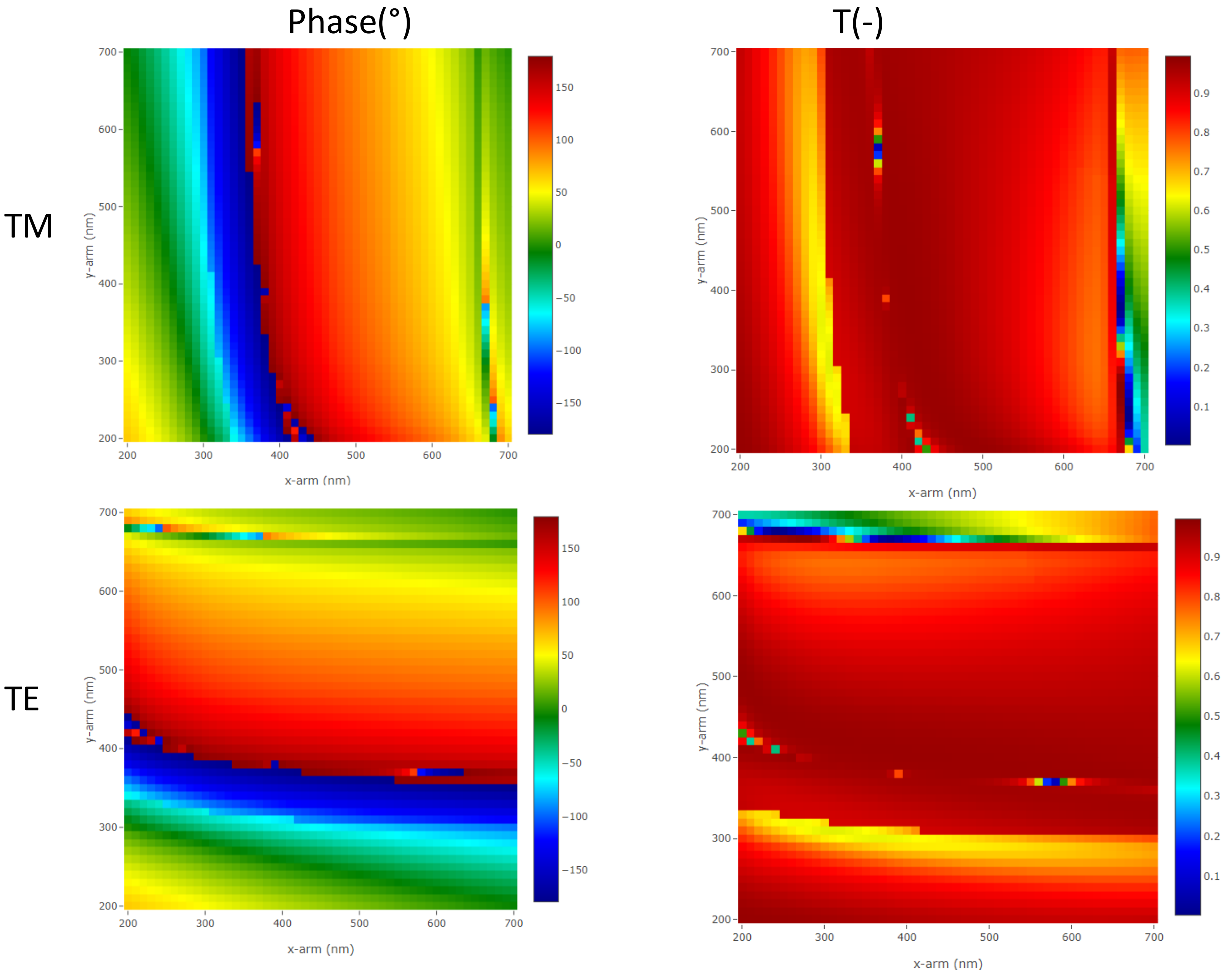


Simulated image TE



Focusing polarizing beamsplitter





- Design for 1,55 µm
- Cross structure:
  - X-arm influences TM polarization (mostly)
  - Y-arm influences TE polarization (mostly)
- Meta-atom **library**:
  - **8 X 8 sampling** of TE/TM phase

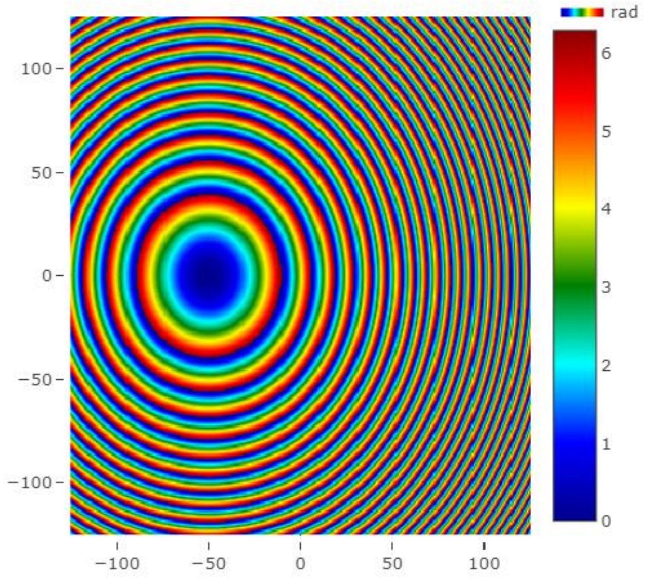
Focusing polarizing beamsplitter

- Analytical phase profile: diffraction limited lens
- Independent targets
  - TE: focal distance 500µm and shifted left 50µm
  - TM: focal distance 500µm and shifted right 50µm

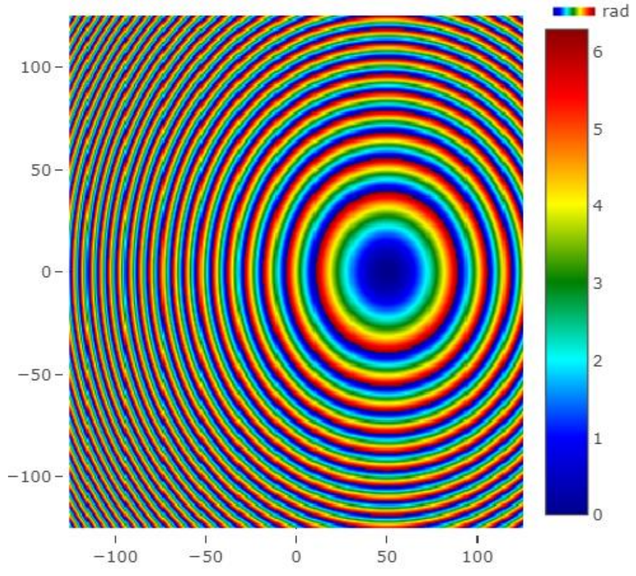
$$\varphi_{TE} = \frac{2\pi}{\lambda}\left(-f + \sqrt{f^2 + y^2 + (\boldsymbol{x} + \mathbf{50})^2}\right)$$

$$\varphi_{TM} = \frac{2\pi}{\lambda}\left(-f + \sqrt{f^2 + y^2 + (\boldsymbol{x} - \mathbf{50})^2}\right)$$

TE target



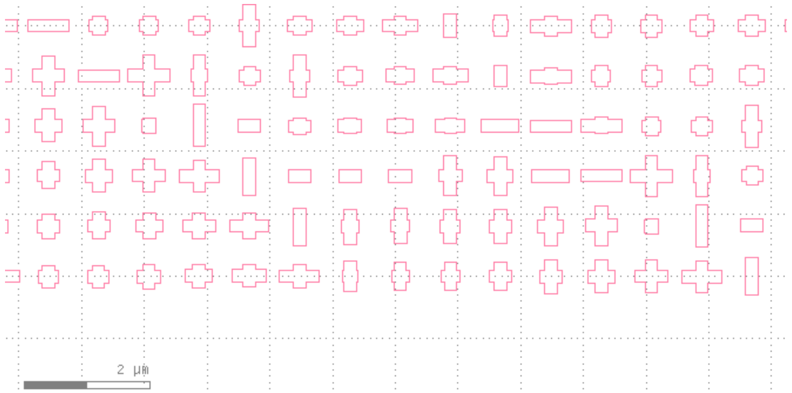
TM target

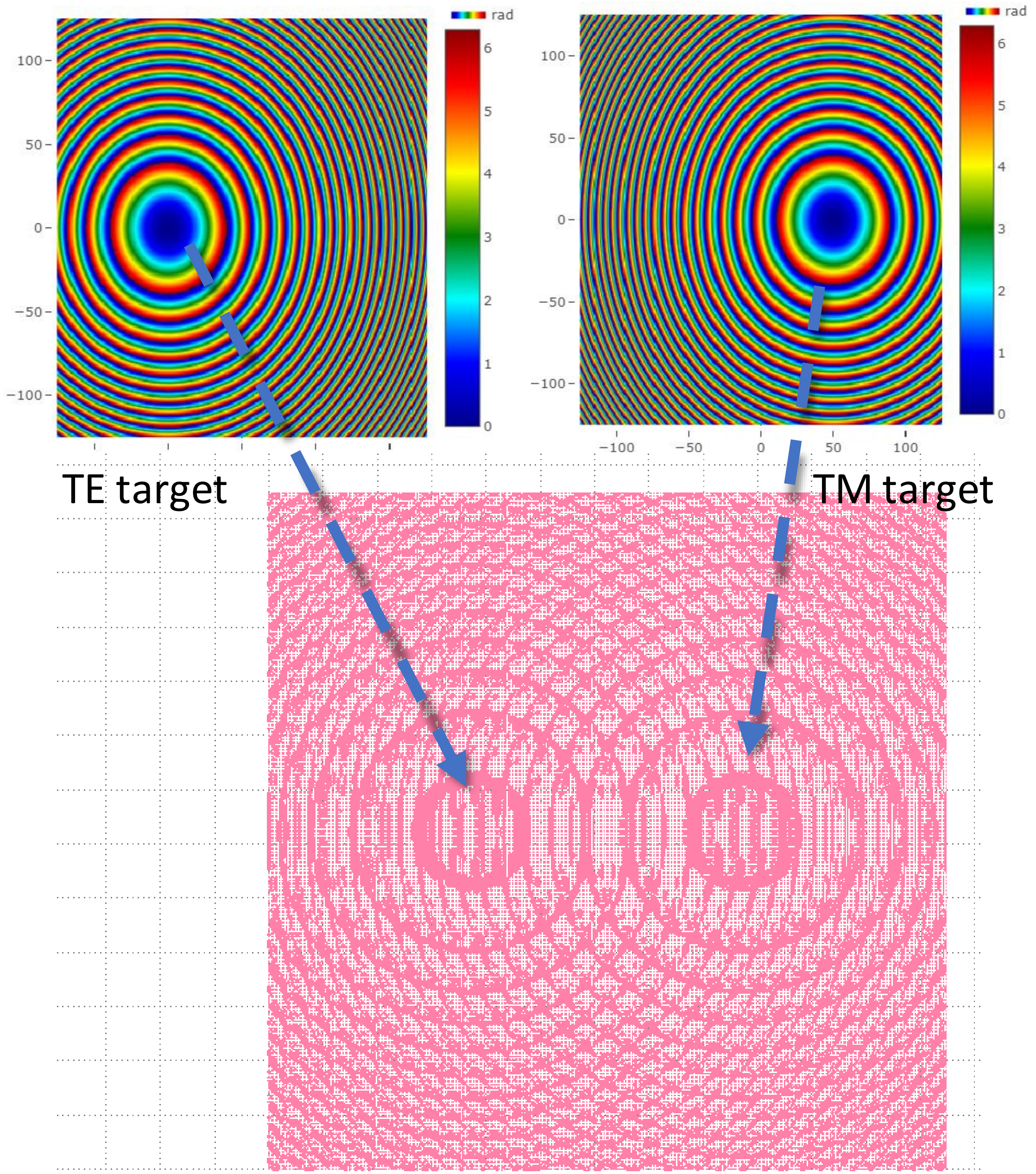


Focusing polarizing beamsplitter

- ❖ Weighted optimization for TE and TM target
- ❖ Indiviual targets recognizable in the layout

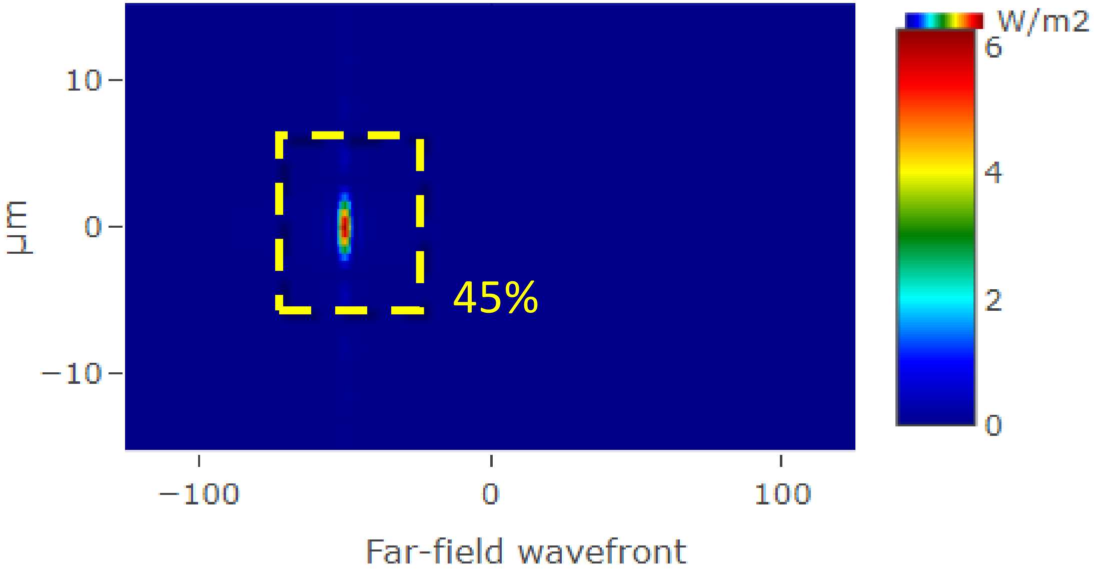
Example structures





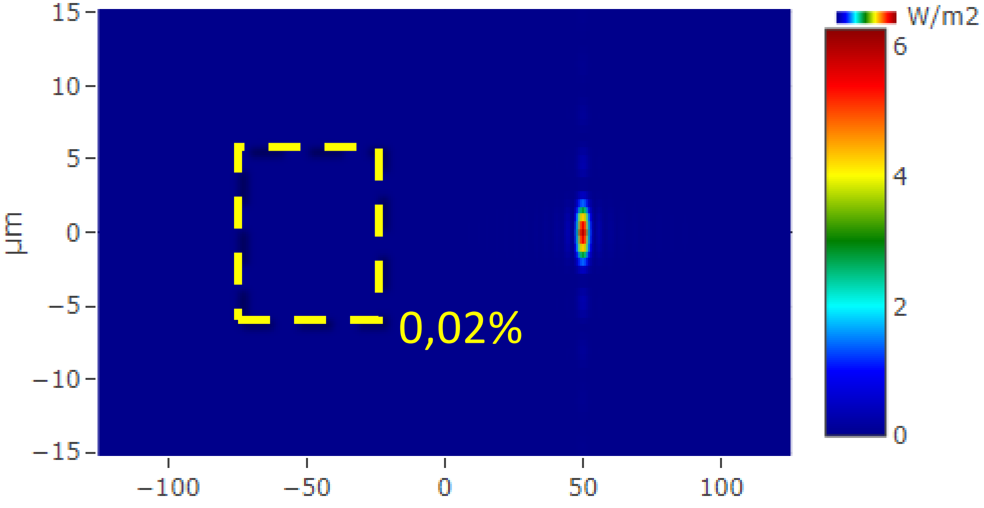
Focusing polarizing beamsplitter

TE incidence

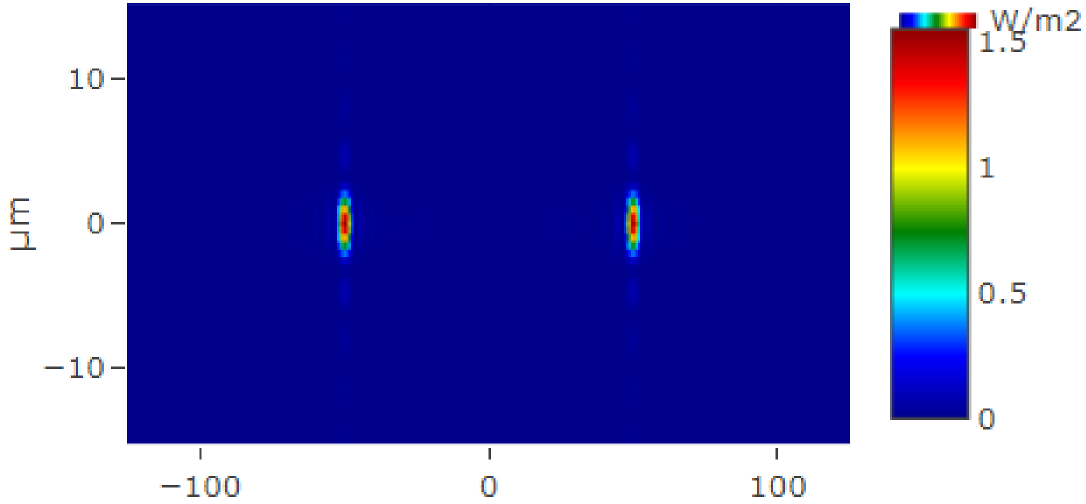


- Simulated Intensity profile **at f** (500µm)
- **TE and TM** polarization **separately focused**
- Transmission efficiency: 89.2%
- Spot efficiency: 65.1%
- Ratio TE/TM 2250:1 in focal point
  - Commercial polarizing beamsplitter cube >1000:1

TM incidence

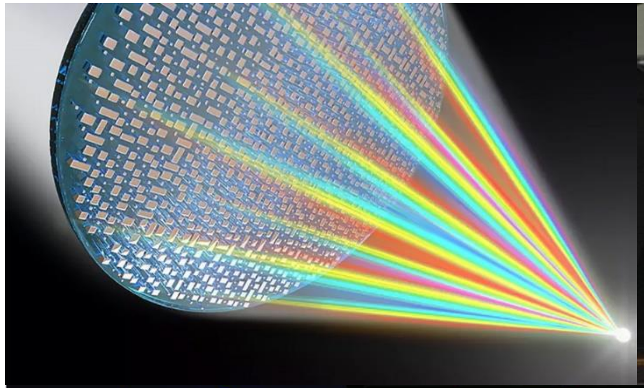
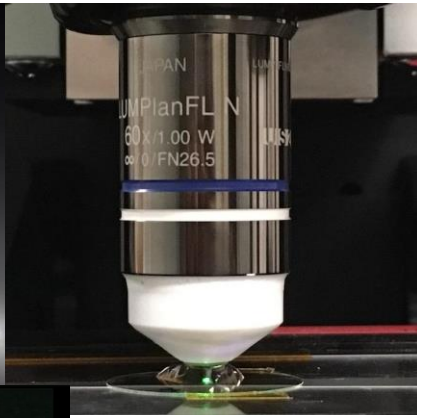


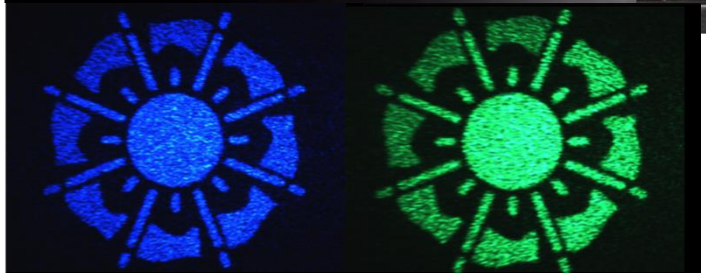
Circular Polarization (R) incidence



Metasurface platform

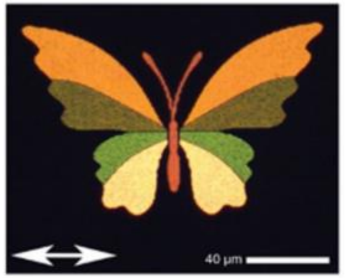
Wavefront control

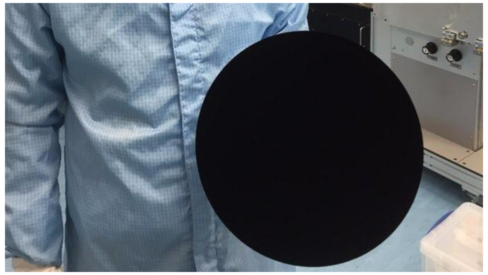





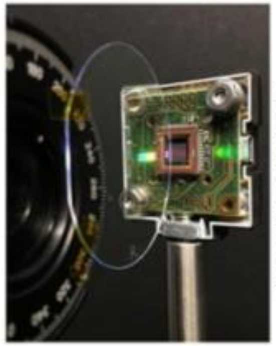
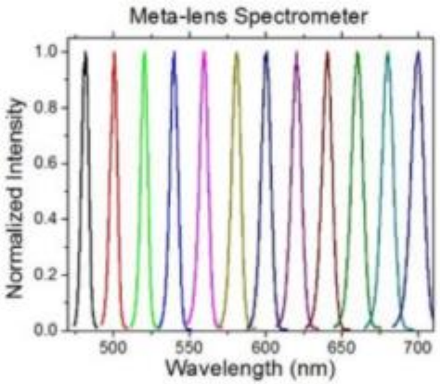
Immersion
& High NA
Holography

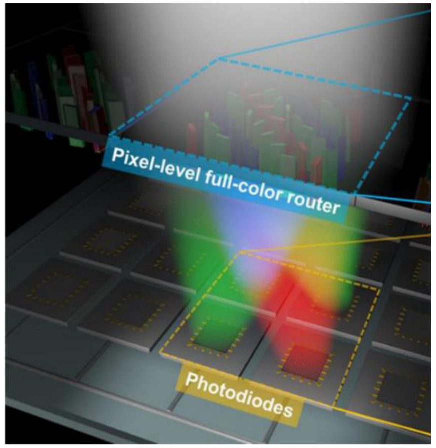
Engineered reflection & transmission
Coating free high power optics

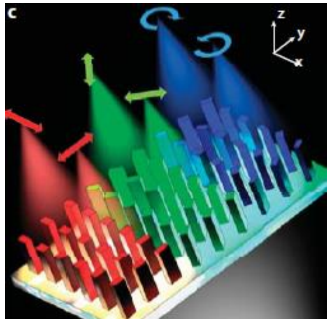




Spectrum & polarization control





Miniaturized & Low weight

Low material
consumption

Conclusion

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- **Meta-surfaces** allow a **path to** previously **“impossible” components**

- A library of **sub-wavelength structures** is available to control polarization response independently of 2 orthogonal polarizations

- **Examples** Applications for **miniaturized** and **simplified** polarization optics

- **Simulation tools** are essential to bring this technology from the **lab into the industry**

Contact info!

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