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Bilayer Metasurfaces: A New Approach to Structured Light

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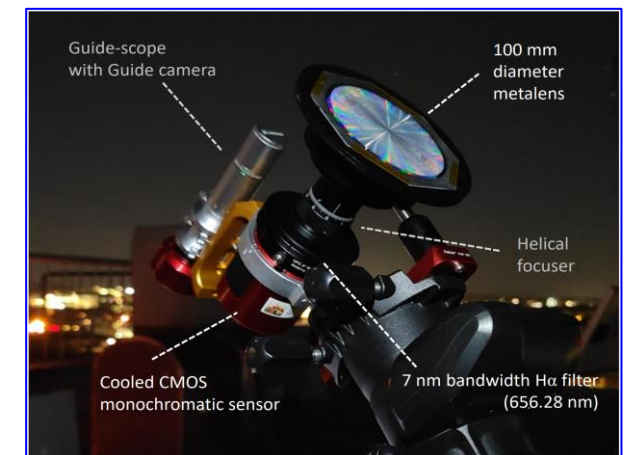
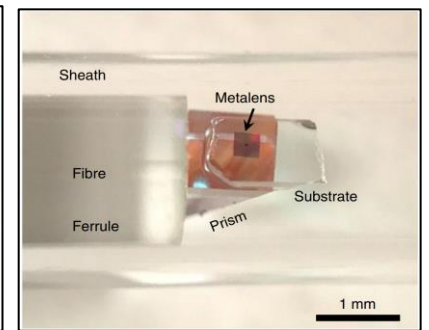
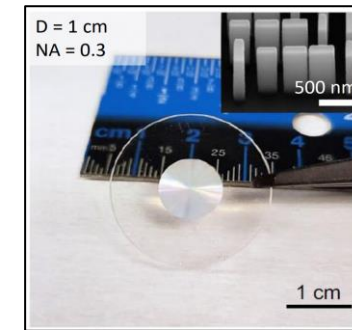
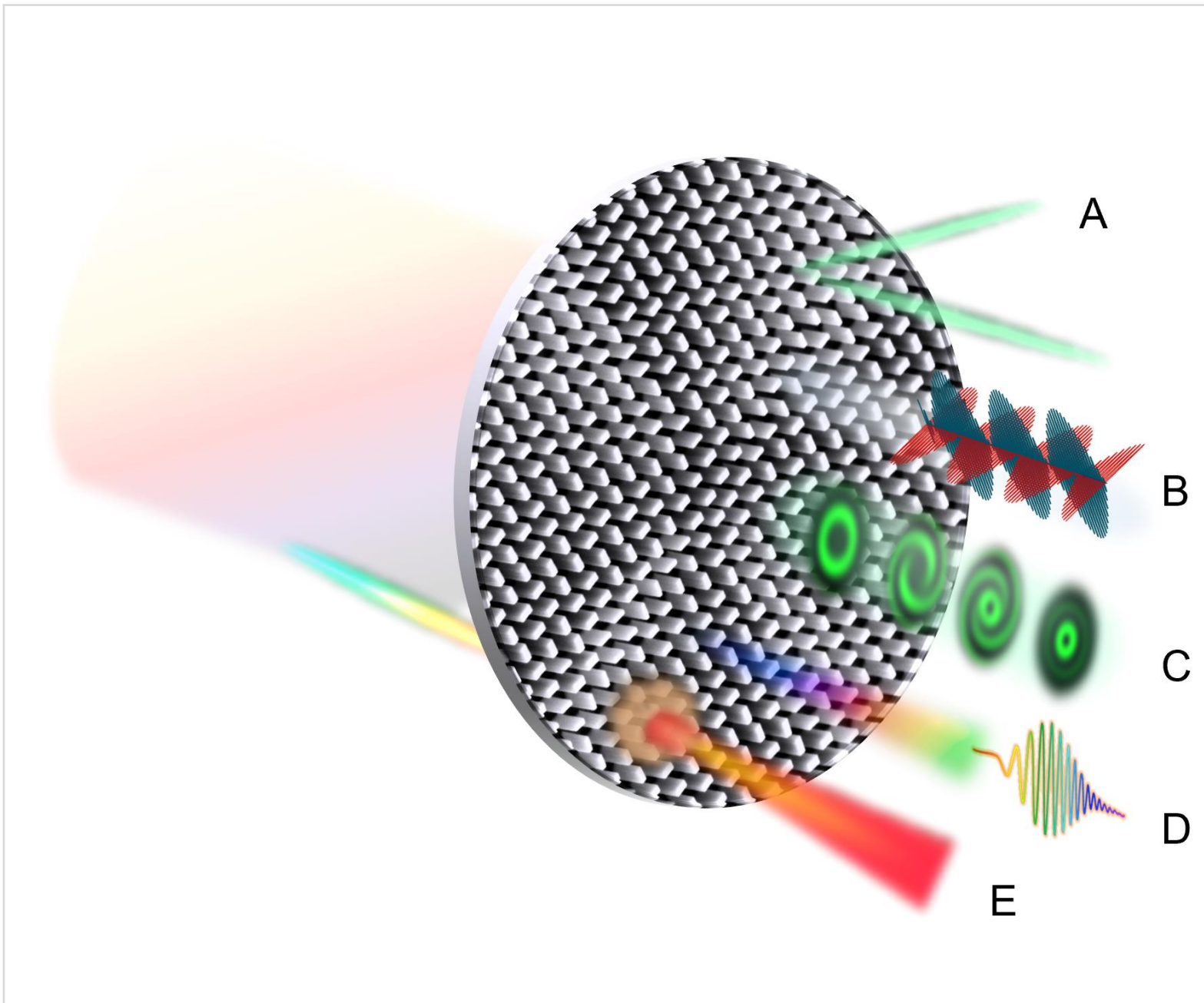
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Systems

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Supported by AFOSR under award FA9550-22-1-0243
“Optical singularity engineering for precision sensing”



The metasurface advantage



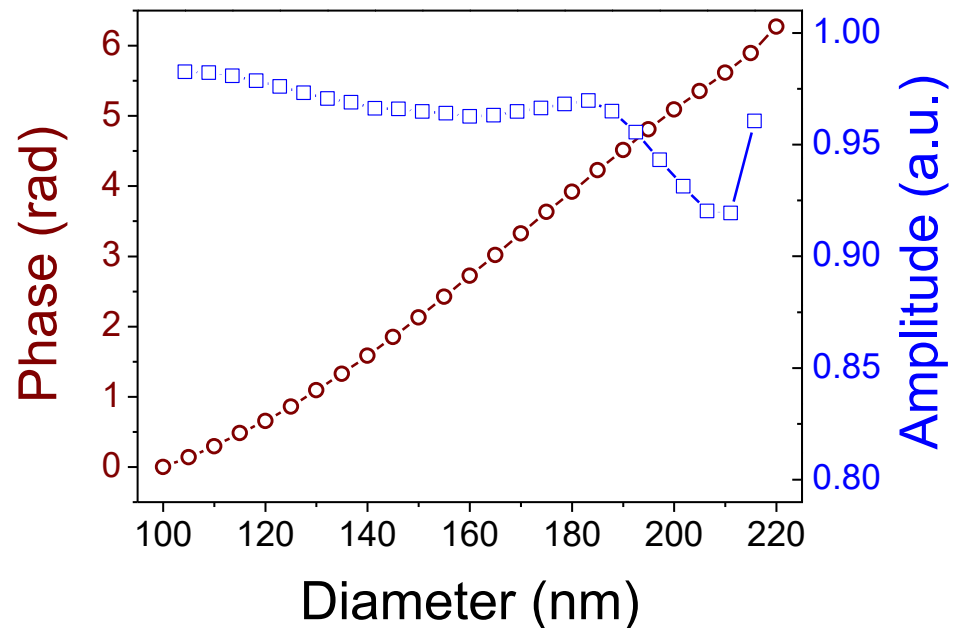
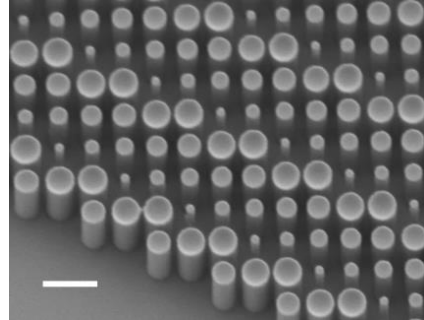
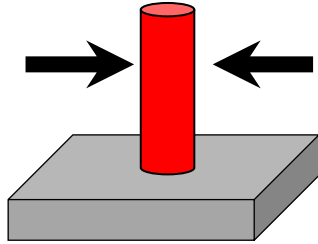
A. H. Dorrah and F. Capasso, "Tunable structured light with flat optics," *Science* 376, Issue 6591 (2022).



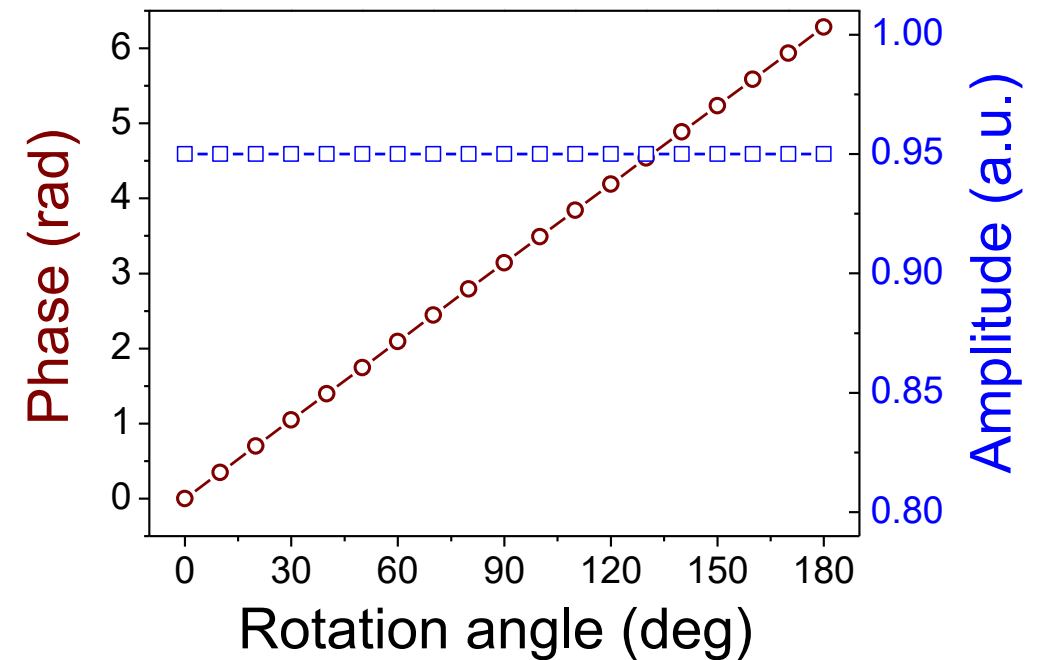
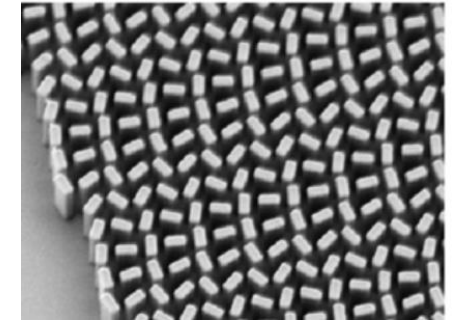
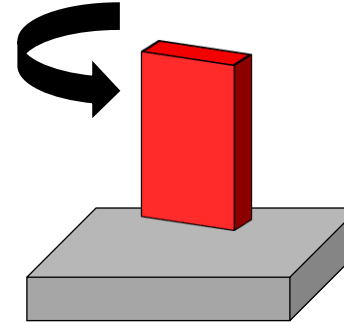
Phase control with metasurfaces



Propagation Phase



Geometric (Berry) Phase

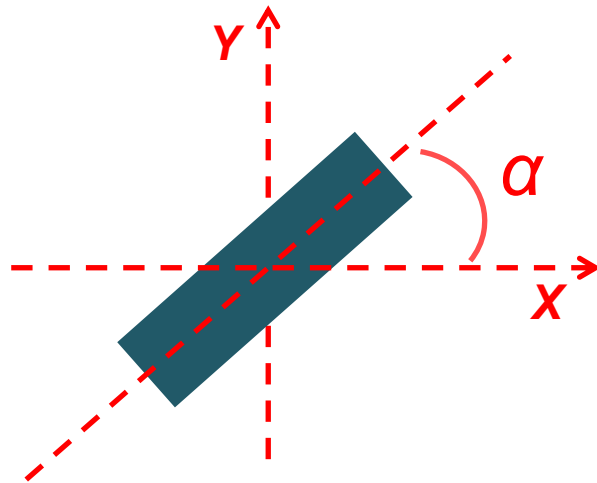


Phase Retarder (macro-, meso- or nano-)



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For **any** plate oriented by α , introducing a phase delay $\Delta\phi$ between X and Y field components



$$M = R(-\alpha) \begin{pmatrix} e^{i\psi} & 0 \\ 0 & e^{i(\psi+\Delta\phi)} \end{pmatrix} R(\alpha)$$

Same handedness of the incident field

Opposite handedness to the incident field

$$\mathbf{E}_{\text{out}} = M \begin{bmatrix} 1 \\ -i \end{bmatrix} = e^{i\psi} \left(\frac{1}{2}(1+e^{i\Delta\phi}) \begin{bmatrix} 1 \\ -i \end{bmatrix} + \frac{1}{2}(1-\mathbf{1}e^{i\Delta\phi})e^{i2\alpha} \begin{bmatrix} 1 \\ i \end{bmatrix} \right)$$

Right-circularly polarized

$2\alpha = \text{Berry (geometric) Phase}$

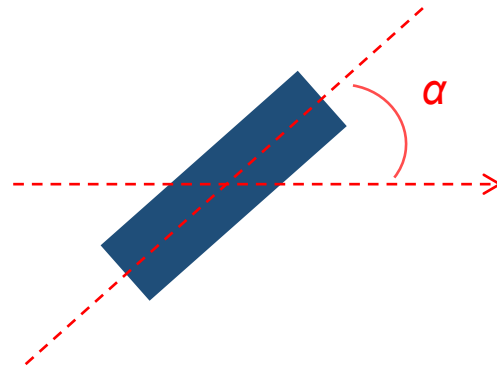
For $\Delta\phi = \pi$ (half waveplate)

Geometric (Berry) Phase Metasurfaces



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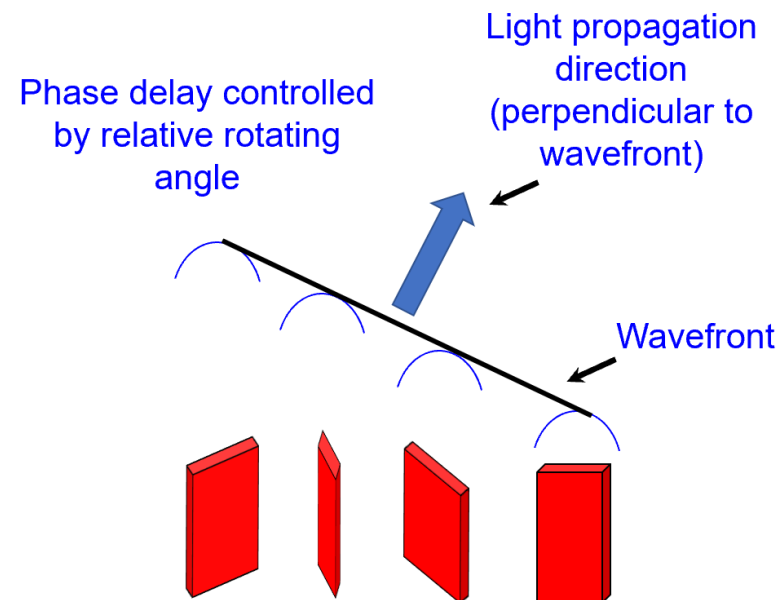
- When the nanofin is designed as a half wave plate incident circularly polarized (CP) light is converted to CP light of opposite chirality and
- It acquires an extra phase factor $\exp(i2\alpha)$ where α is the rotation angle



One can now design a metasurface with sub-wavelength spaced nanofins of different orientations that impart position dependent phase shifts on the incident light wavefronts

$$\Delta\phi(x, y) = 2\alpha(x, y)$$

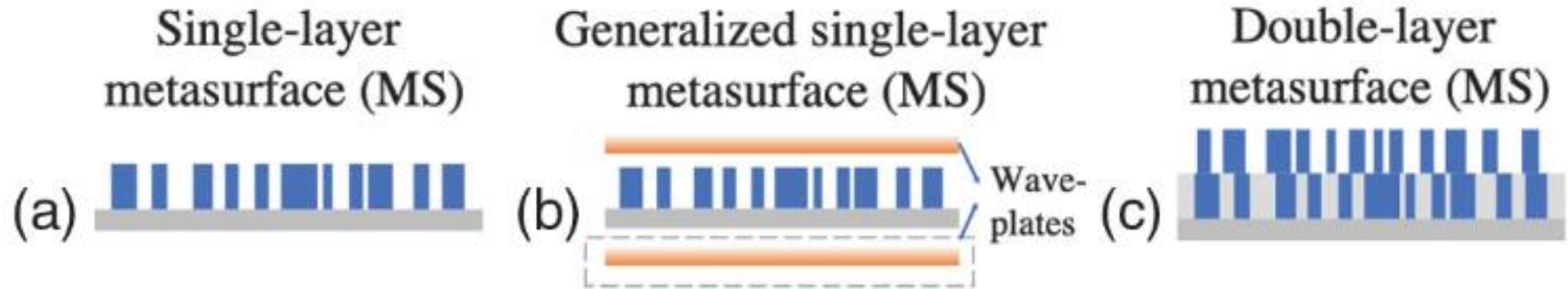
Beam Deflector



Going Beyond Single Layer Metasurfaces



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- Bilayer Metasurfaces greatly expand opportunities for wavefront engineering, structuring light (singularities etc.) and realizing arbitrary polarization transformations
- We will showcase three strategies: **shape optimization, shape optimized bilayer metasurfaces and free-standing bilayer metasurfaces**

Z. Shi, F. Capasso, *et al.*, *Phys. Rev. Lett.* 129, 167403 (2022)
A. Palmieri, A. H. Dorrah, F. Capasso, *et al.*, *Optics Express* 32, 5, (2024)

Engineering the Meta-atoms Dispersion



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➤ Dispersion-engineering of meta-atoms

: Meta-atom's n_{eff} is frequency dependent.

$$\varphi(\omega) = \frac{2\pi}{\lambda} n_{eff}(\omega) \cdot H = \frac{\omega}{c} n_{eff}(\omega) \cdot H$$

Taylor expand around ω_0

$$\varphi(\omega) \approx \varphi(\omega_0) + \left. \frac{\partial \varphi}{\partial \omega} \right|_{\omega_0} (\omega - \omega_0) + \frac{1}{2} \left. \frac{\partial^2 \varphi}{\partial \omega^2} \right|_{\omega_0} (\omega - \omega_0)^2 + \dots$$

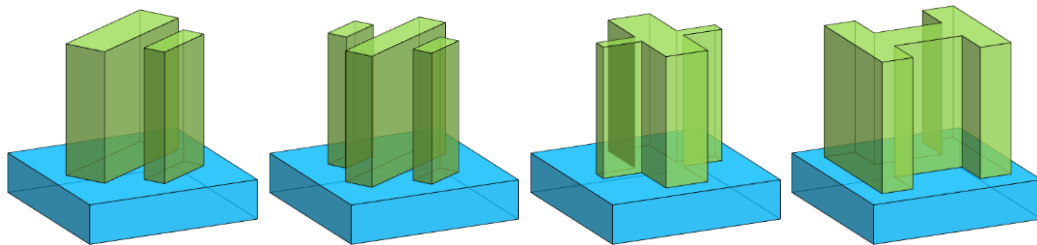
Group delay
(GD)

$$\frac{\partial \varphi}{\partial \omega} = \frac{H}{c} n_{eff} + \frac{\omega H}{c} \frac{\partial n_{eff}}{\partial \omega}$$

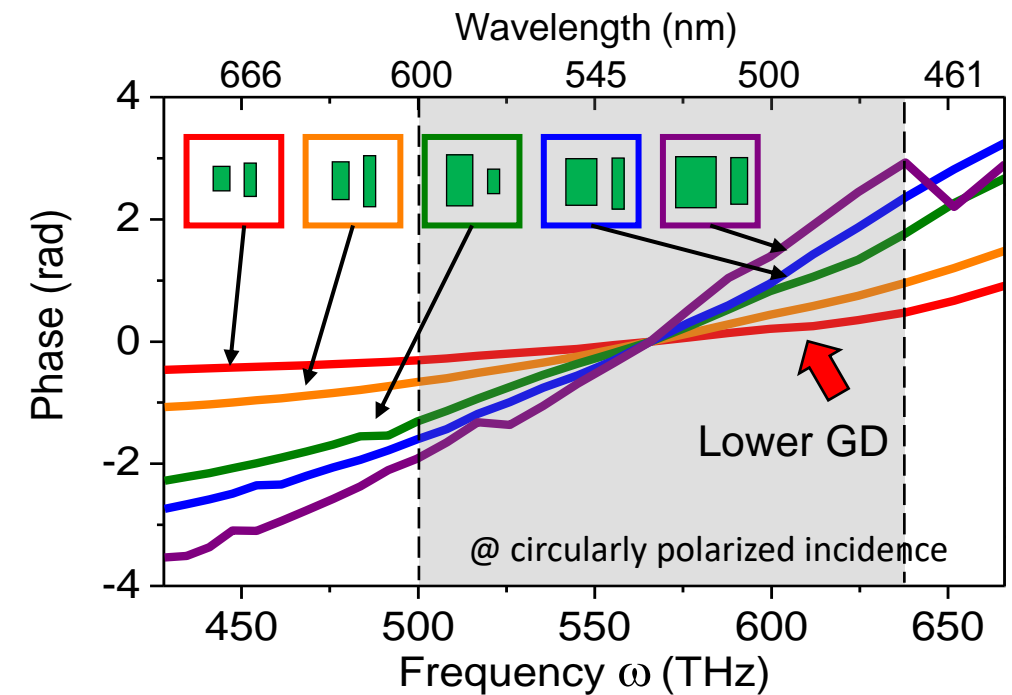
Group delay
dispersion
(GDD)

Third order
dispersion
(TOD)

Use anisotropic meta-atoms: Induce dispersion by shape!



➤ Structure-induced dispersion example

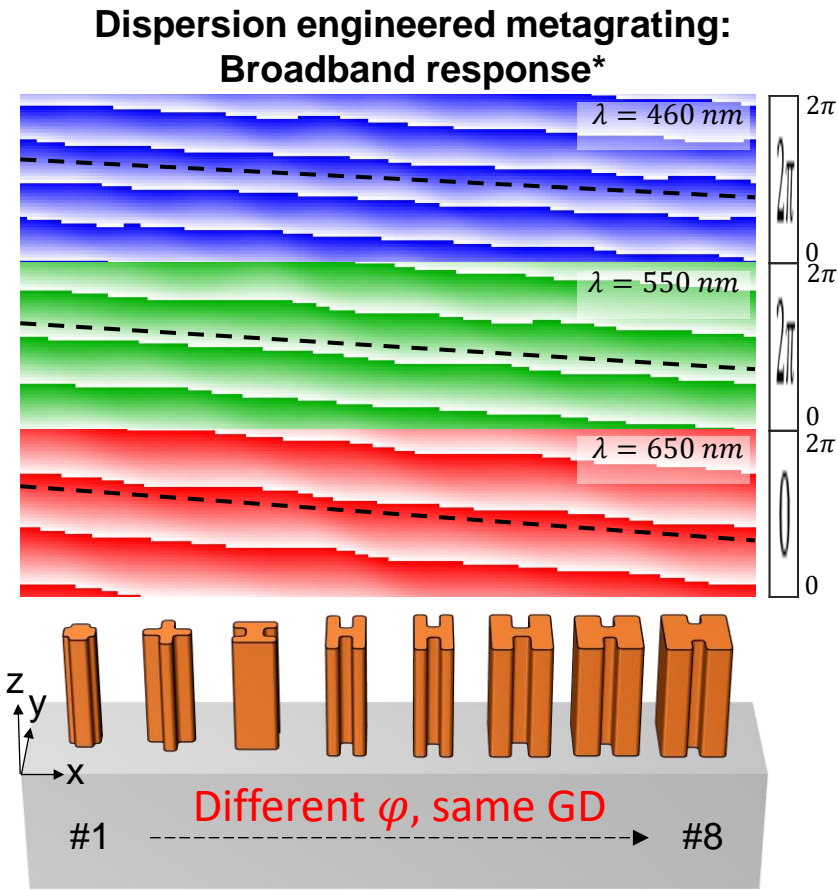
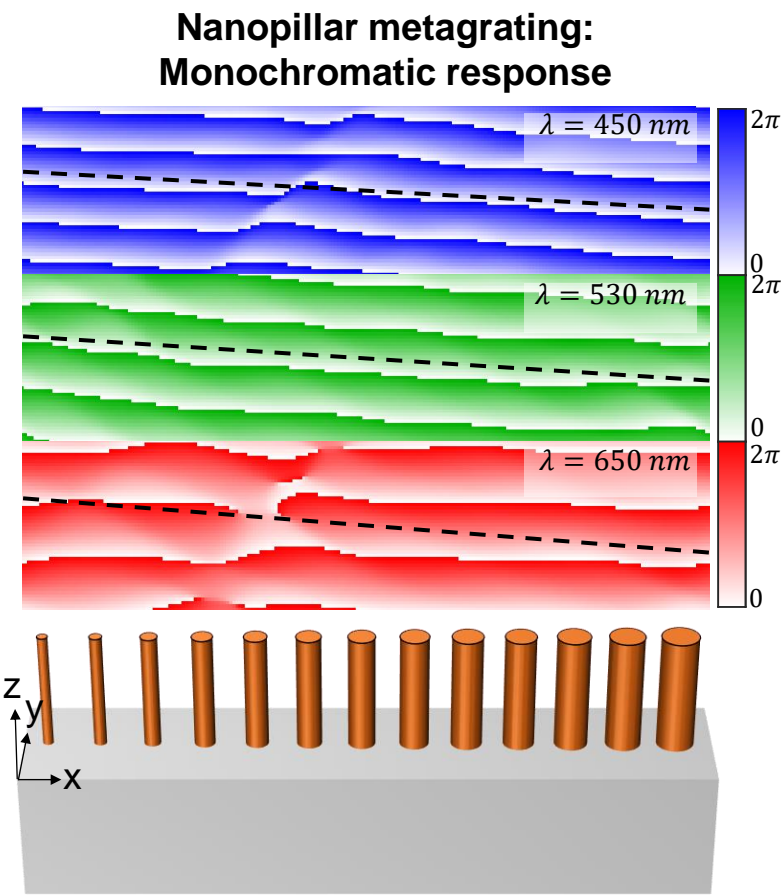


W. T. Chen, *et al.*, *Nature Communications* 10, 355 (2019)
W. T. Chen, *et al.*, *Nature Nanotechnology* 13, 220-226 (2018)

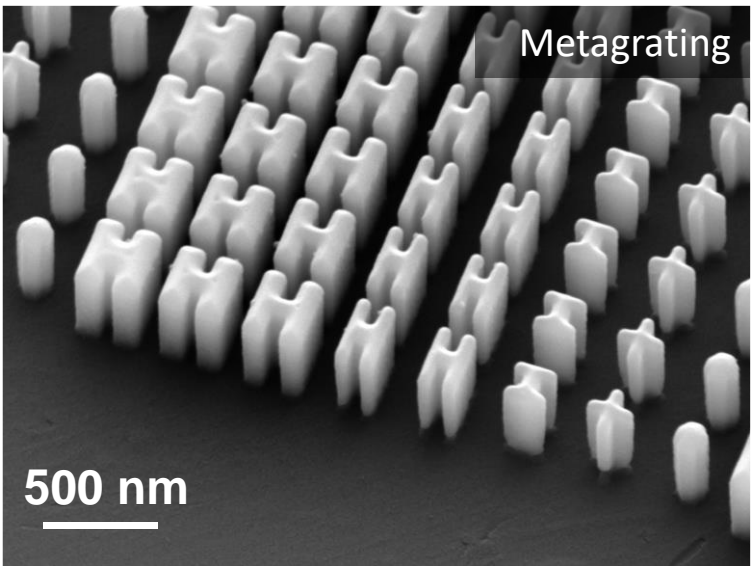
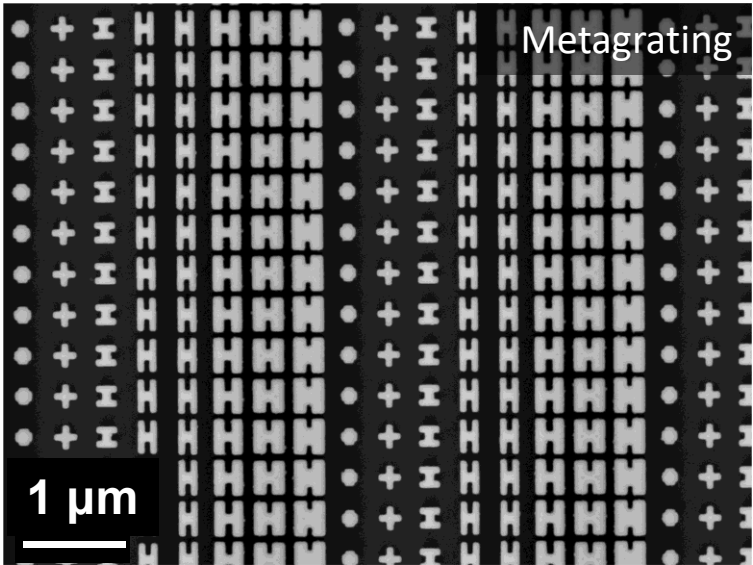
Shape optimized Meta-atoms



➤ Dispersion-engineered meta-atoms



*Polarization-insensitive operation



W. T. Chen*, J.-S. Park*, J. Marchioni, S. Millay, K. M. A. Yousef, and F. Capasso,
“Dispersion-engineered metasurfaces reaching broadband 90% relative diffraction efficiency,”*Nature Communications* 14 (2024).



Wei Ting Chen

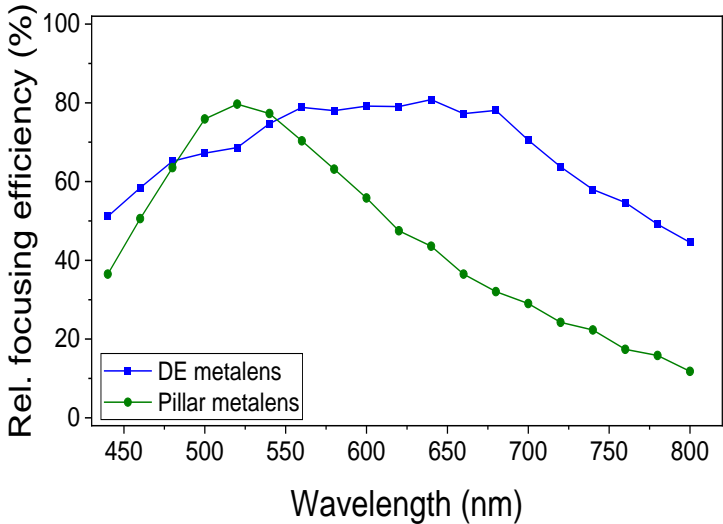
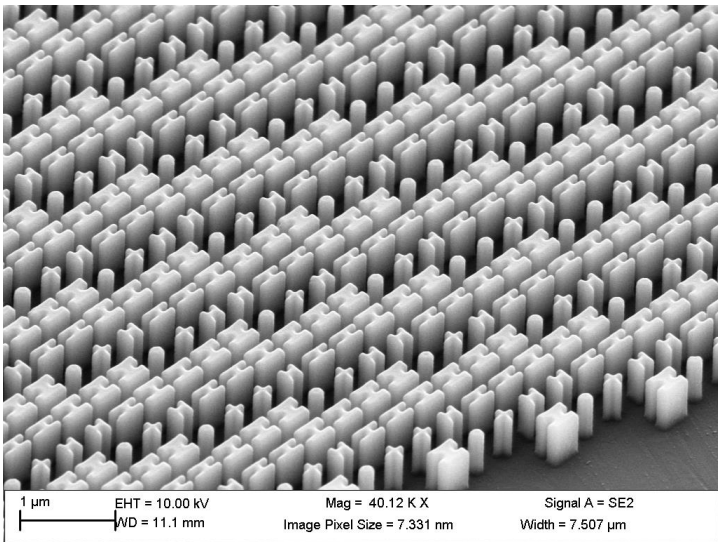
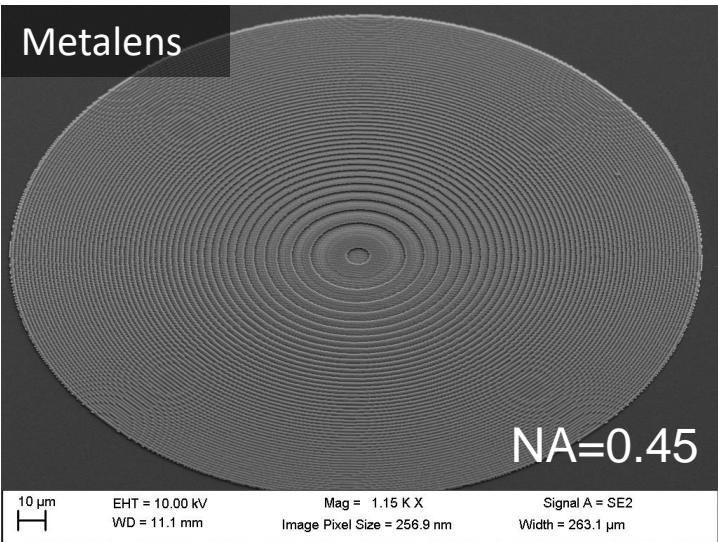
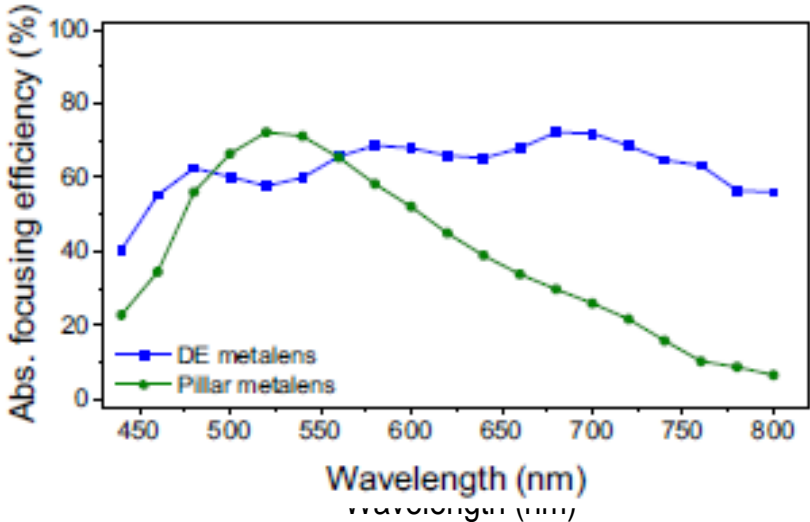
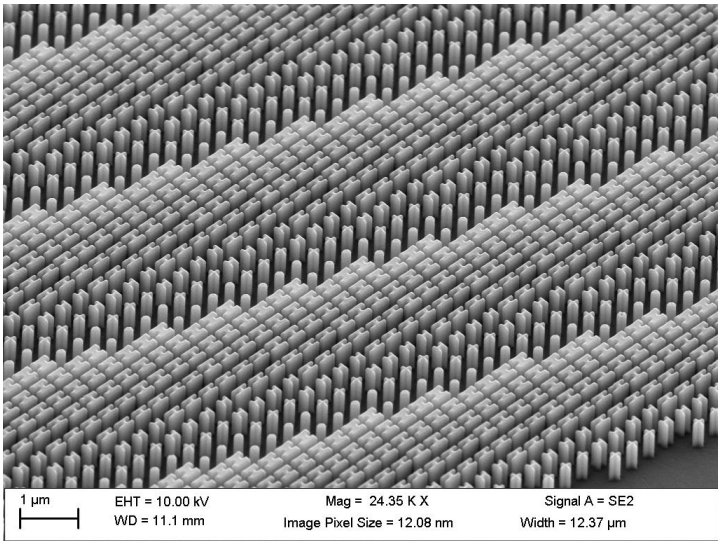
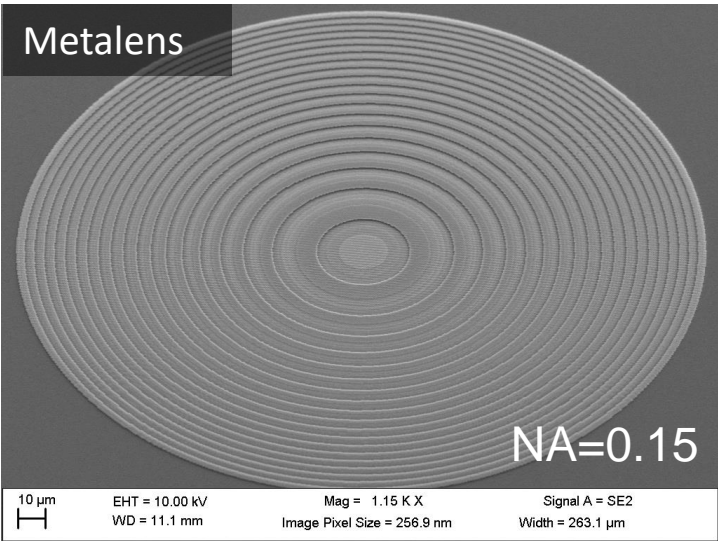


Joon-Suh Park

Broadband High-Efficiency Metalenses



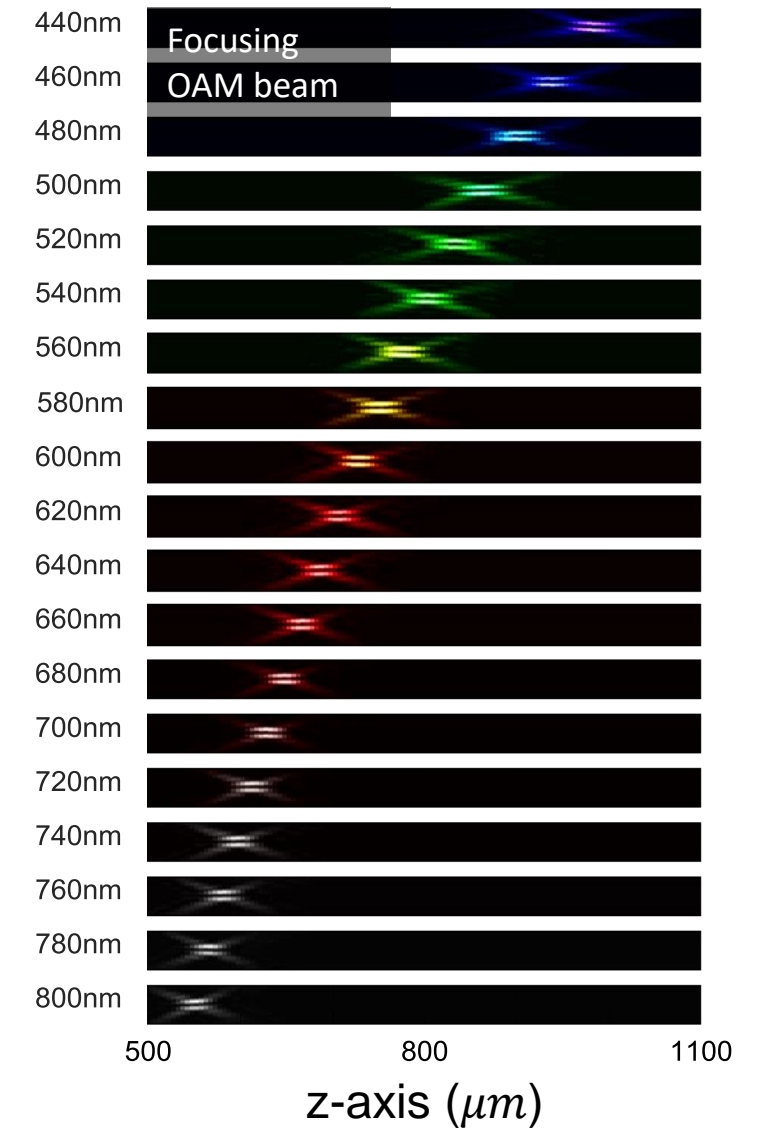
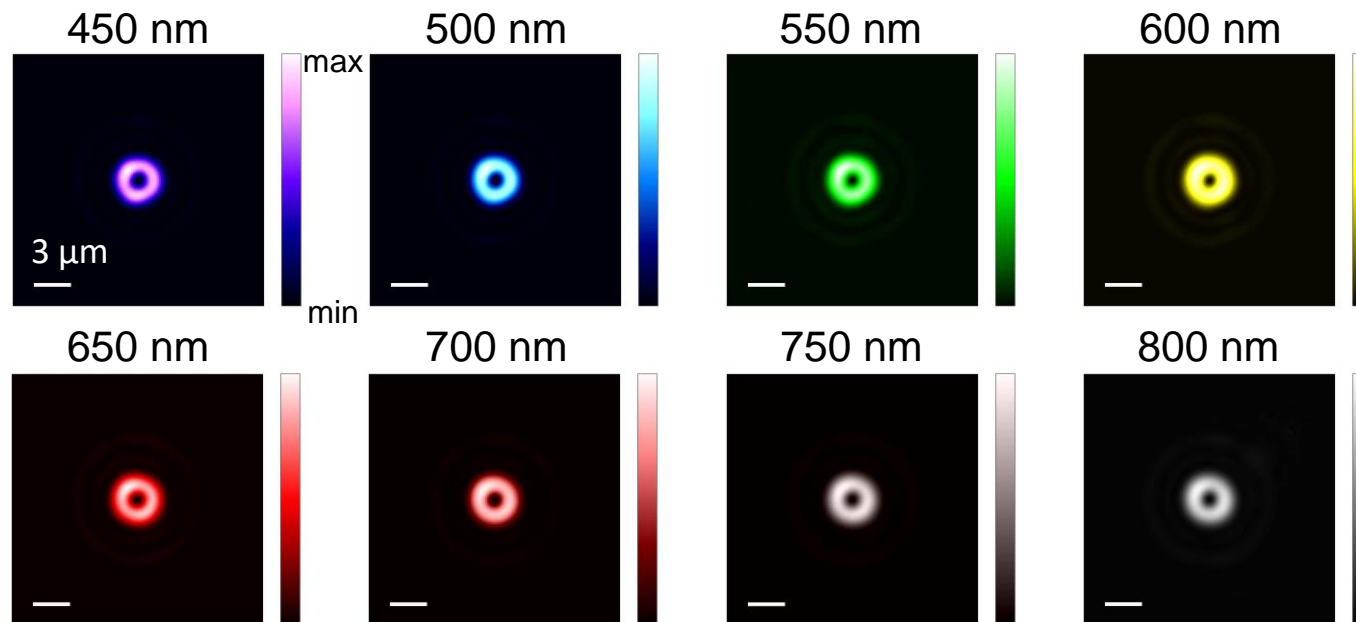
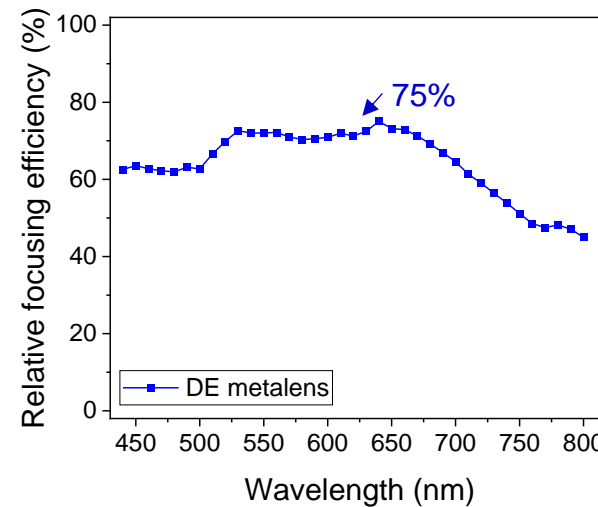
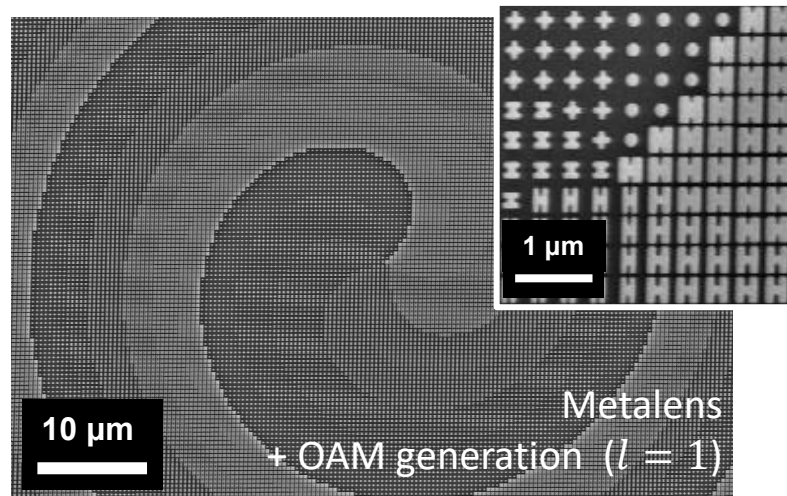
➤ Dispersion-engineered broadband high-efficiency metalenses



A Broadband, Multifunctional Vortex Metalens



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W. T. Chen*, J.-S. Park*, J. Marchioni, S. Millay, K. M. A. Yousef, and F. Capasso,
“Dispersion-engineered metasurfaces reaching broadband 90% relative diffraction efficiency,” *Nature Communications* 14 (2024).

More Dispersion Control: *Bilayer Metasurfaces (1)*



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Zhaoyi Li



Joon-Suh Park



S. D. Campbell, PSU

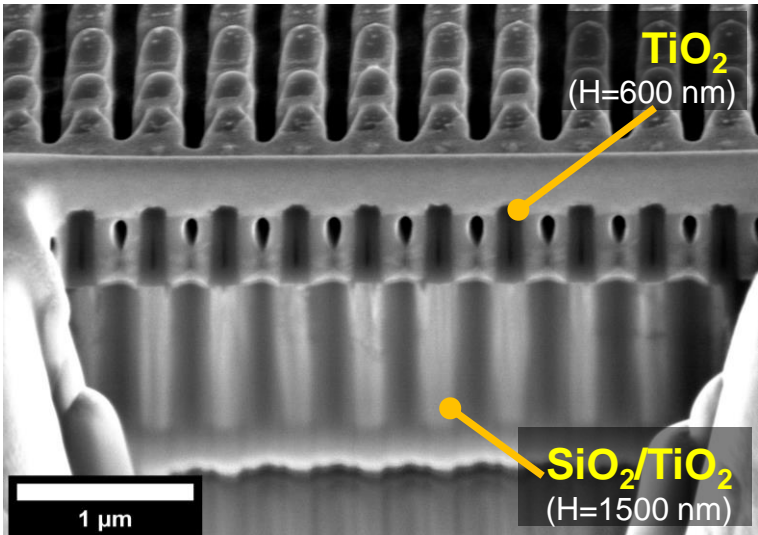
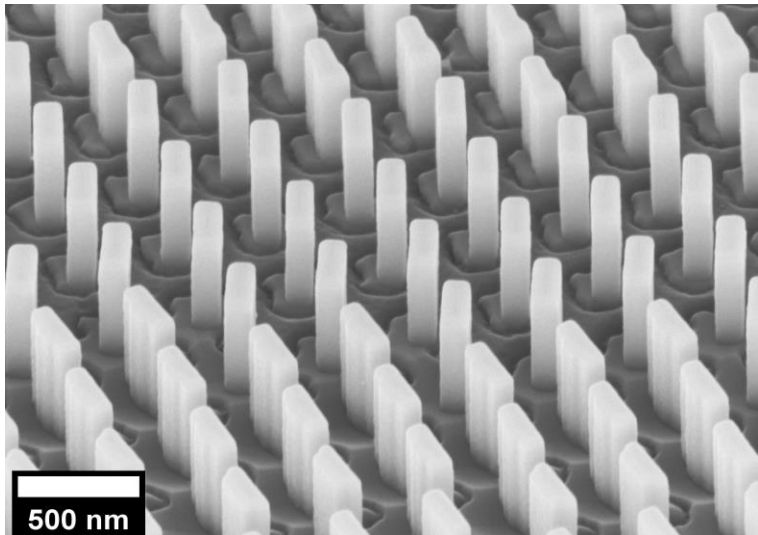
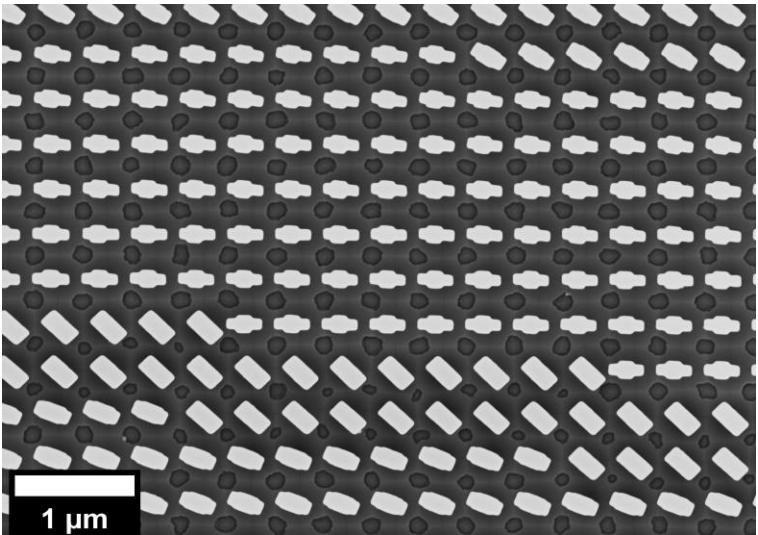
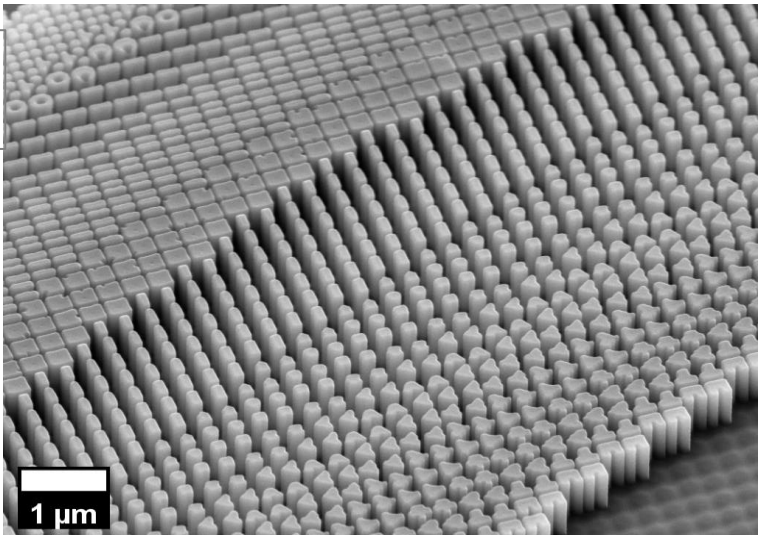
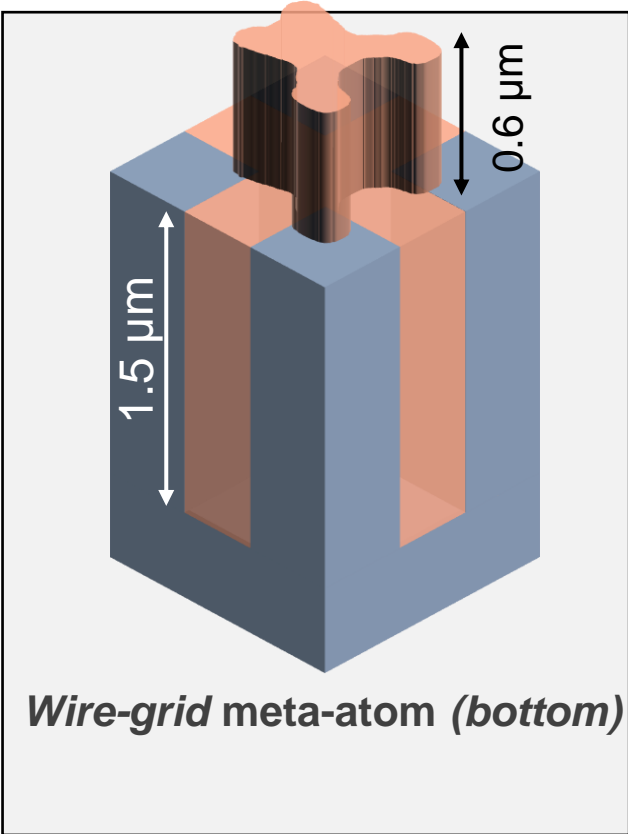


D. Werner PSU

Z. Li*, S. D. Campbell*, J.-S. Park* D. Werner
Heterogeneous Freeform Metasurfaces: A Platform for Advanced Broadband Dispersion Engineering [arXiv:2412.12028](#) (2024).

Group delay: $\frac{\partial \phi}{\partial \omega} = \frac{H}{c} n_{eff} + \frac{\omega H}{c} \frac{\partial n_{eff}}{\partial \omega}$

Free-form meta-atom (top)

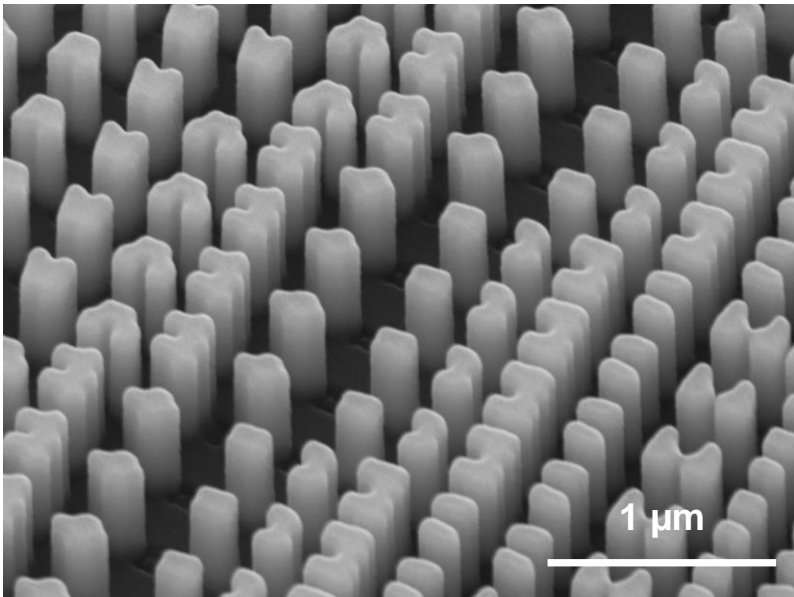
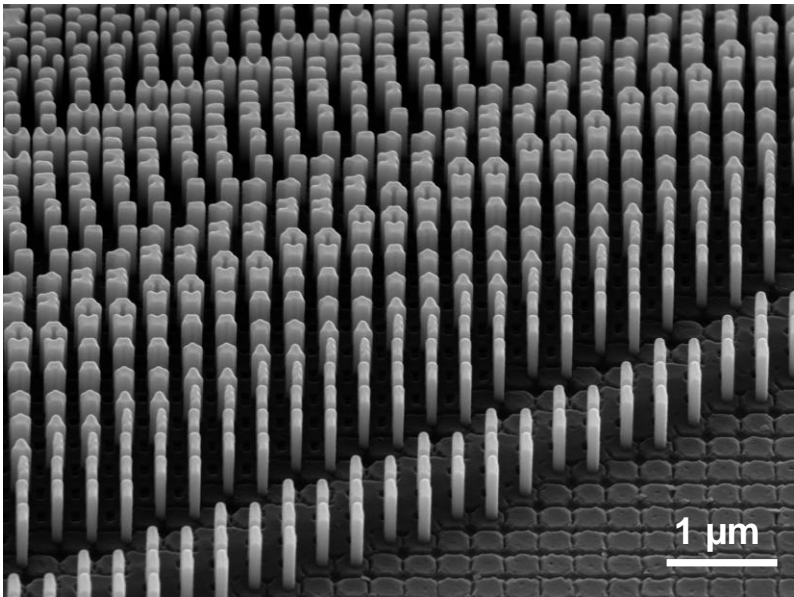
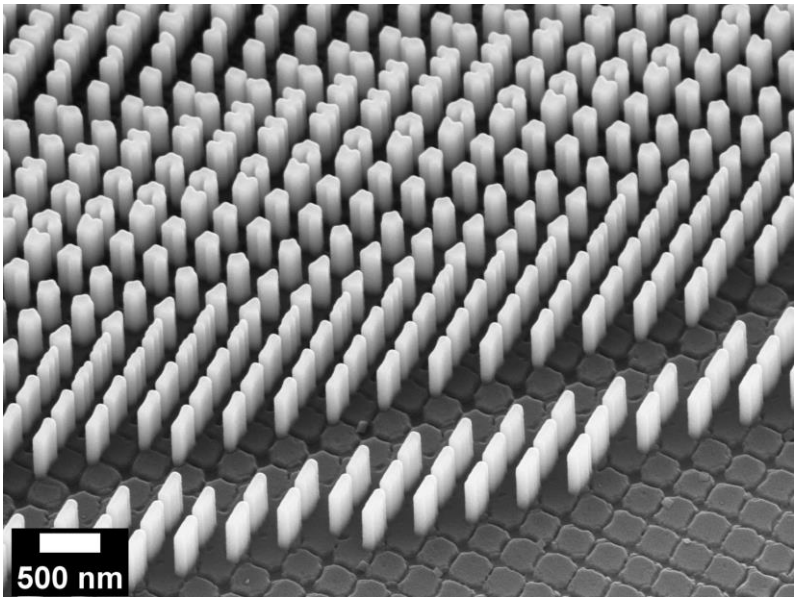
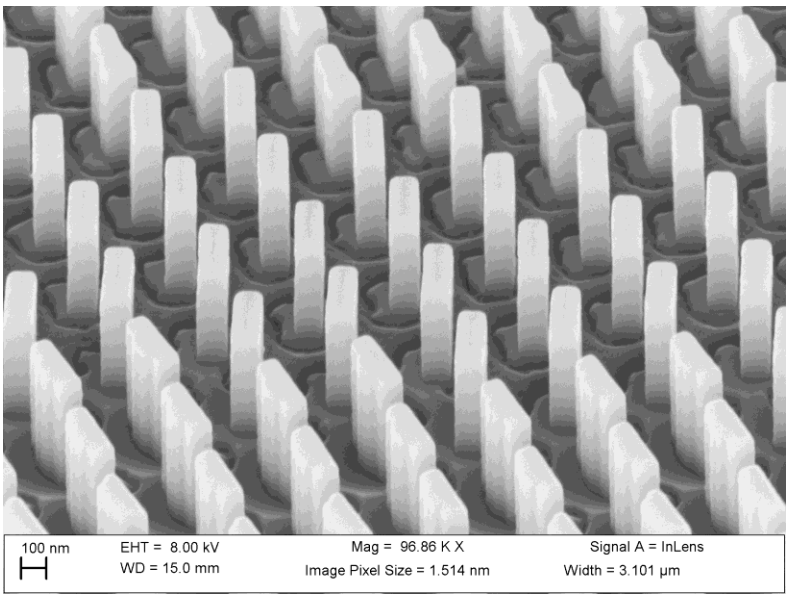
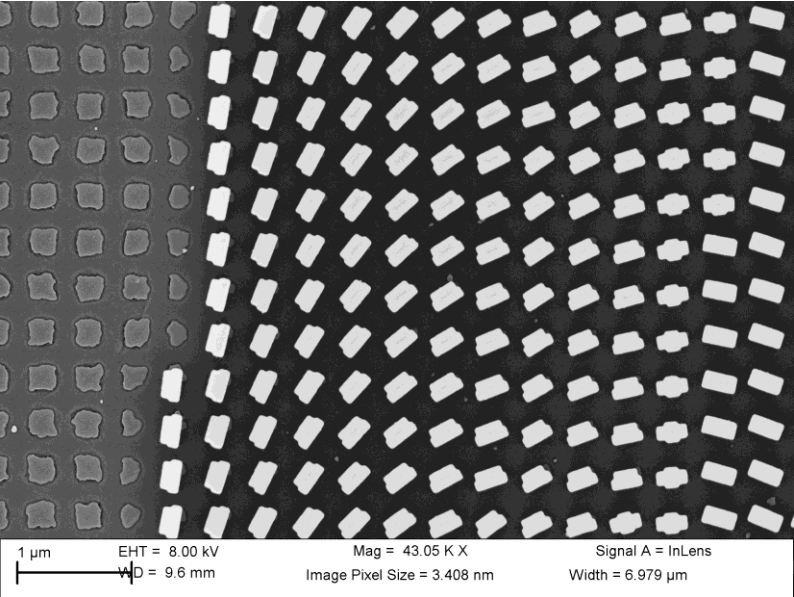
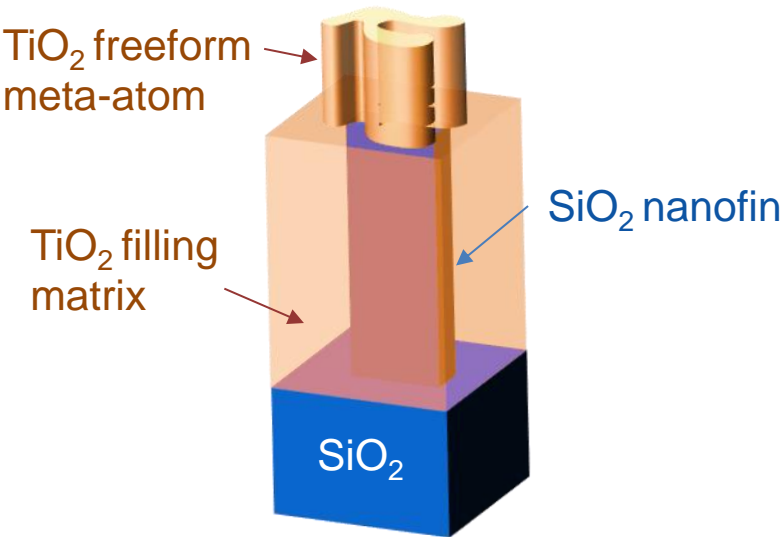


Bilayer Metasurfaces (2)



Z. Li*, S. D. Campbell*, J.-S.Park* *et al.*, *In preparation.*

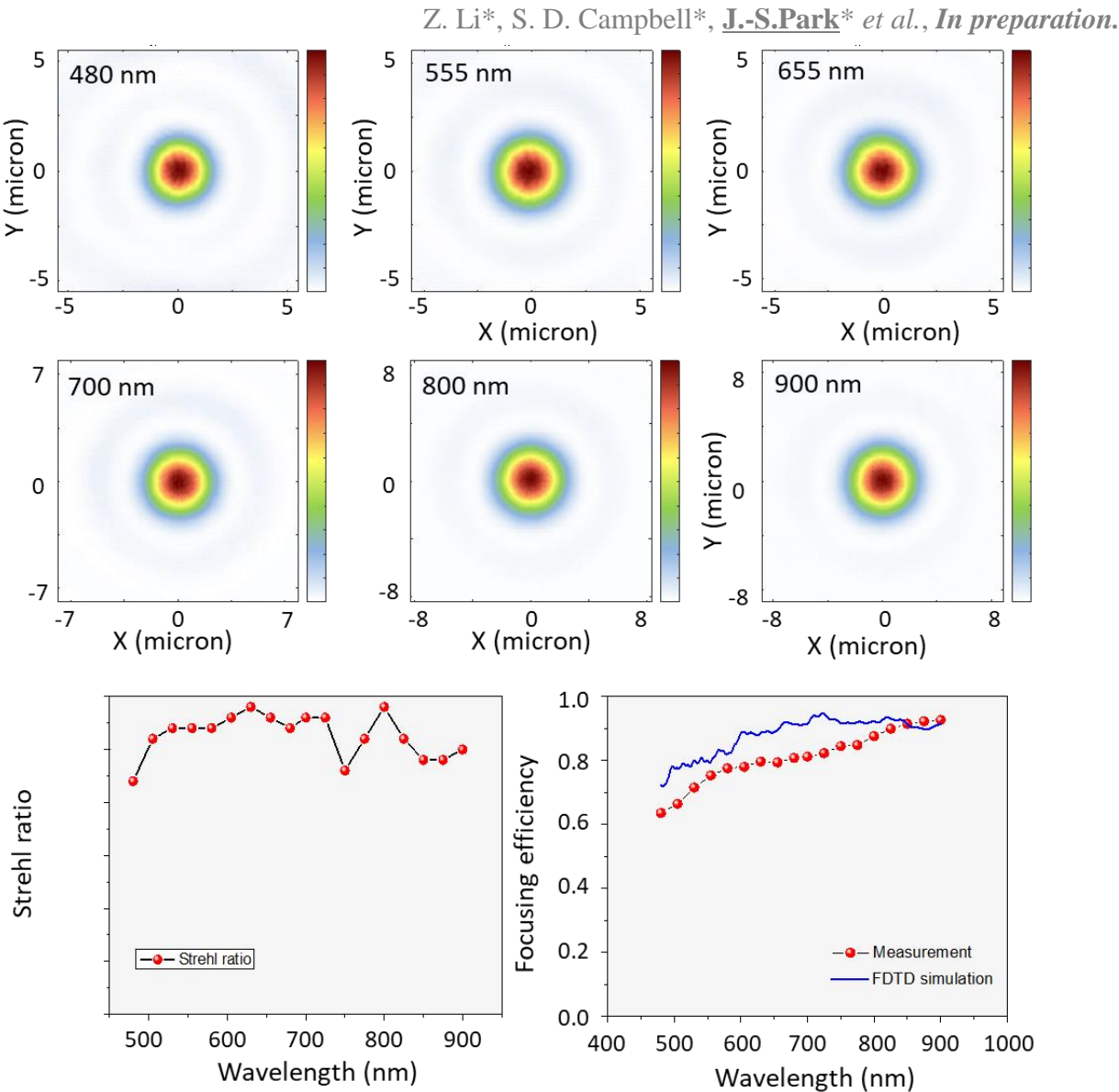
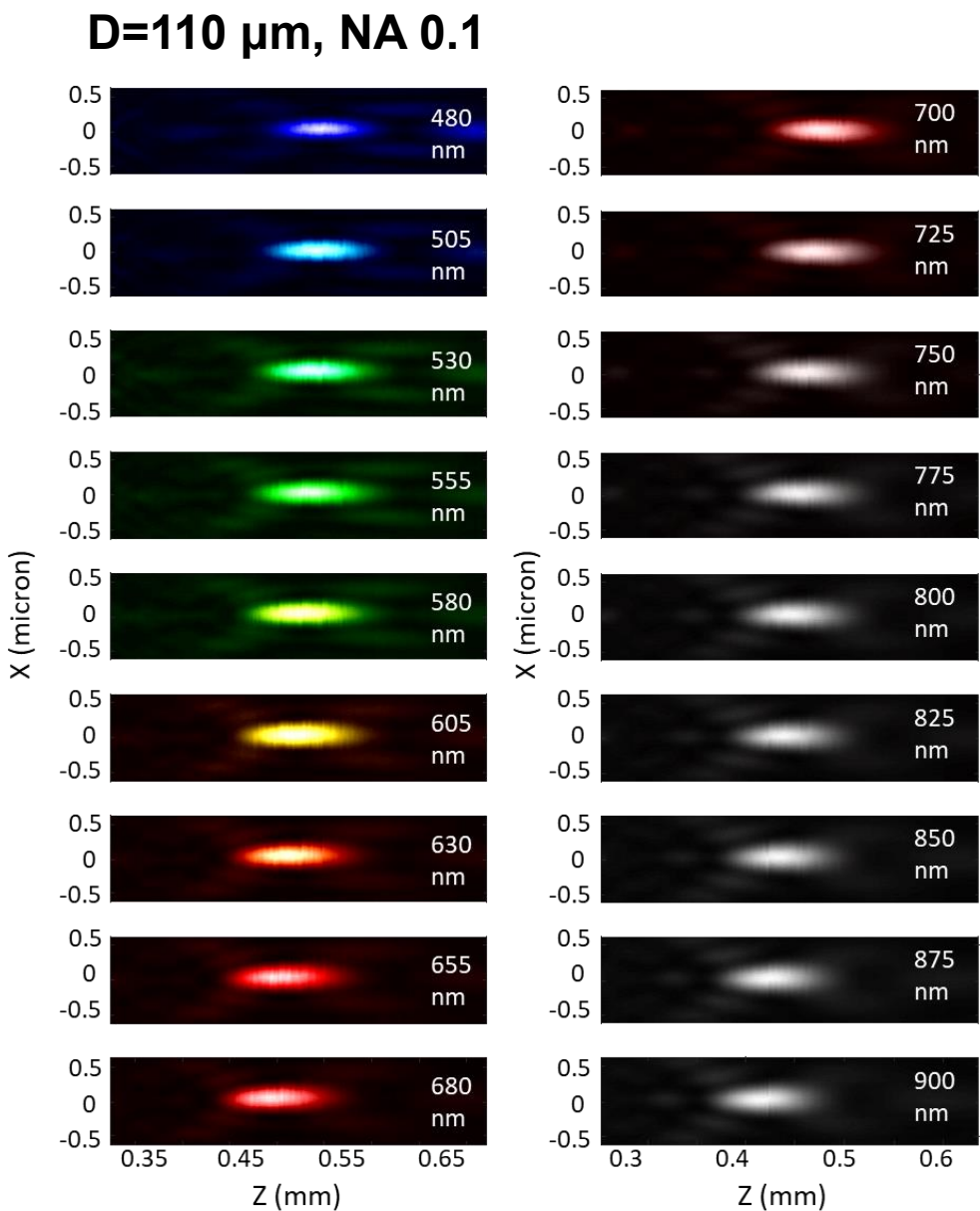
➤ Meta-atom structure



Broadband, High-efficiency, Bilayer Metalens



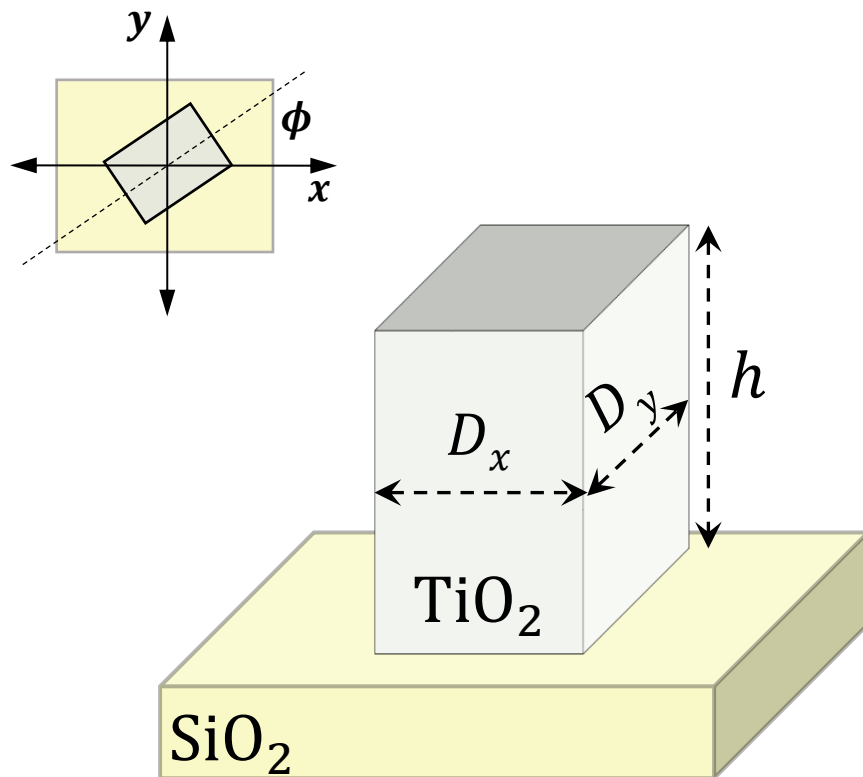
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Nearly achromatic from the visible to the near-IR

Polarization Control: The Jones matrix of a single layer metasurface

The single layer suffers from some **intrinsic limitations** related to the restricted set of allowable Jones matrices.



Each pixel modeled by 2x2 Jones matrix:

$$\tilde{J} = [R(-\phi)] \begin{bmatrix} e^{i\theta_x} & 0 \\ 0 & e^{i\theta_y} \end{bmatrix} [R(\phi)] =$$

$$= \begin{bmatrix} \cos^2(\phi)e^{i\theta_x} + \sin^2(\phi)e^{i\theta_y} & \frac{e^{i\theta_x}}{2}\sin(2\phi) - \frac{e^{i\theta_y}}{2}\sin(2\phi) \\ \frac{e^{i\theta_x}}{2}\sin(2\phi) - \frac{e^{i\theta_y}}{2}\sin(2\phi) & \cos^2(\phi)e^{i\theta_y} + \sin^2(\phi)e^{i\theta_x} \end{bmatrix}$$

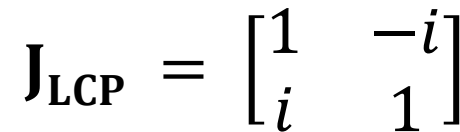
The Jones matrix must be symmetric.

The diagram illustrates two sets of 3x3 matrices, each set enclosed in a colored circle (green on the left, red on the right). Each set contains 12 matrices arranged in a 4x3 grid. The matrices are labeled with elements j_{11} , j_{12} , j_{21} , and j_{22} .

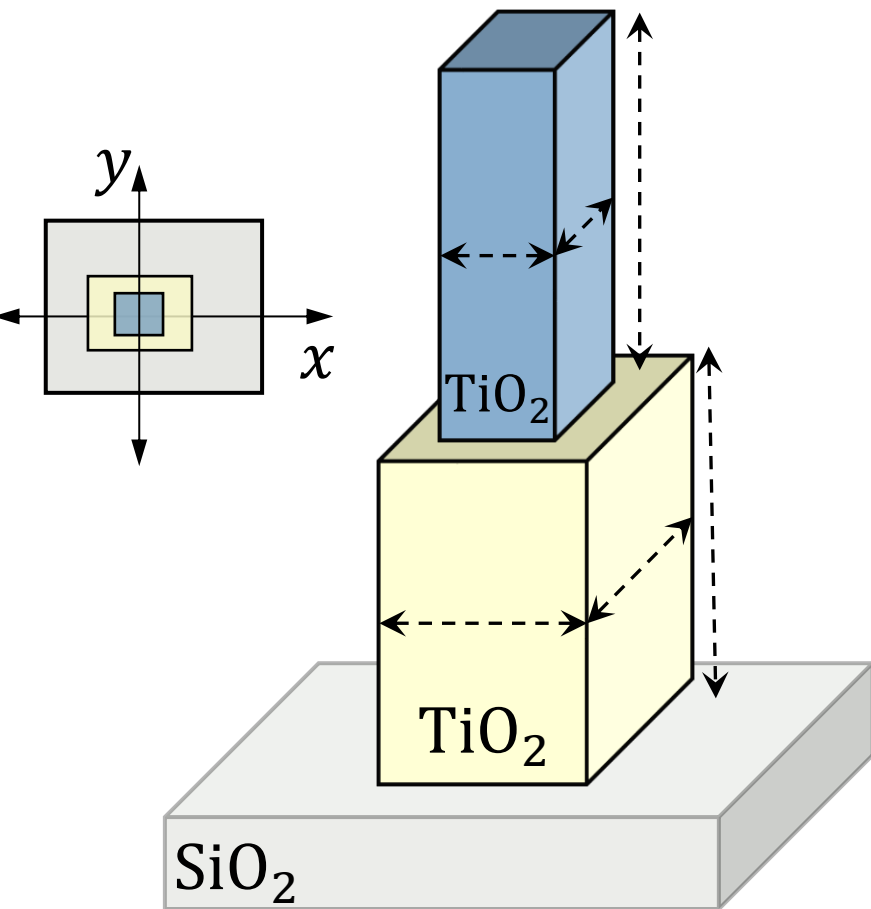
Left Set (Green Circle): The matrices are arranged in a 4x3 grid. The first column contains matrices with j_{11} and j_{21} in the first column and j_{12} and j_{22} in the second column. The second column contains matrices with j_{11} and j_{21} in the first column and j_{12} and j_{22} in the second column. The third column contains matrices with j_{11} and j_{21} in the first column and j_{12} and j_{22} in the second column. The fourth column contains matrices with j_{11} and j_{21} in the first column and j_{12} and j_{22} in the second column.

Right Set (Red Circle): The matrices are arranged in a 4x3 grid. The first column contains matrices with j_{21} and j_{12} in the first column and j_{21} and j_{22} in the second column. The second column contains matrices with j_{21} and j_{12} in the first column and j_{21} and j_{22} in the second column. The third column contains matrices with j_{21} and j_{12} in the first column and j_{21} and j_{22} in the second column. The fourth column contains matrices with j_{21} and j_{12} in the first column and j_{21} and j_{22} in the second column.

$$\mathbf{J}_{\text{RCP}} = \begin{bmatrix} 1 & i \\ -i & 1 \end{bmatrix}$$



Free-standing bilayer metasurfaces



$$J_{\text{bilayer}} = J_{\text{bottom}} \times J_{\text{top}}$$

$$= \begin{bmatrix} J_{11,\text{bottom}} & J_{12,\text{bottom}} \\ J_{21,\text{bottom}} & J_{22,\text{bottom}} \end{bmatrix} \times \begin{bmatrix} J_{11,\text{top}} & J_{12,\text{top}} \\ J_{21,\text{top}} & J_{22,\text{top}} \end{bmatrix} =$$

$$\begin{bmatrix} J_{11,\text{bilayer}} & J_{12,\text{bilayer}} \\ J_{21,\text{bilayer}} & J_{22,\text{bilayer}} \end{bmatrix}$$

The Jones matrix of a bilayer metasurface can be made **not symmetric**.

Can we **neglect the coupling** between the two nanofins? Yes

Situations to avoid

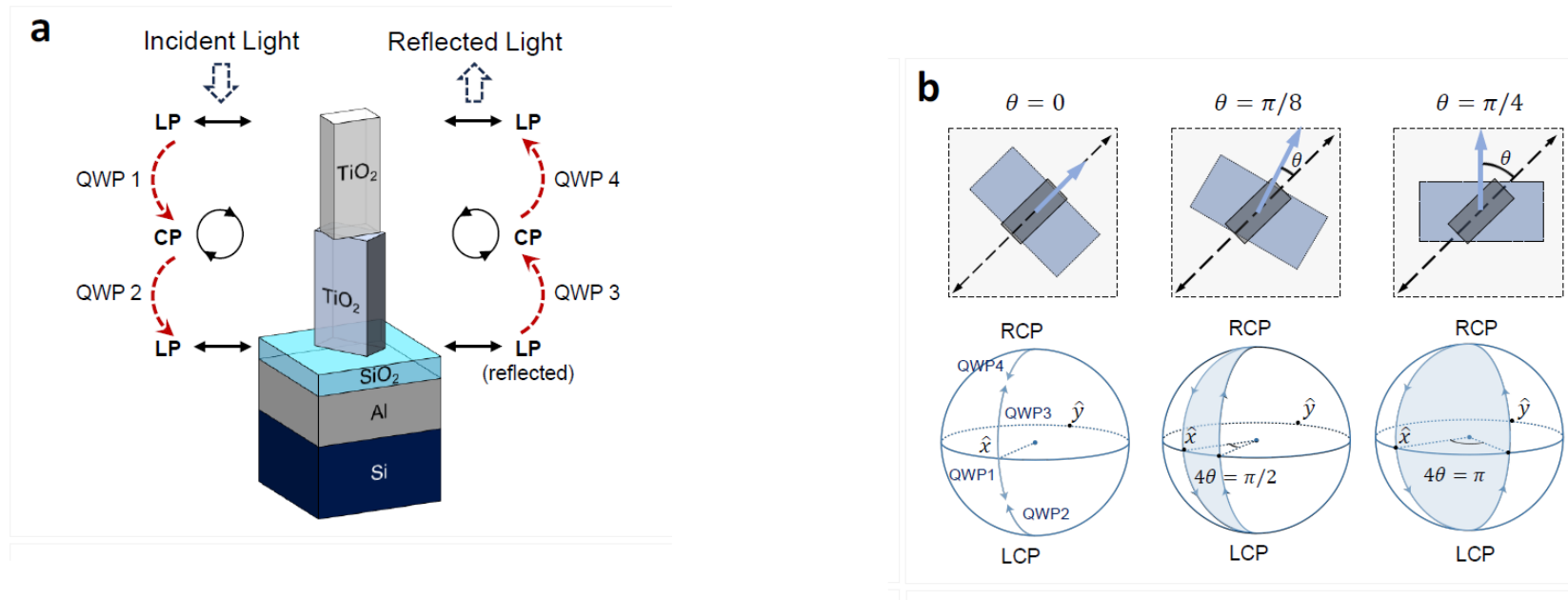
- Geometries that involve large back reflections (small spatial overlap between top and bottom nanofins);
- Geometries that lie close to resonances.

A. Palmieri, A.H. Dorrah, J. Yang, J. Oh, P. Dainese, and F. Capasso. “*Do dielectric bilayer metasurfaces behave as a stack of decoupled single layer metasurfaces ?*” Opt. Express, 32, 8146 (2024)

Geometric (Berry) phase bilayer metasurface



Bilayer metasurface enable polarization transformation that are impossible with single layer metasurfaces:
e.g. Imparting geometric phase to linearly polarized light



A rotation angle θ gives rise to a solid angle of 4θ , thereby imparting a geometric phase of $\pm 2\theta$ on x- and y-polarized light, respectively. By locally changing the relative rotation angle between the top and bottom nanofins, point-by-point, across the metasurface, a 1D blazed grating and a vortex can be designed

A. Dorrah J-S Park, A. Palmieri, F. Capasso *Free-standing bilayer metasurfaces in the visible* arXiv:2409.16969 (2024)



Alfonso Palmieri

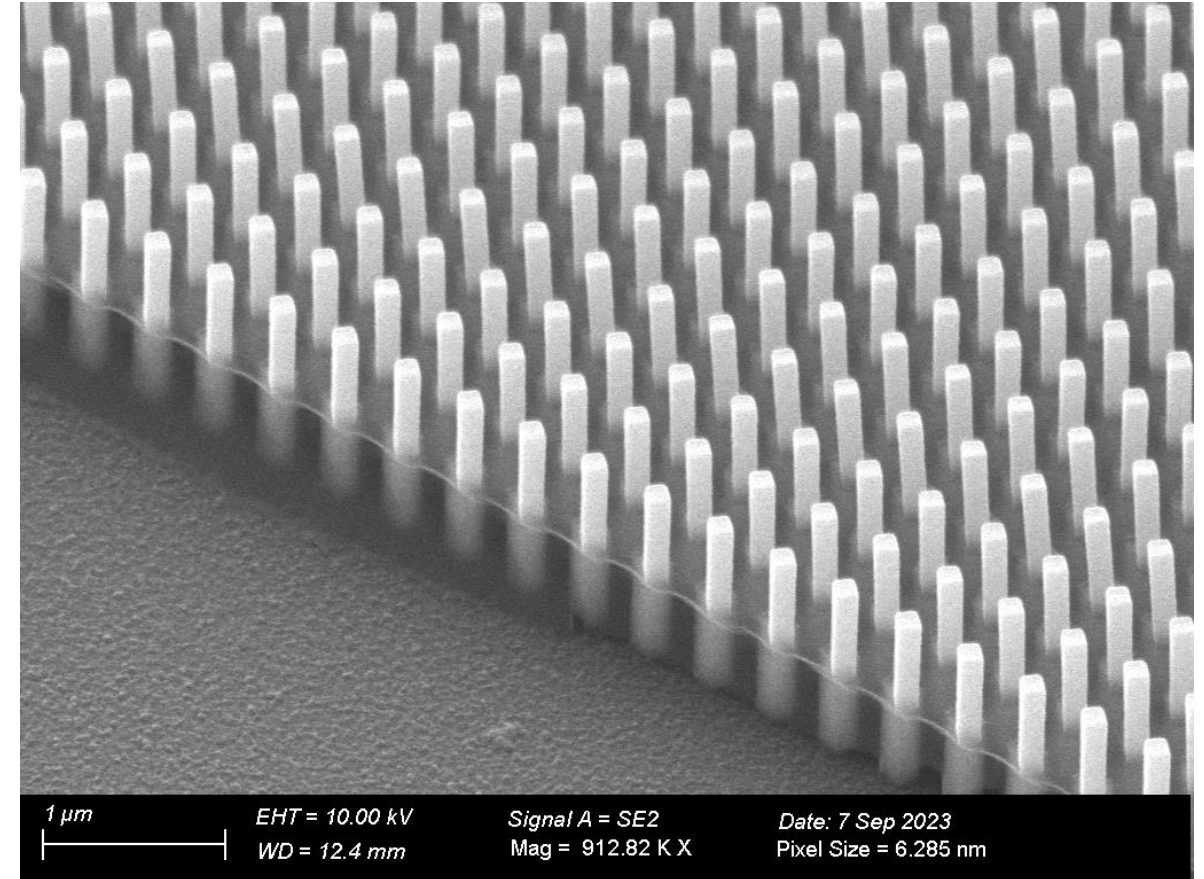
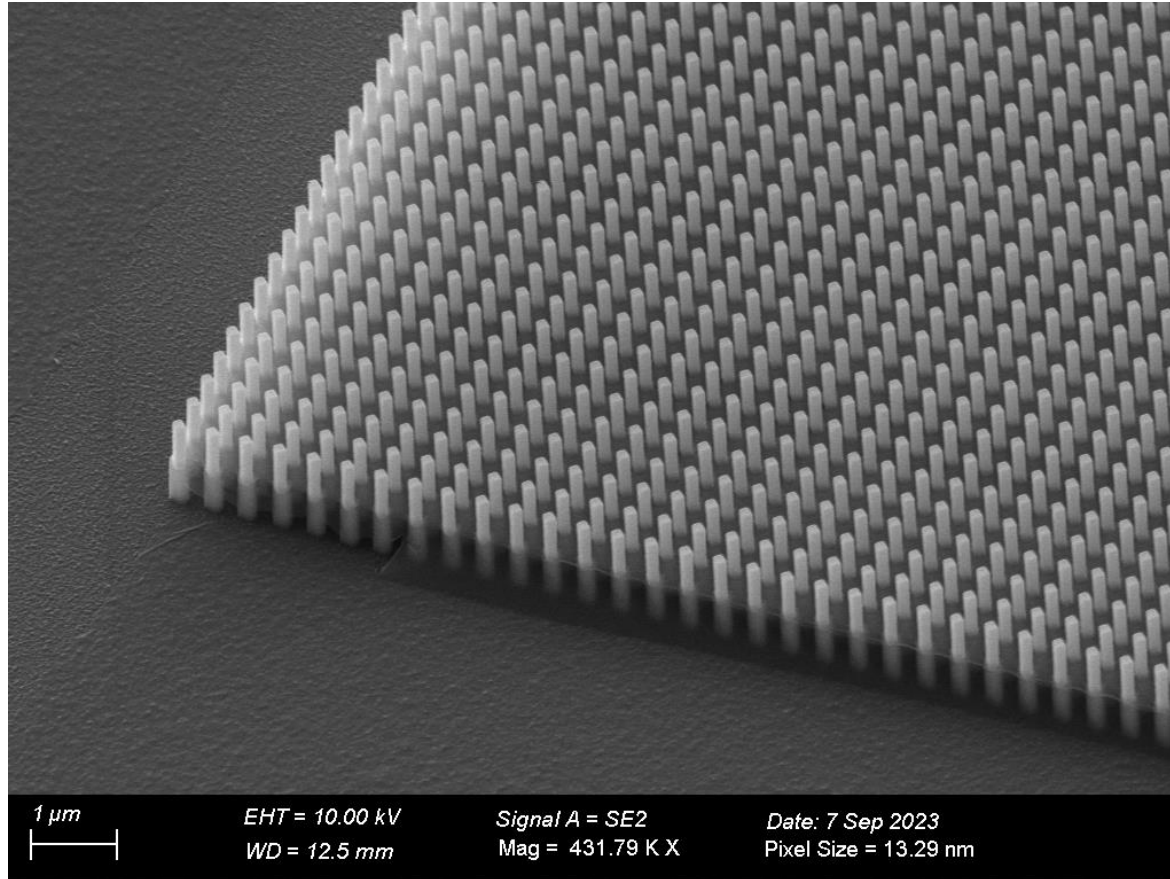


Ahmed Dorrah

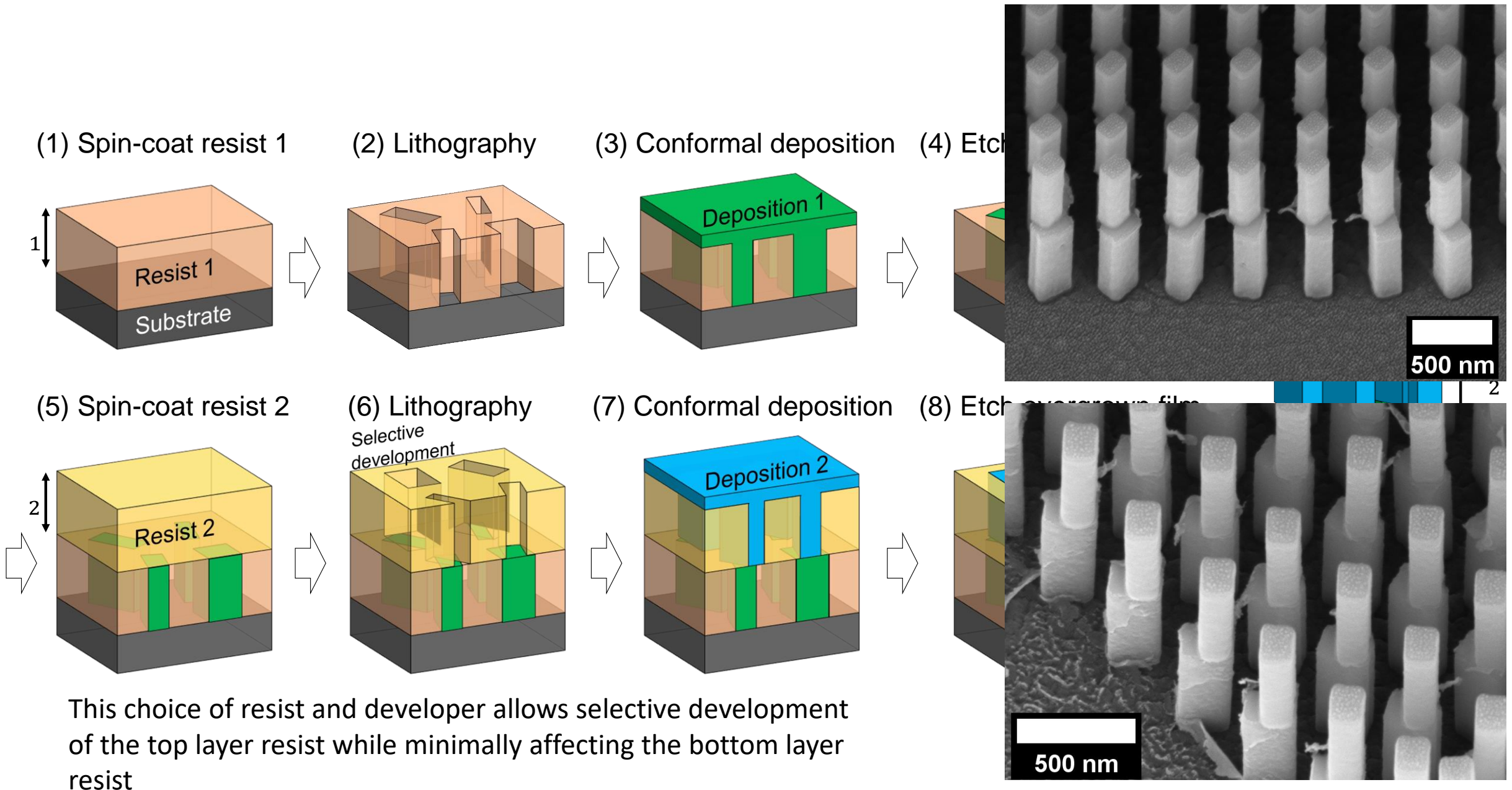


Joon-Suh Park

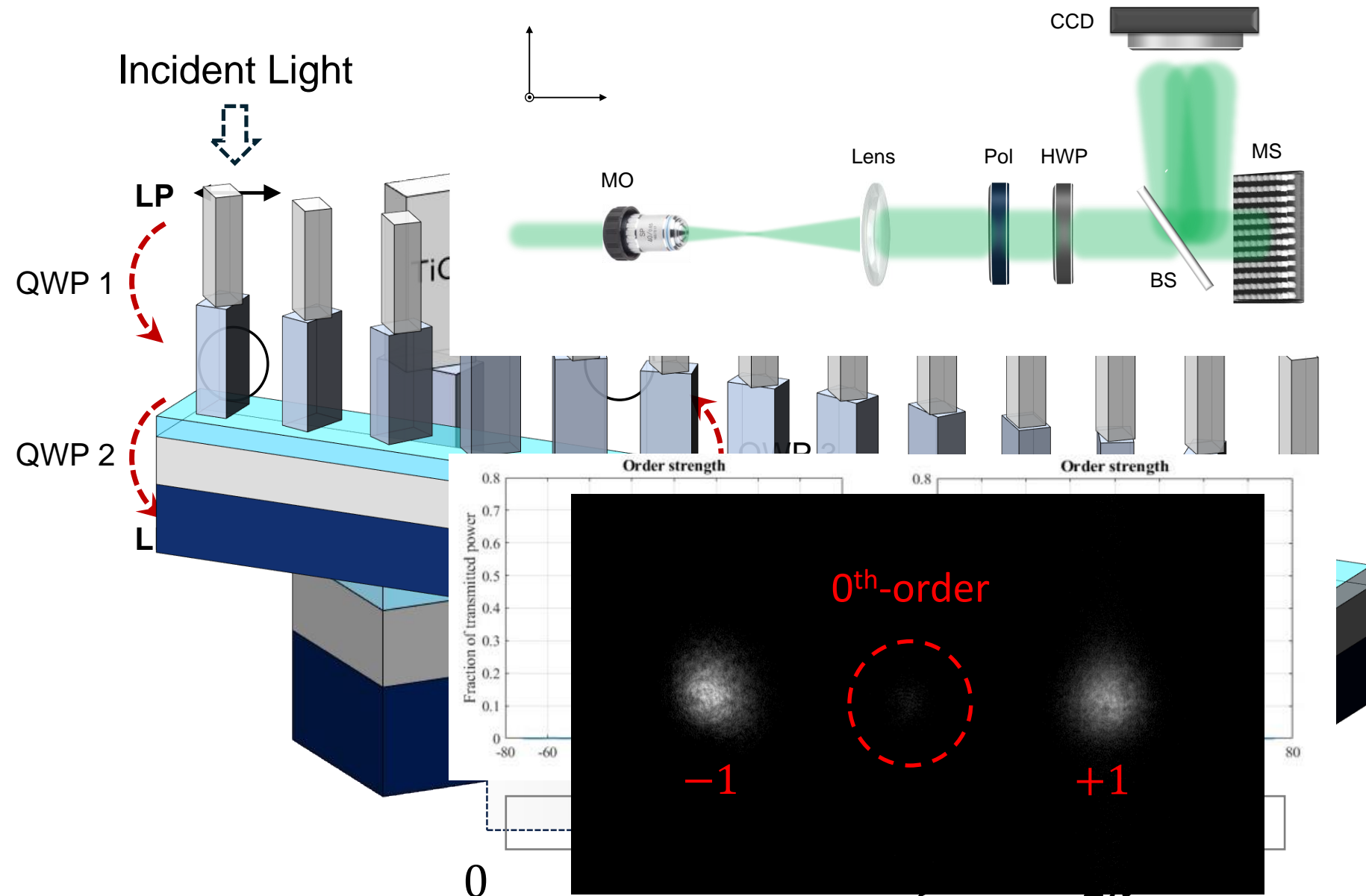
The first free standing bilayer metasurface - SEM



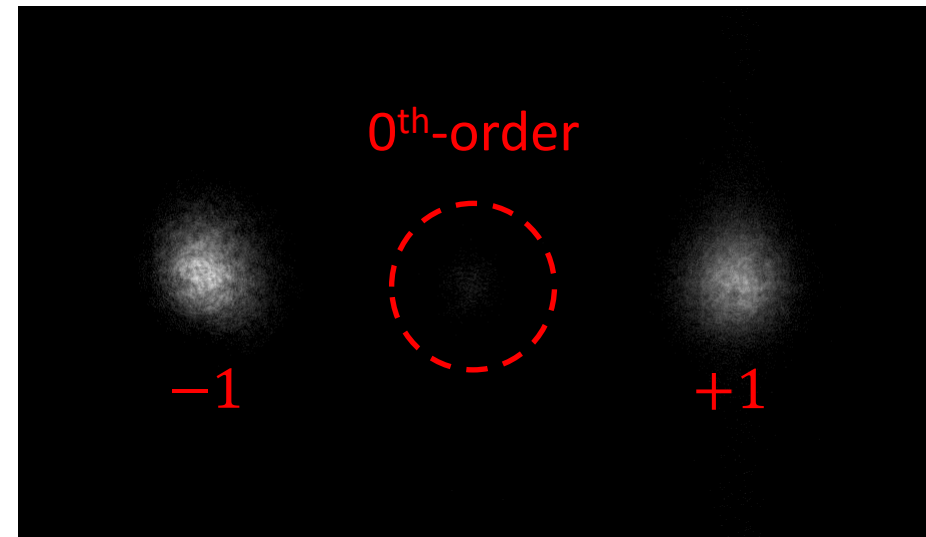
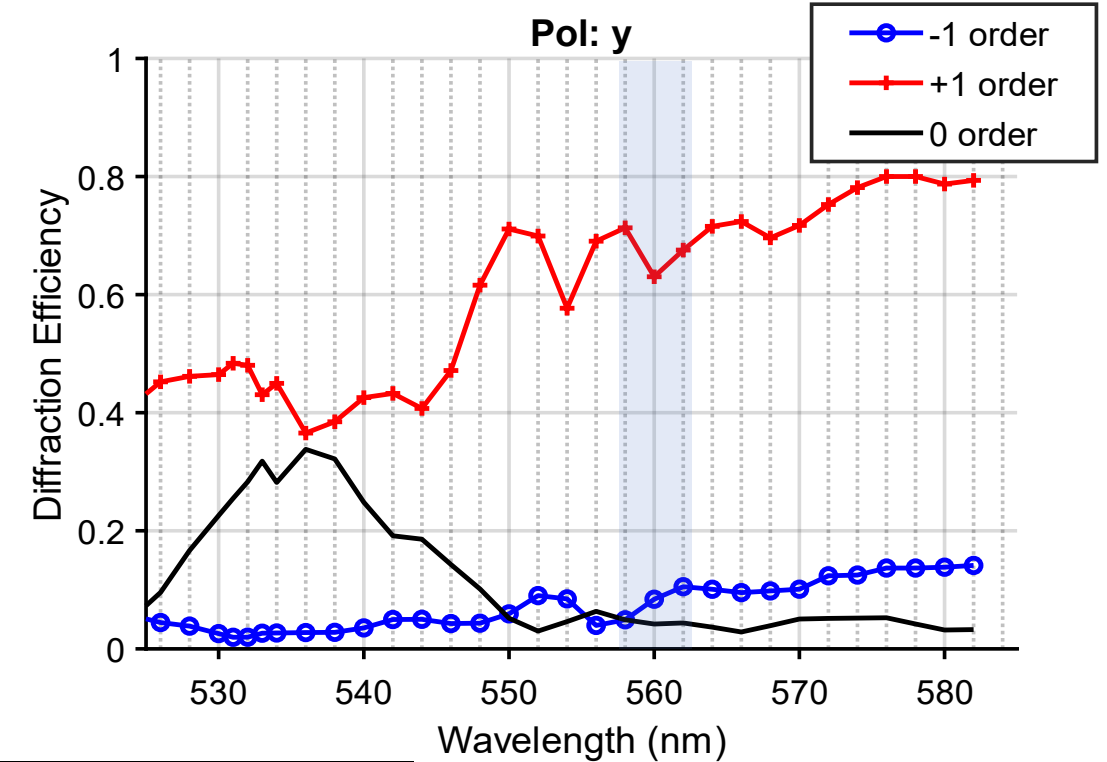
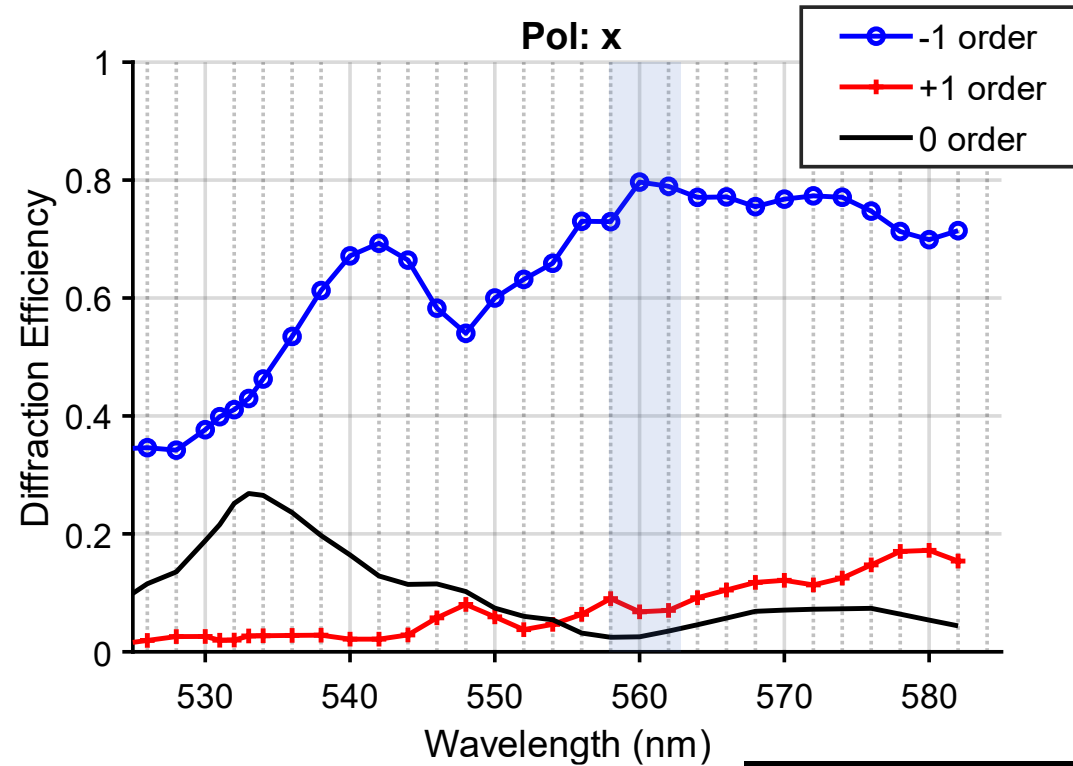
Fabrication process for free-standing bilayer metasurface



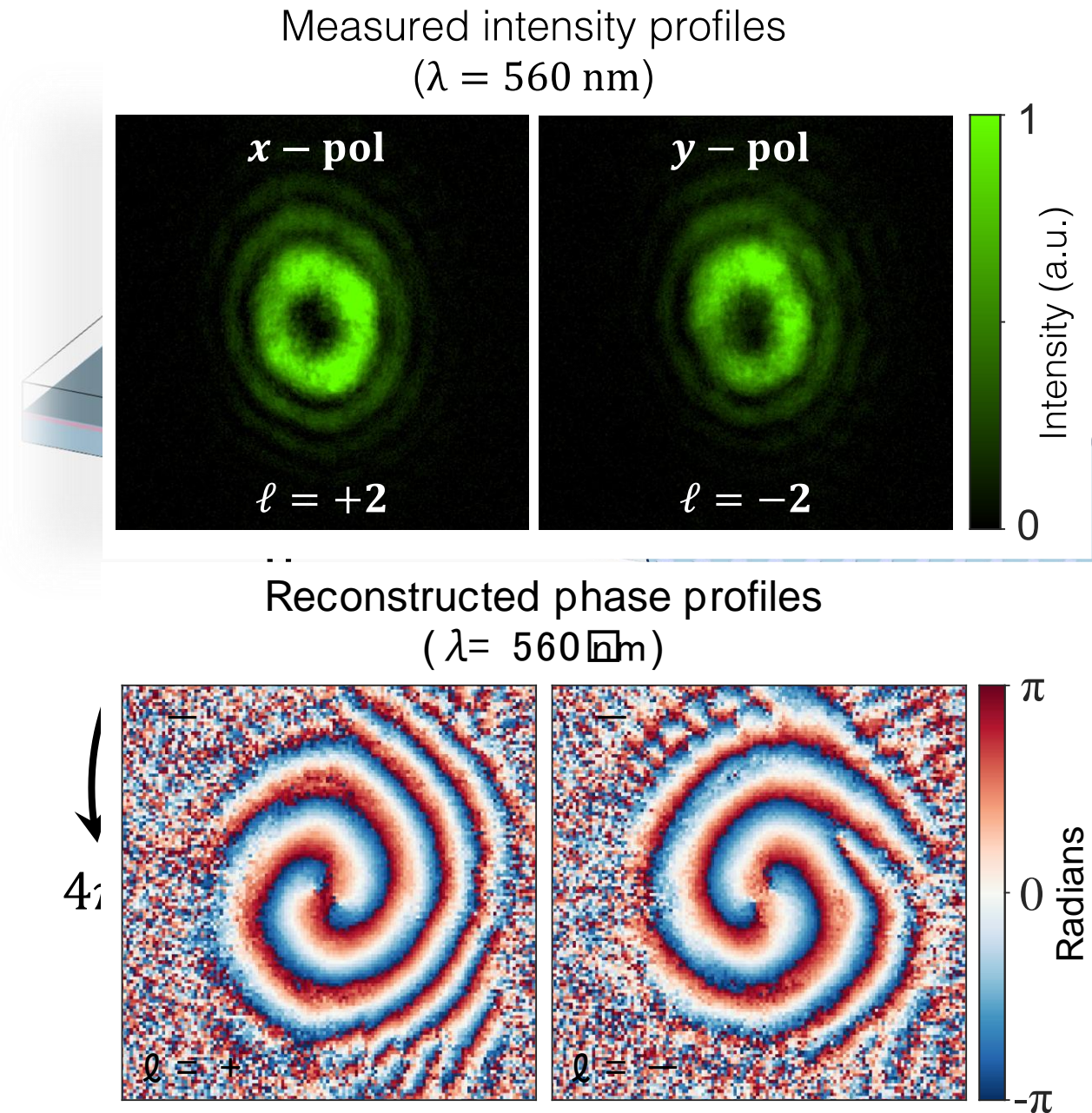
Free-standing bilayer metasurface: Grating



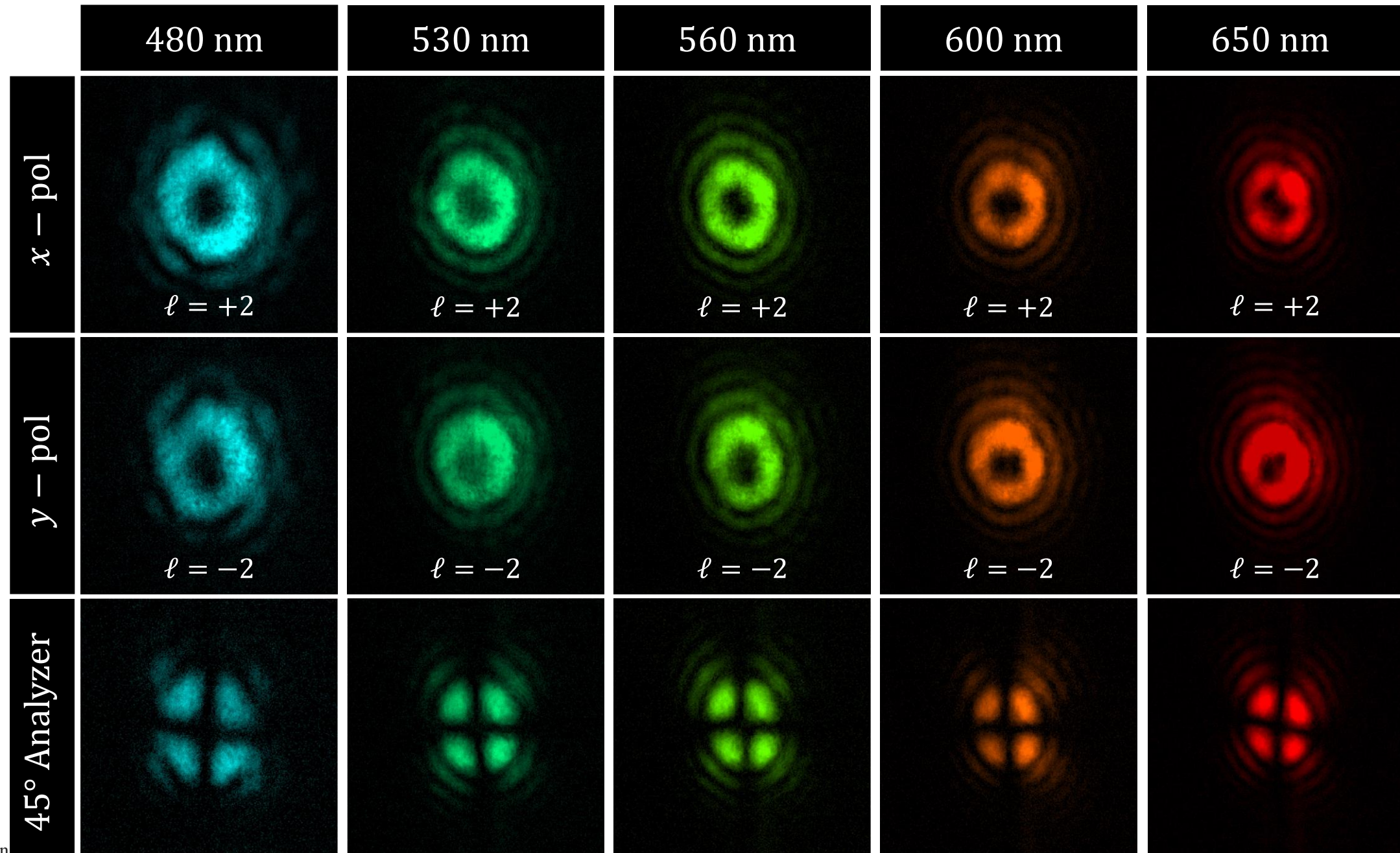
Free-standing bilayer metasurface: Grating measurement



Free-standing bilayer metasurface: Vortex generation



Free-standing bilayer metasurface: OAM measurements



In preparation

Summary



- Bilayer metasurface greatly expand the design space of metasurfaces for structured light
- Shape optimized metasurfaces:
 - High efficiency broadband operation
 - Broadband optical vortex focusing
- Free standing bilayer Berry metasurfaces offer new ways to control polarization
 - Polarization sensitive beam deflector
 - Polarization control of optical vortices

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Alfonso Palmieri



Ahmed Dorrah



Wei Ting Chen



Zhaoyi Li



Marcus Ossiander



S. W. Daniel Lim



Sawyer D. Campbell,
PSU



Douglas Werner,
PSU

