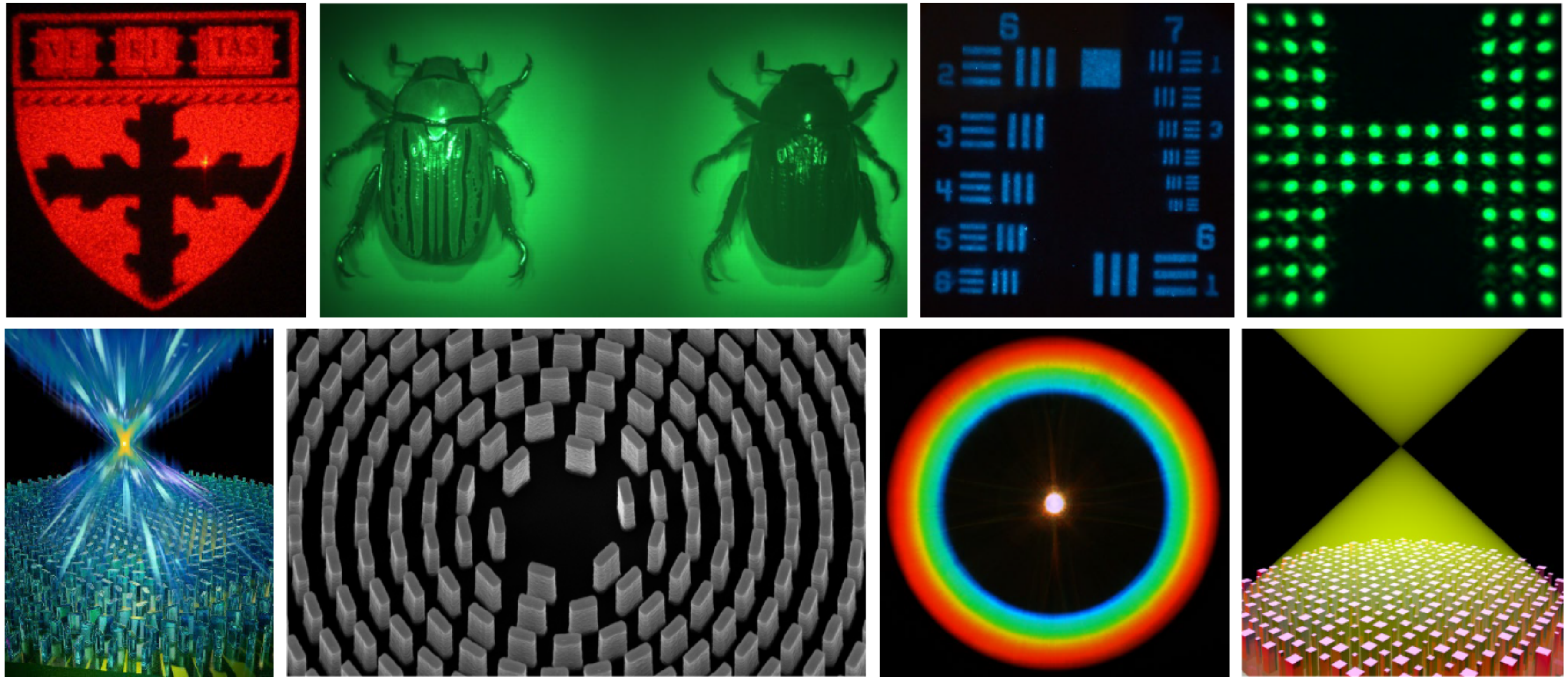
Multifunctional Metaoptics



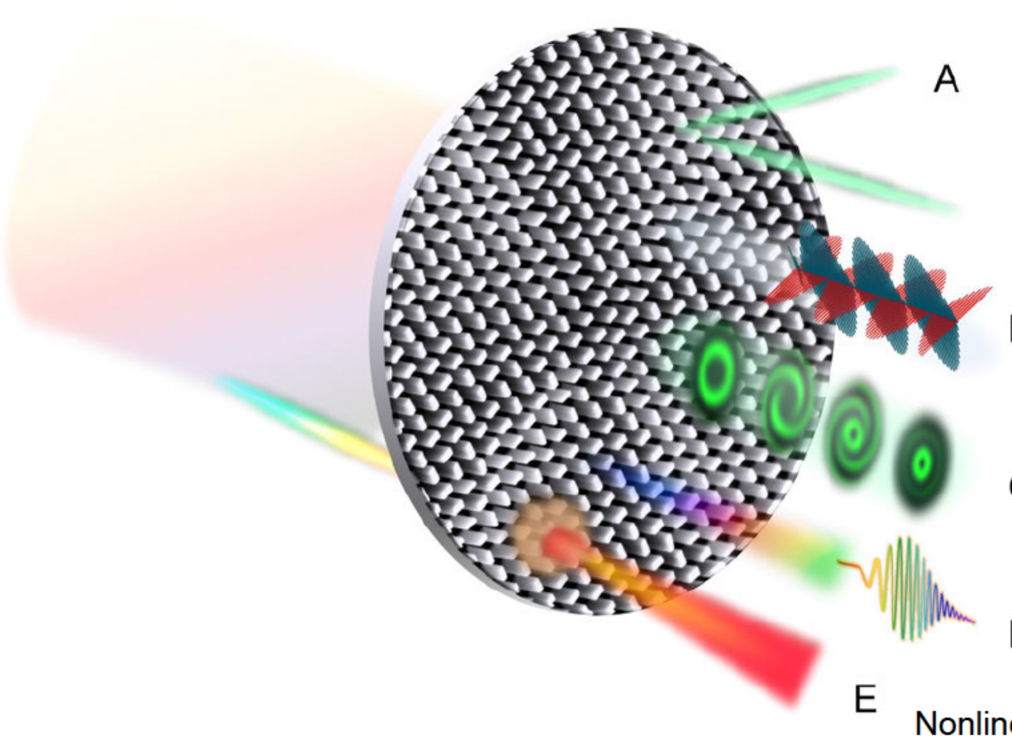
Optica Holography and Diffractive Optics Technical Group Webinar
March 4, 2024

Federico Capasso

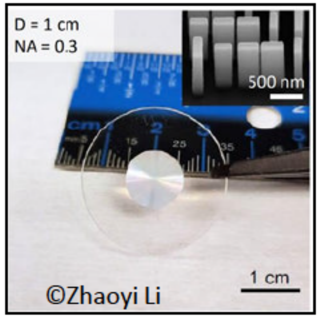
DARPA
Office of Naval Research Science & Technology ONR
Air Force Office of Scientific Research United States Air Force
NSF
NASA
Center for Nanoscale Systems Harvard University

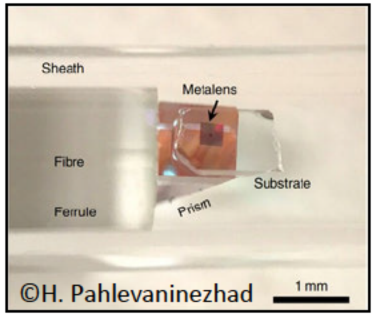
Capasso Group
Harvard School of Engineering and Applied Sciences

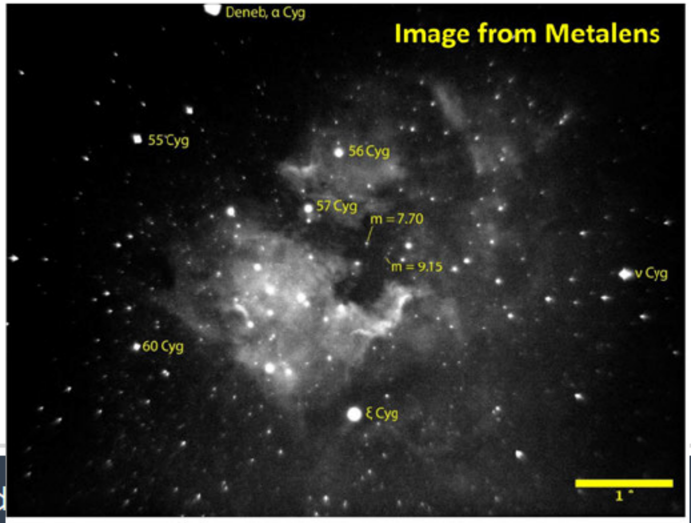
Multifunctional Metaoptics



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

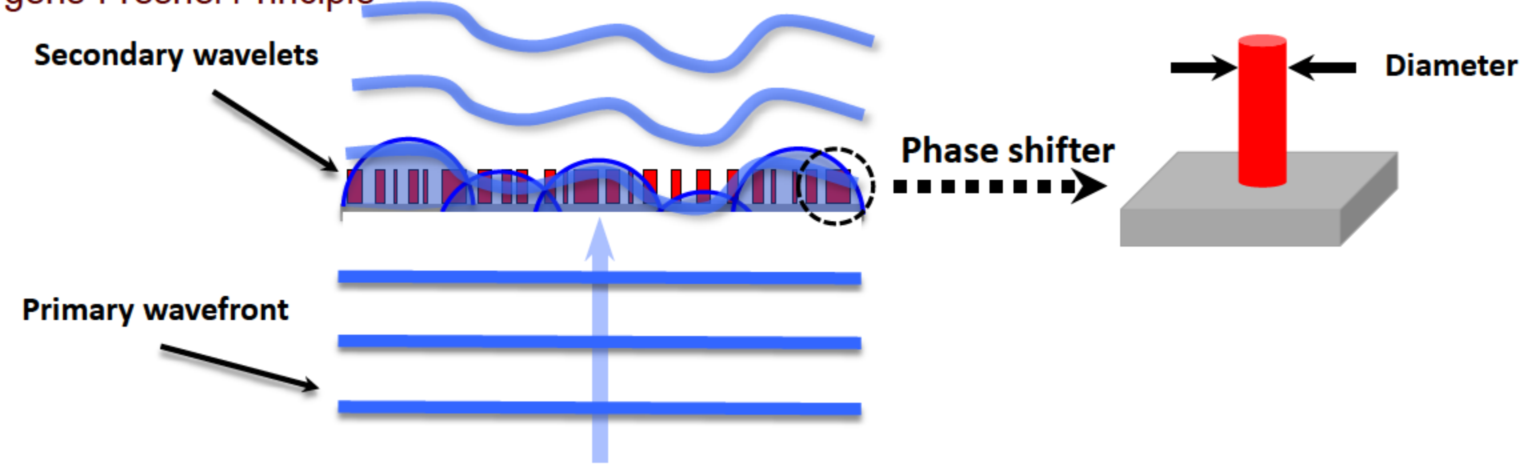






Metasurfaces: complete wavefront control

- Huygens-Fresnel Principle



Benefits

- **Straight-Forward Fabrication**
  - Lithographically defined: same technology of chip making
- **Compact**
  - Optically thin, small footprint, capability to be vertically integrated
    ease of optical alignment
- **Unprecedented Control of Dispersion: local design of the effective refractive index**
- **Overcome Limitations of Conventional Optics**
  - Aberrations, multifunctionality

W T Chen, A. Y. Zhu, and F. Capasso. "Flat optics with dispersion-engineered metasurfaces." Nature Reviews Materials, 5, 604 (2020)

Vision for Flat Optics based on Metasurfaces

F. Capasso, *Nanophotonics*, **6** 953 (2018)

- **Metasurfaces provide arbitrary control of the wavefront (phase, amplitude and polarization)**
- **Metasurfaces enable flat optics:** compact, thinner, easier fabrication and alignment

- **Multifunctionality: single flat optical components can replace multiple standard components**

- **Flat Optics for a wide range of optical components** (lenses, holograms, polarizers, phase plates, etc.) and applications: machine vision, biomed imaging, drones, polarimetry, polarization sensitive cameras
- **Same foundries will manufacture camera sensor and lenses using same technology (deep-UV stepper)** CMOS compatible flat optics platform for high volume markets:
  Examples: lenses in cell phone camera modules will be replaced by metalenses fabricated by DUV lithography (same foundry that makes the sensor chip)
  Displays, wearable optics (augmented reality).

- **Metasurfaces can generate arbitrary vector beams** (structured light) well beyond the capabilities of SLM
- **Importance of inverse design, co-design of hardware & software, impact of AI on optics**

Metasurfaces by DUV Lithography

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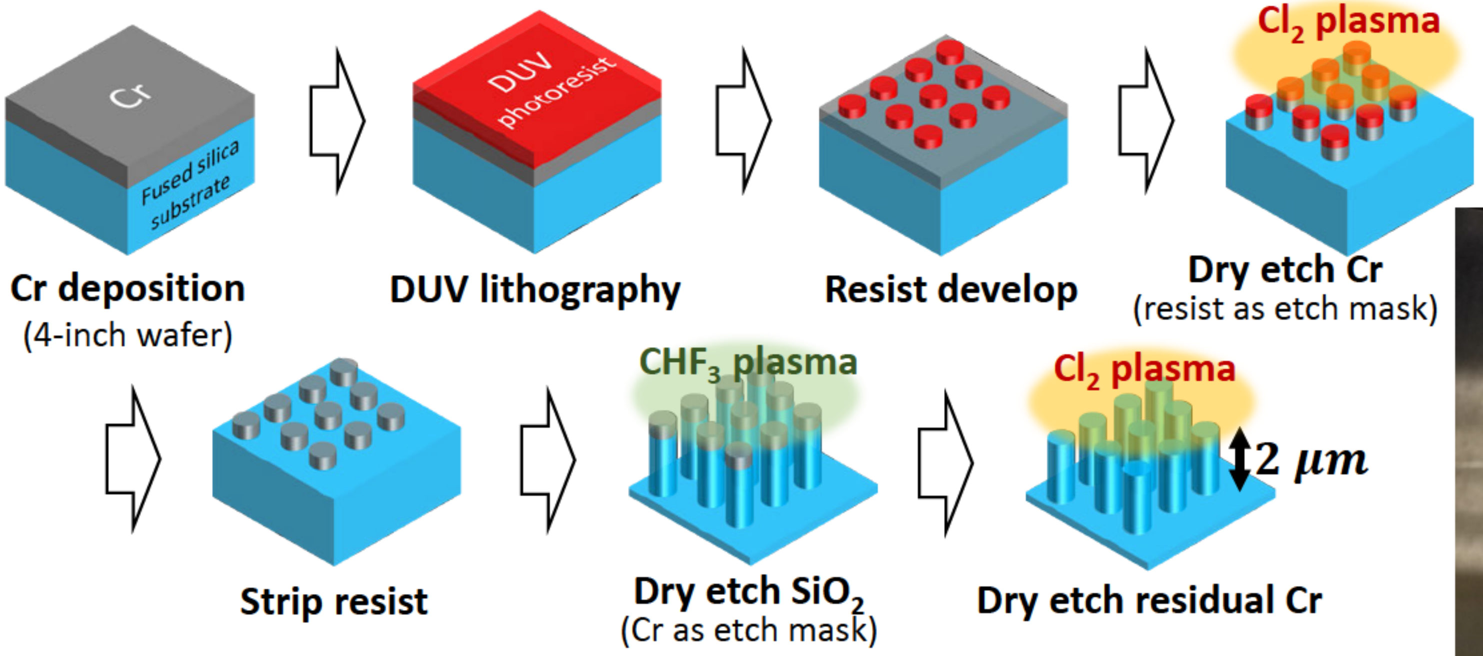
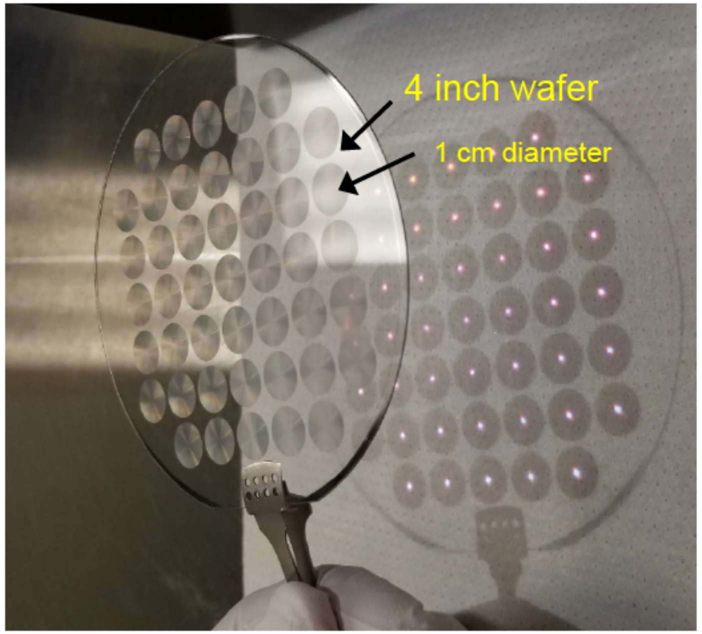
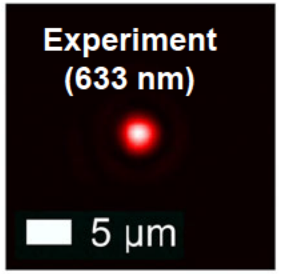
School of Engineering
and Applied Sciences

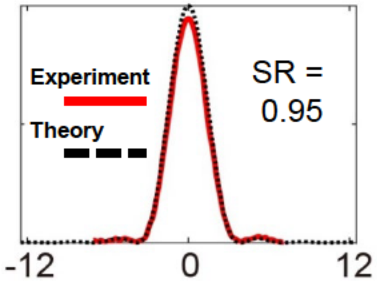


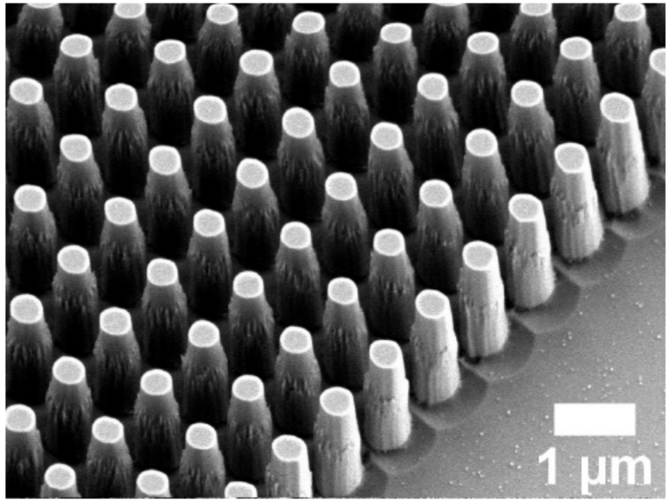
*248 nm KrF, Dry
ASML PAS 5500/300C DUV Stepper

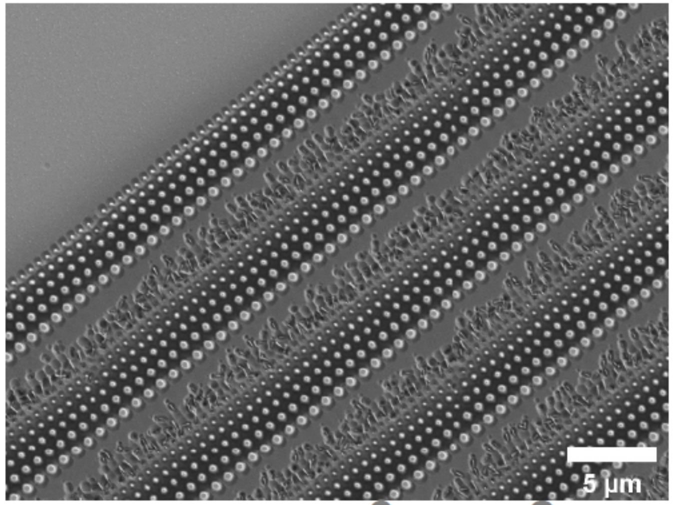
Metalens diameter: 1 cm











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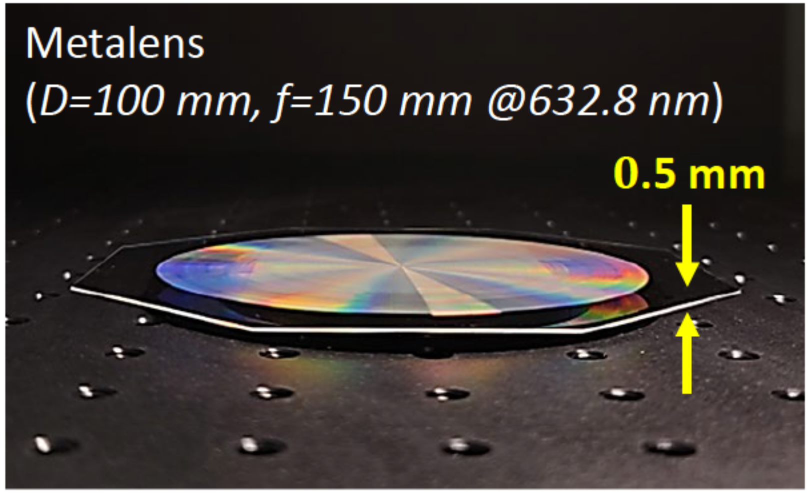
Manufactured with deep ultraviolet (DUV: 248 nm (KrF) projection lithography: used in semiconductor IC chip manufacturing. **Unification of two industries: ICs and Optics**

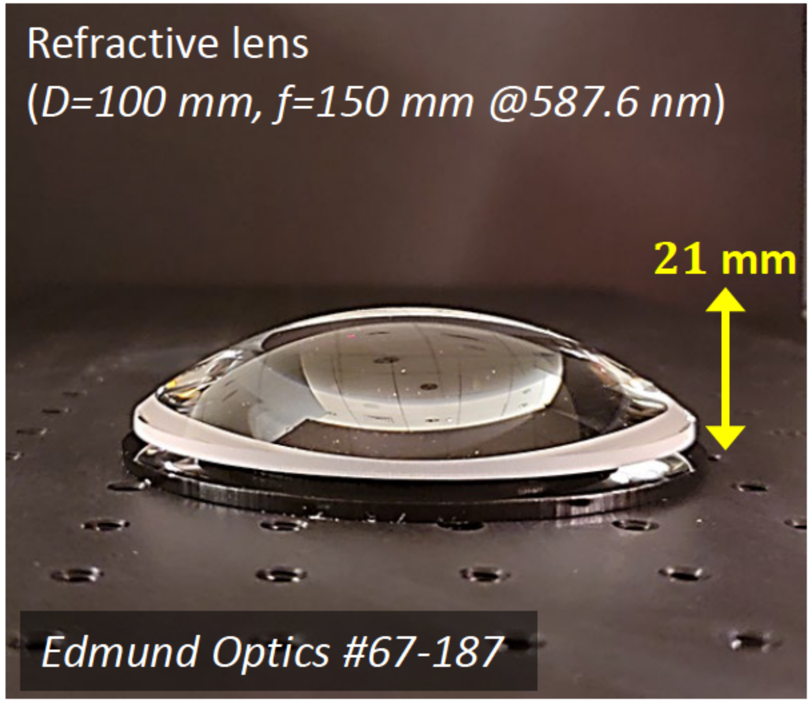
~160 million nanostructures per lens

J.-S. Park et al ., *Nano Letters* 19, 8673 (2019)

Comparison with Similar Optical Power Refractive Lens

Harvard John A. Paulson School of Engineering and Applied Sciences





- **42x reduction in thickness, 16.5x reduction in weight**
- **Entire lens is monolithic fused silica.**
  - Low thermal expansion coefficient, high laser damage threshold.
- **Substrate's backside** can be used for anti-reflective coating, color filter stack, polarization filter, etc.

Meta-imaging the Heavens

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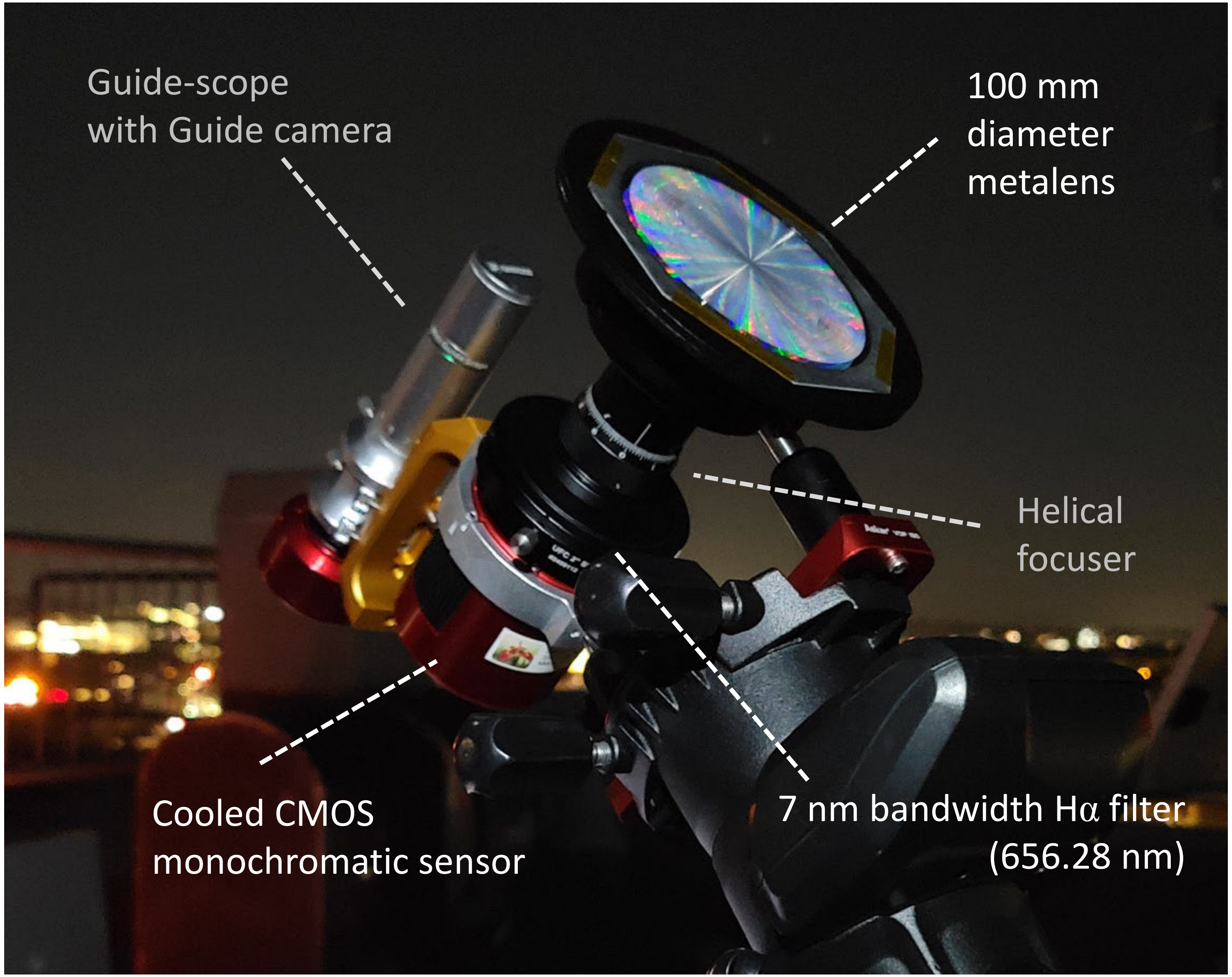

Astrophotography with 100 mm Metalens

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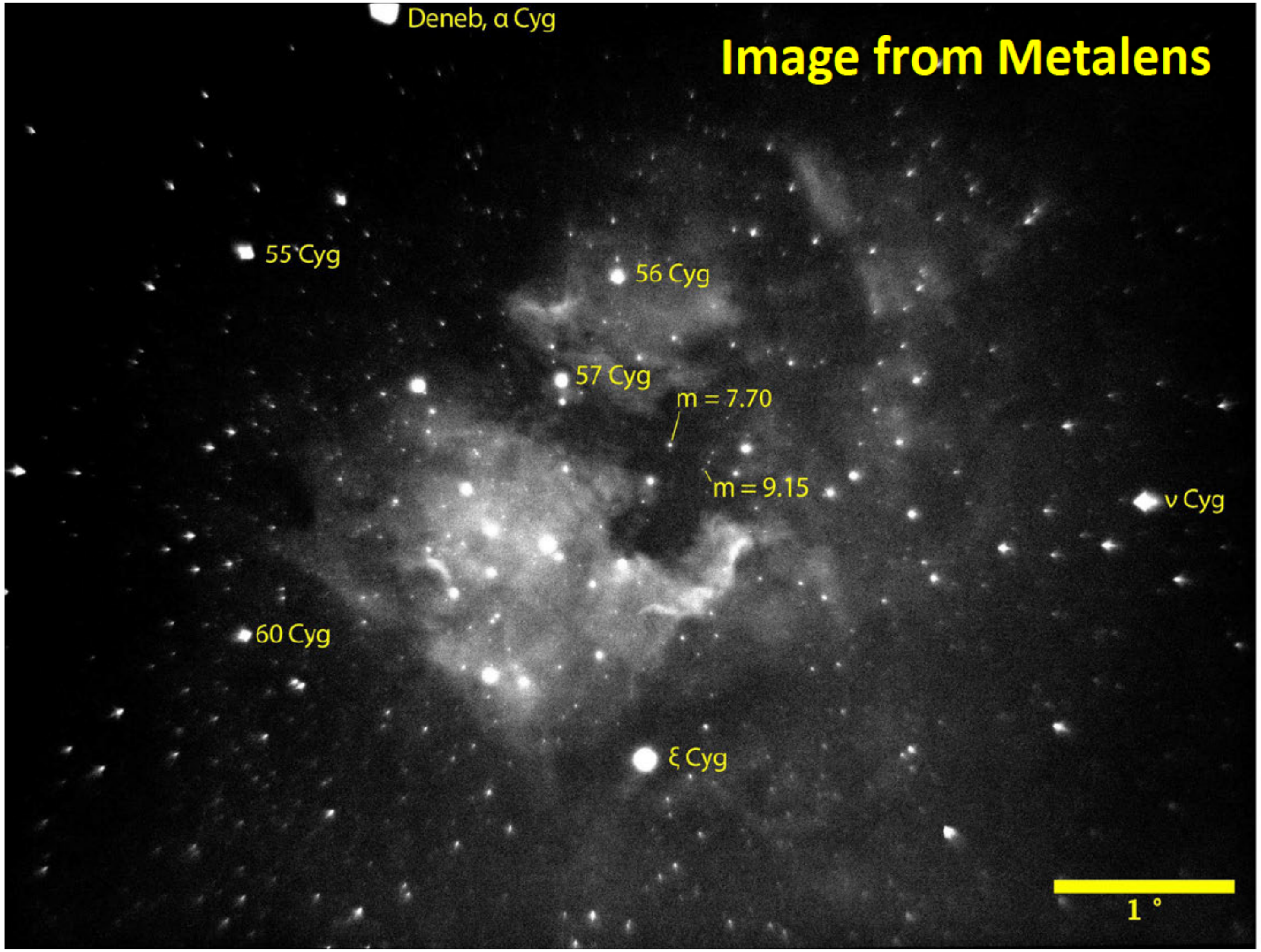
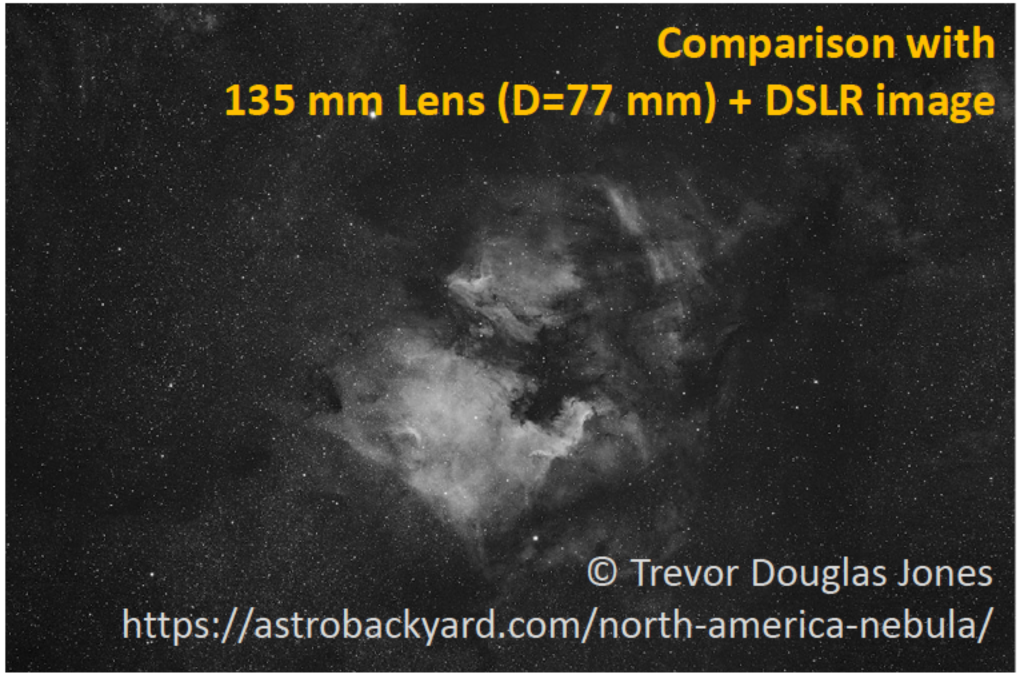
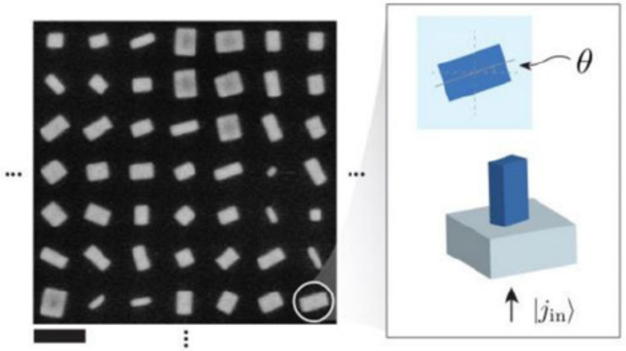
➢ **North America Nebula (NGC7000),** Cambridge, MA, USA



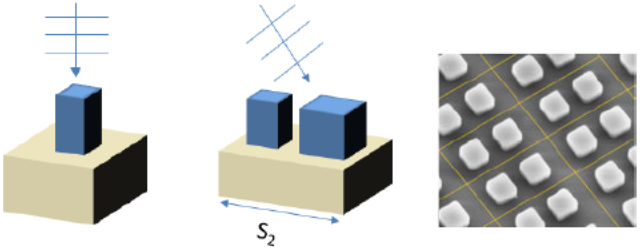


Metasurface Optics - Generation

Subwavelength arrays of dielectric nanofins with structured birefringence

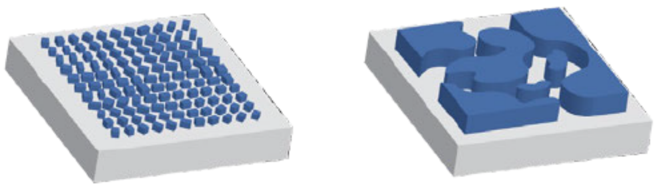


Constructed from single unit cells or coupled nanofins (supercells) for enhanced functionality



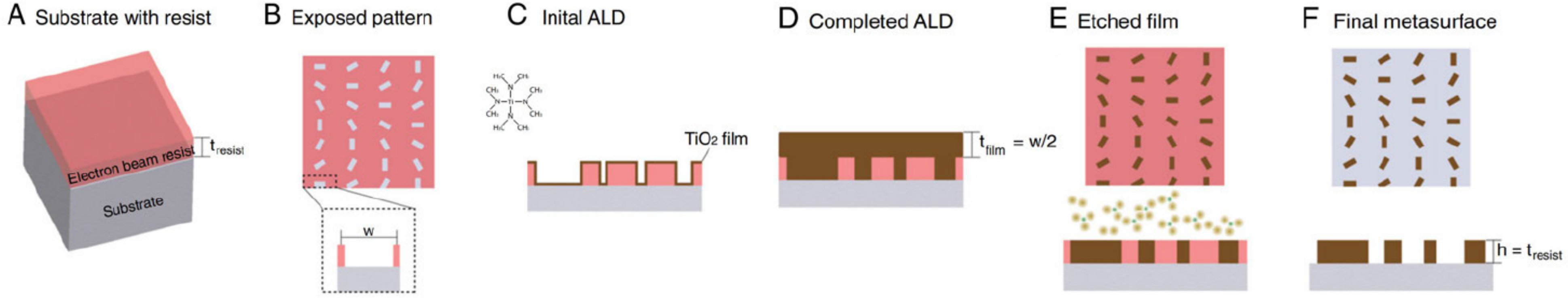
Unit cell **Supercell**

Inverse designed meta-optics are typically made of non-intuitive freeform geometries



Pillars Freeform

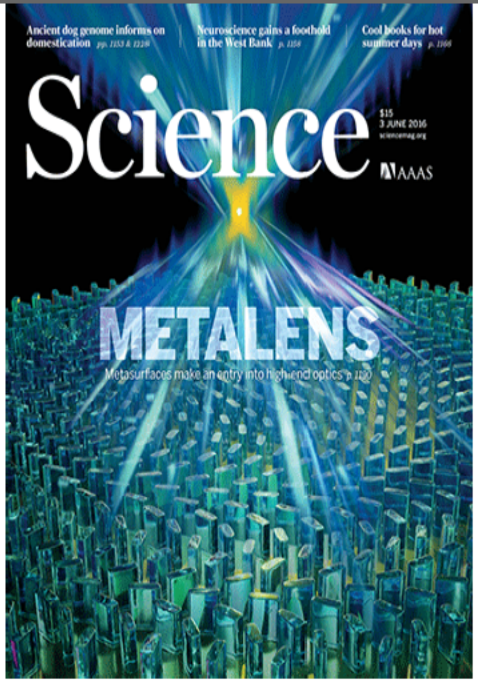
Fabrication Protocol – *Bottom-up approach*

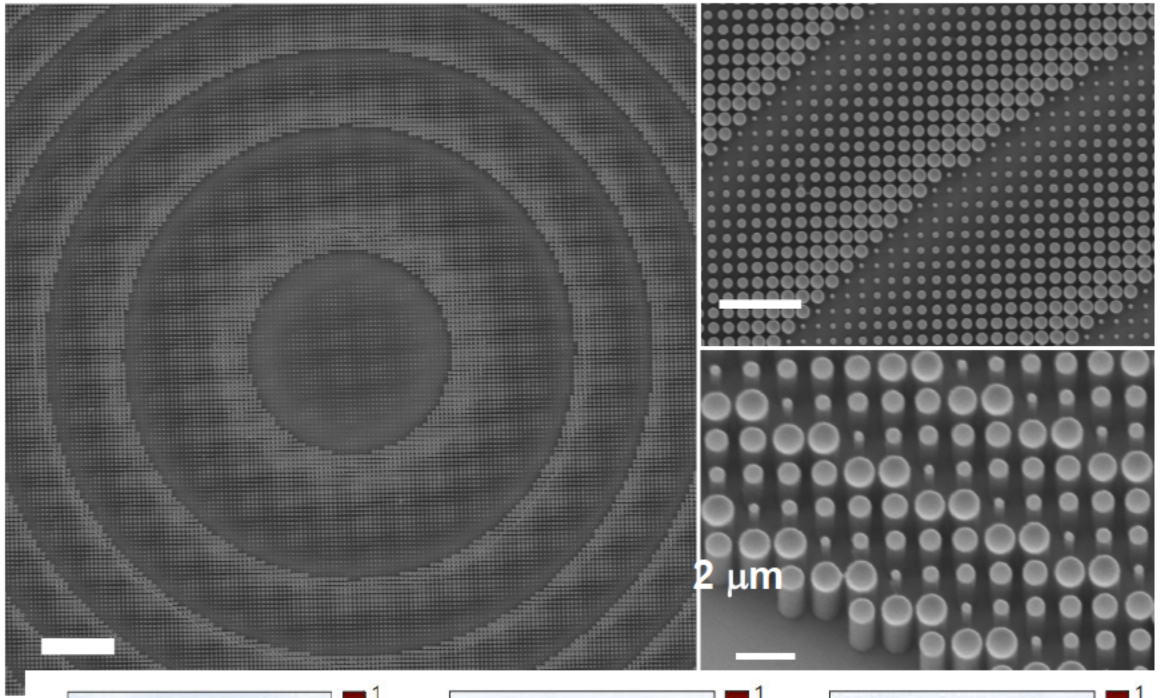


RC Devlin, M Khorasaninejad, WT Chen, J Oh, F Capasso. Broadband high-efficiency dielectric metasurfaces for the visible spectrum. Proc Natl Acad Sci U S A. ***113*** *(38):10473-8, 2016*

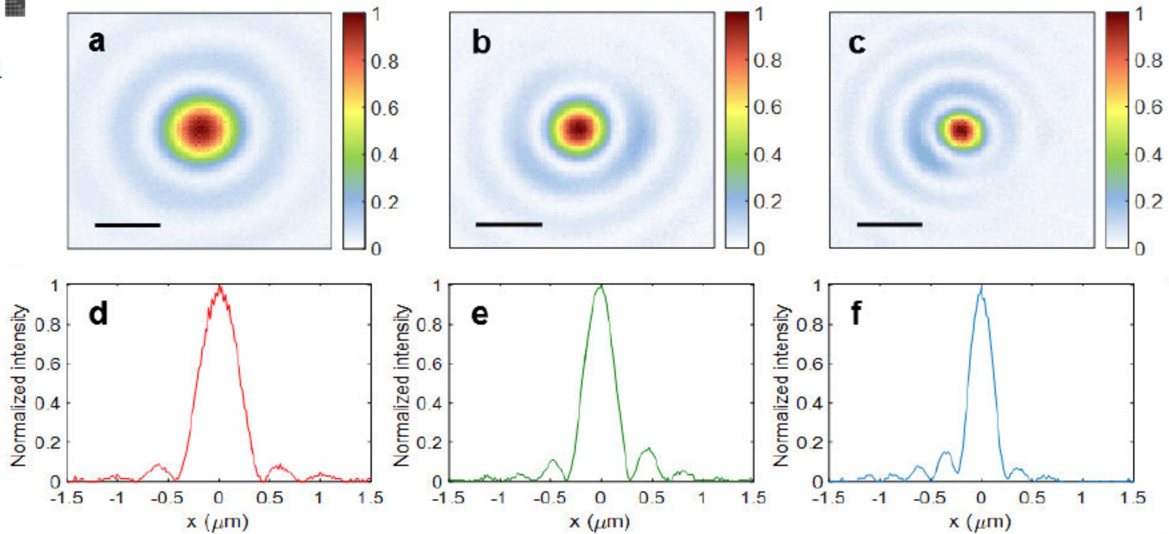
Diffraction Limited High NA Metalenses

M. Khorasaninejad et al. *Nano Lett.*, **16**, 7229 (2016).





Ø = 2 mm; f= 800μm
NA= 0.8



Focusing efficiency:
60% to 80 % depending
For NA in 0.8 to 0.6 range

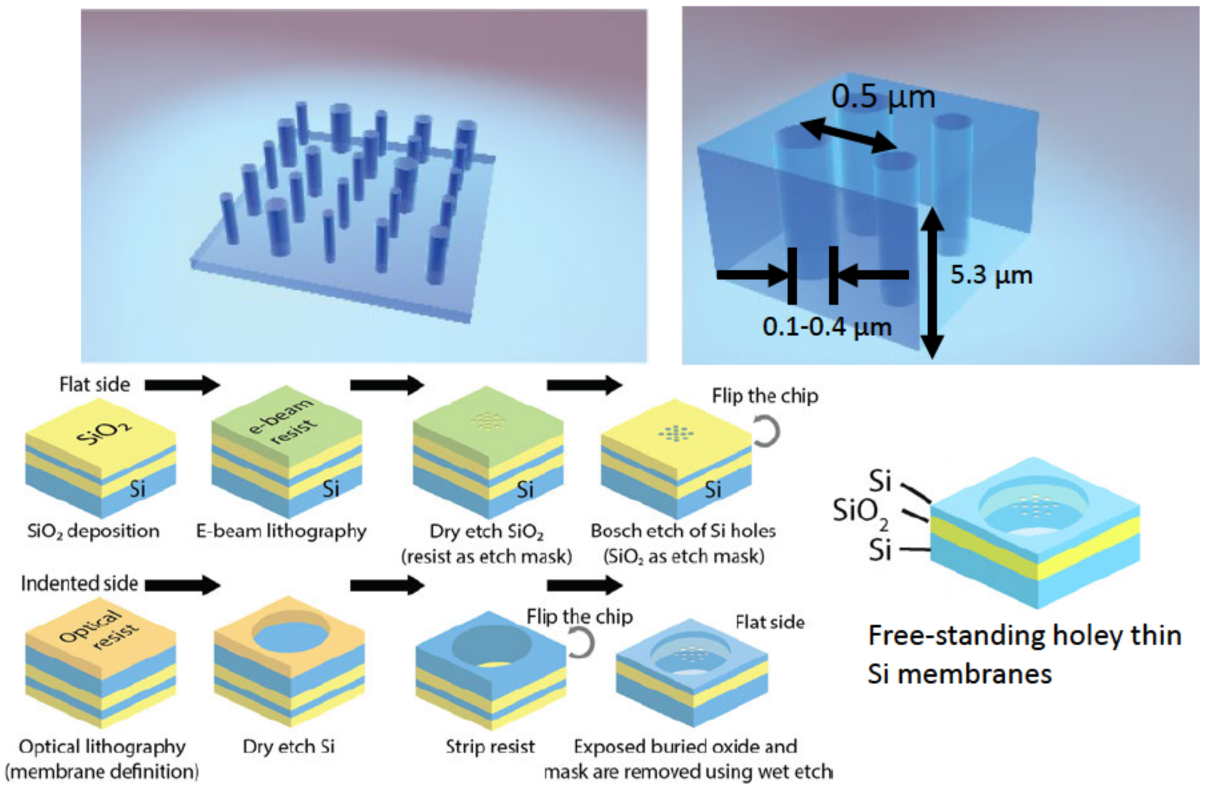
High aspect ratio Silicon based spherical-aberration-free holey metalenses

Motivation: Useful optical properties (e.g., range of chromatic behavior) scale linearly with nanostructure thickness.

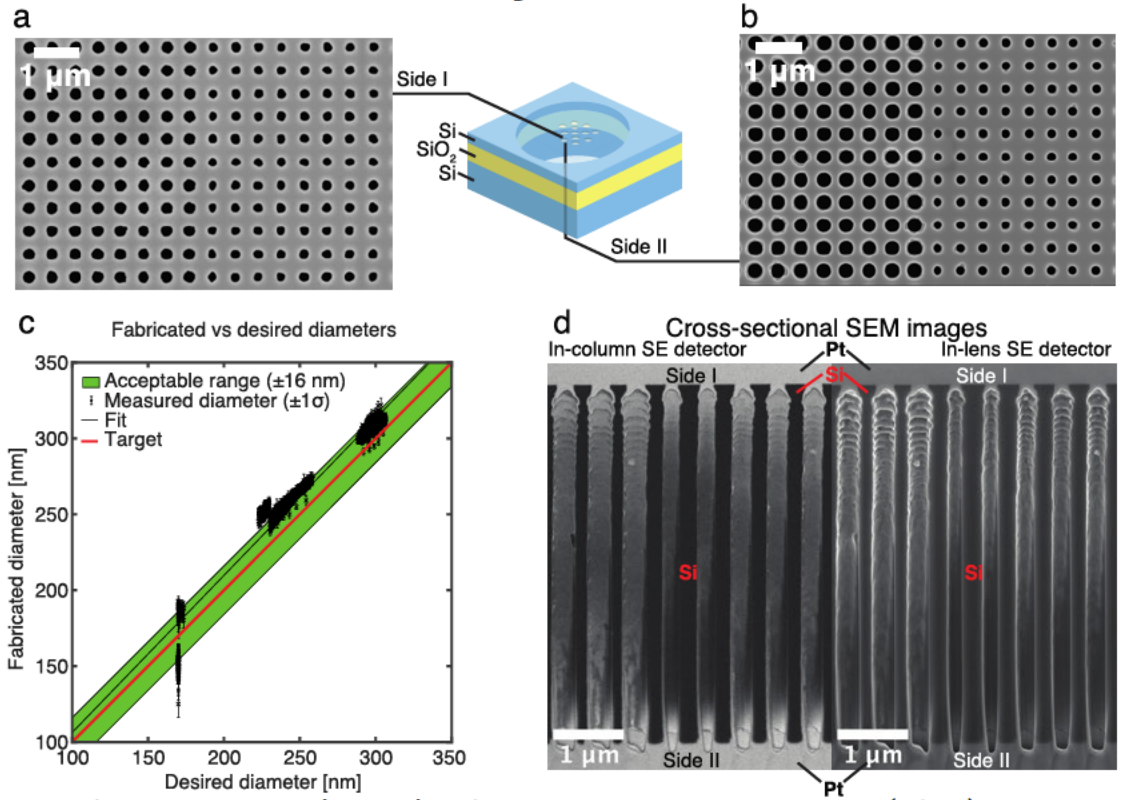
Conventional metalenses: Free-standing pillars have limited aspect ratios (e.g., 20:1 for TiO_2).

This approach: Use high aspect ratio via-holes in Si membranes CMOS-compatible fabrication protocol

Free-standing nanopillars **Deep nano-holes**



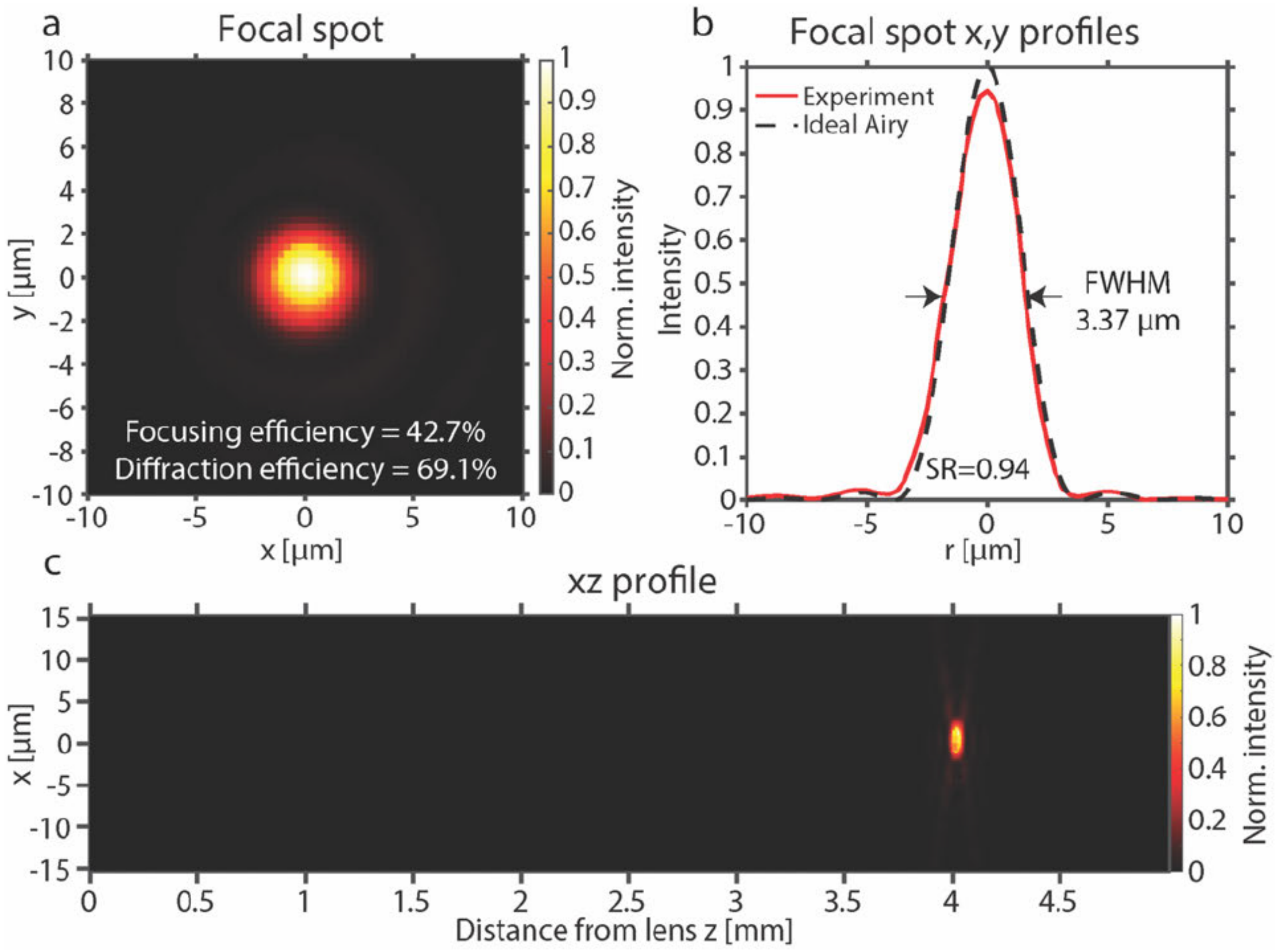
Fabricated holey metalenses

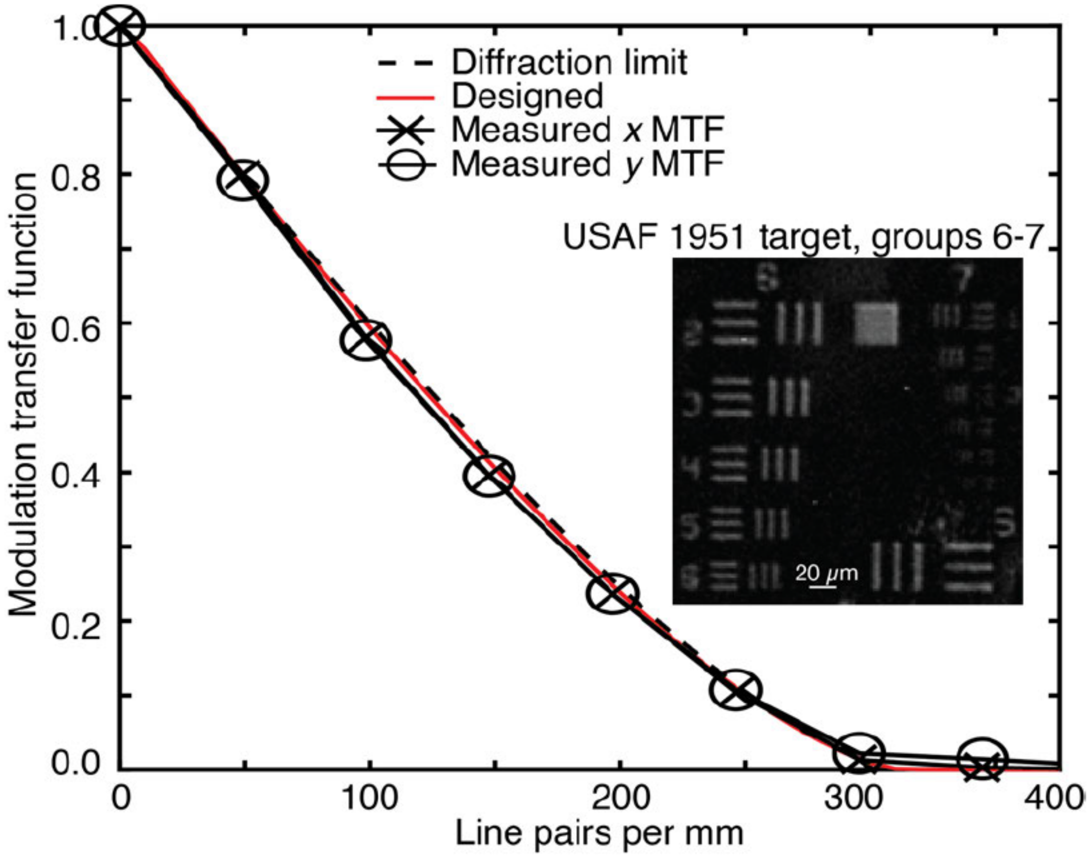


S W D Lim, M. L. Meretska, and F. Capasso *Nano Lett.*, 21, 8642 (2021)

Optical performance

- Diffraction limited imaging performance attained.





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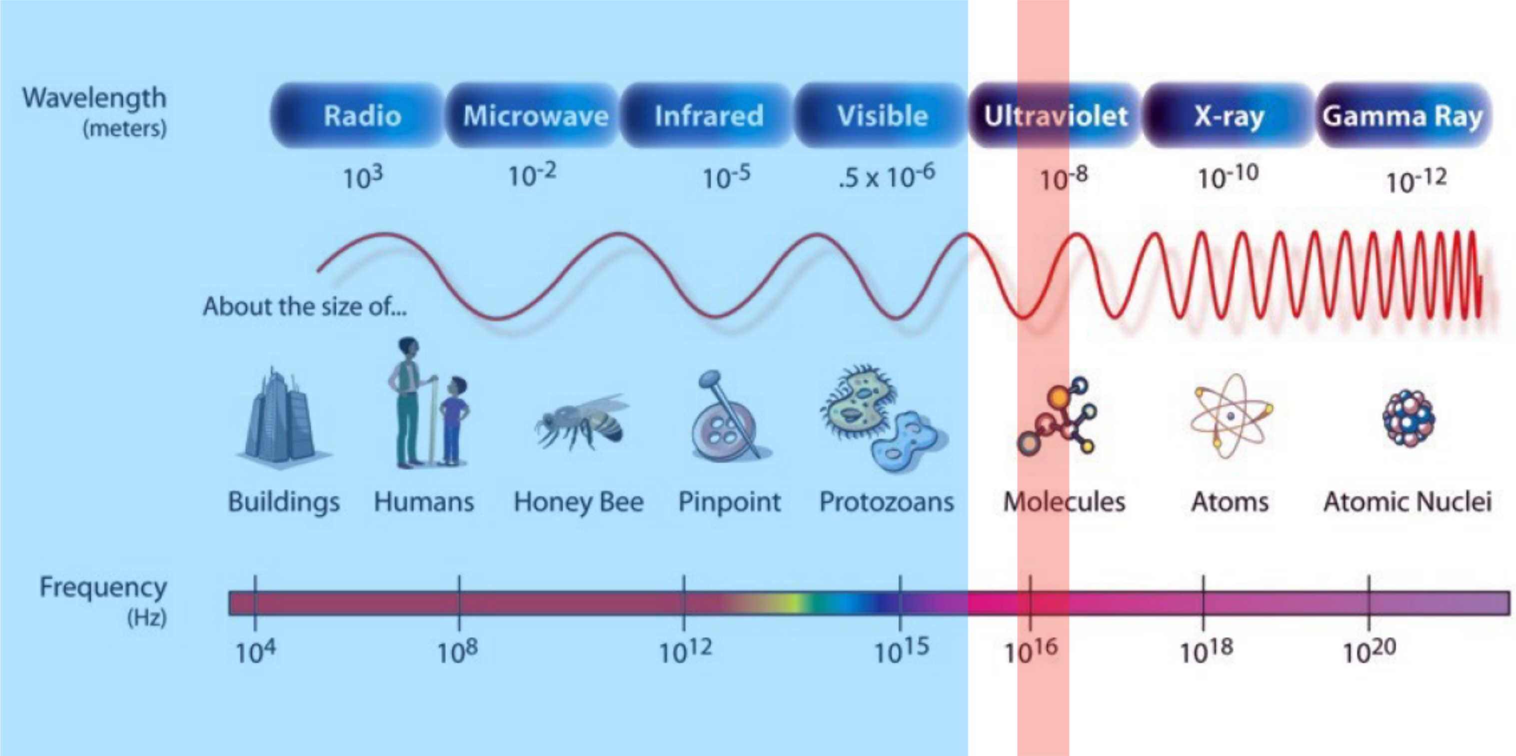
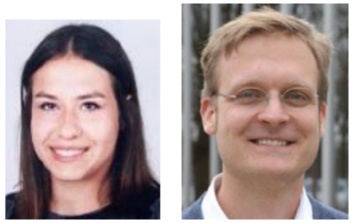
Extreme Ultraviolet Metalenses

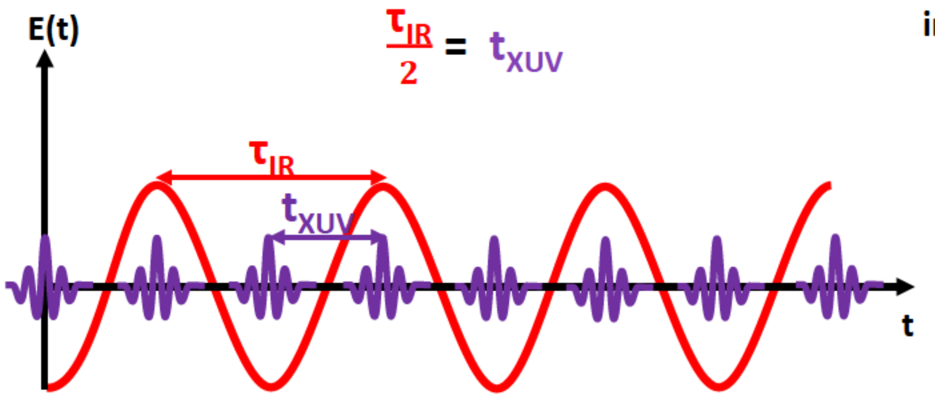


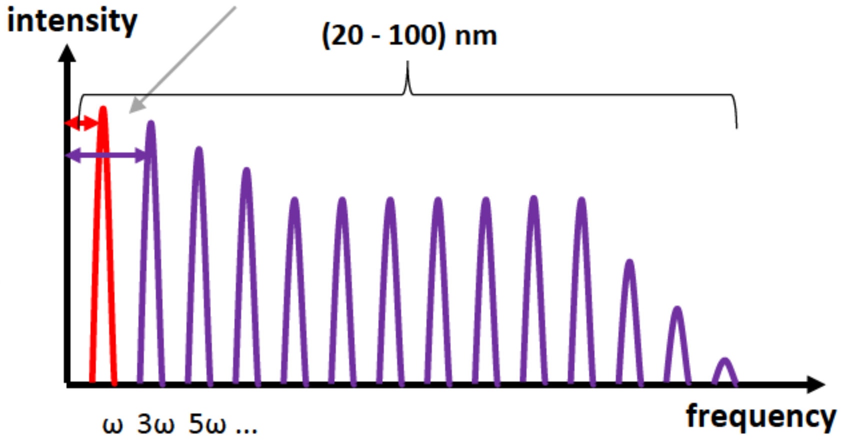
TU Graz



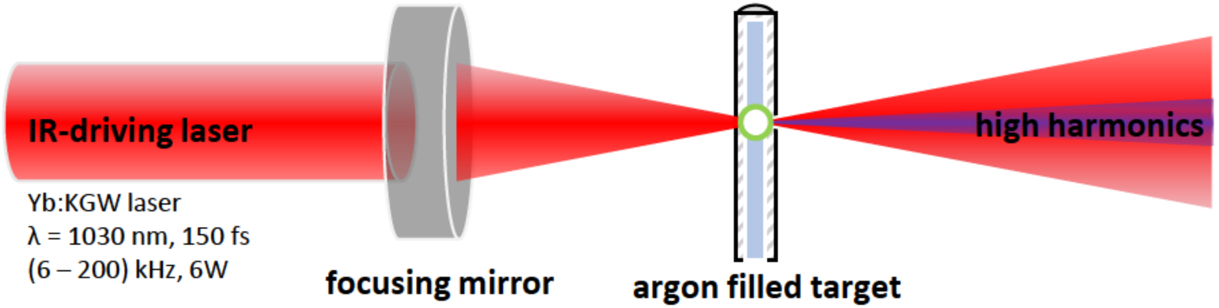
Hana Hampel Martin Schultze

High harmonic generation: spectrum

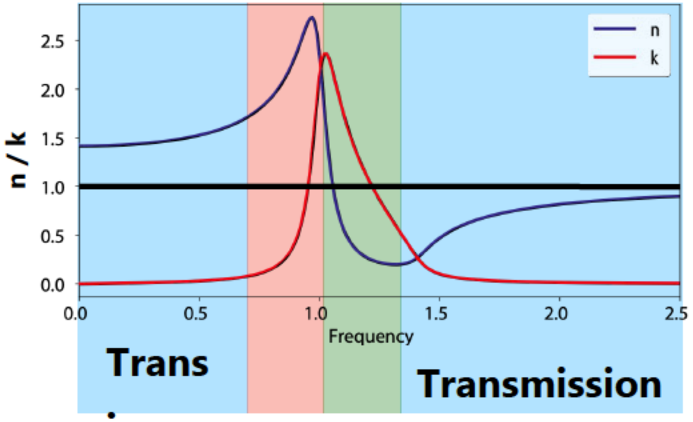




one attosecond pulse is generated every half-cycle of the driving laser
-> extreme ultraviolet harmonics are spaced by two fundamental photon energies
(Fourier transform)

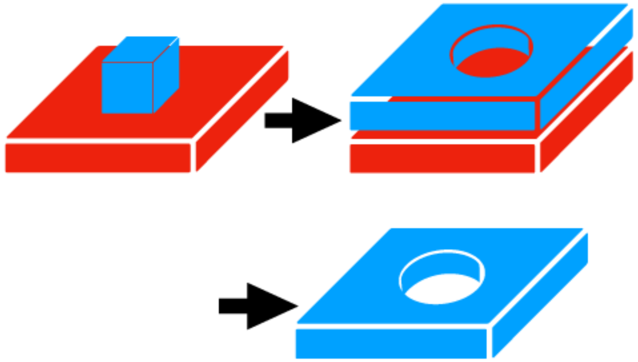


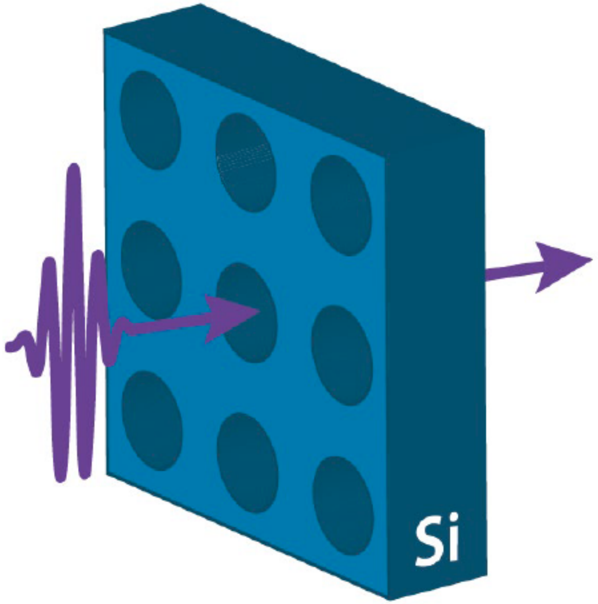
EUV Material Properties



$n_{material} < n_{vacuum}$
→ vacuum suddenly guiding

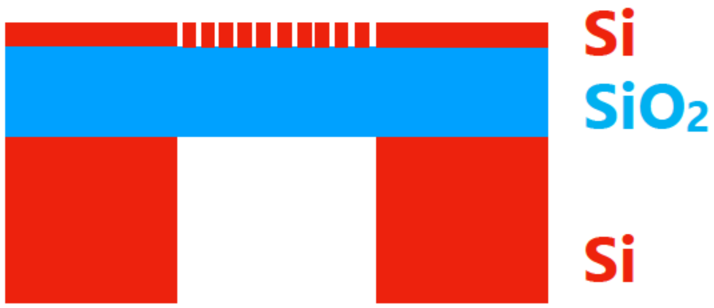
$k_{material} > 0$
→ thin device
→ thin / no substrate



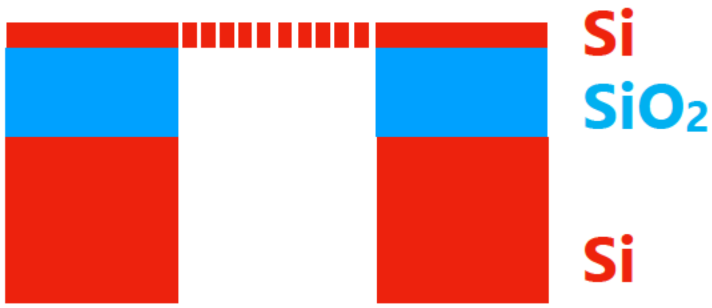


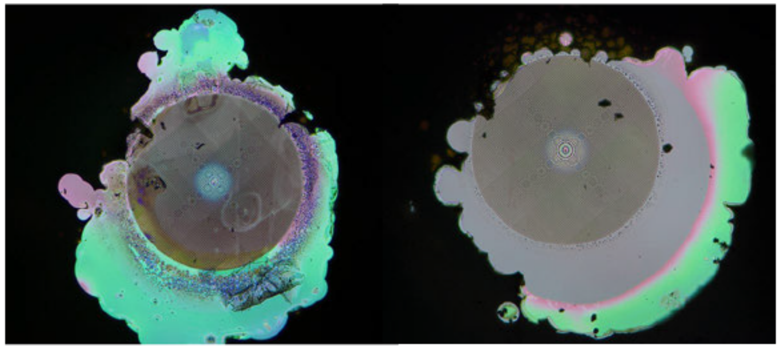
EUV Metalens Fabrication

back side spin coat
MLA membrane area
RIE-10 Bosch etch



BHF wet etch

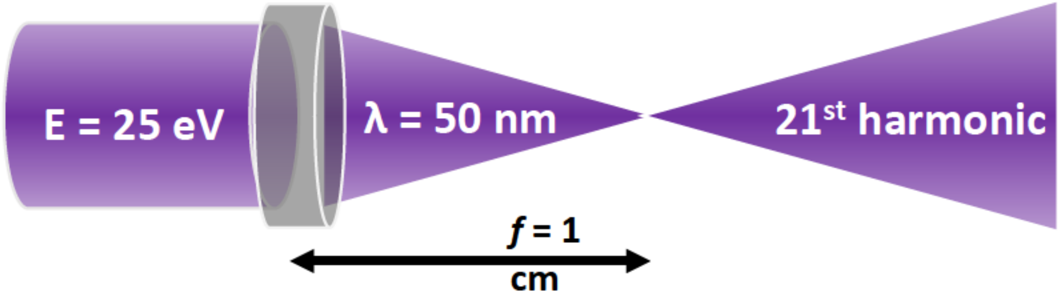




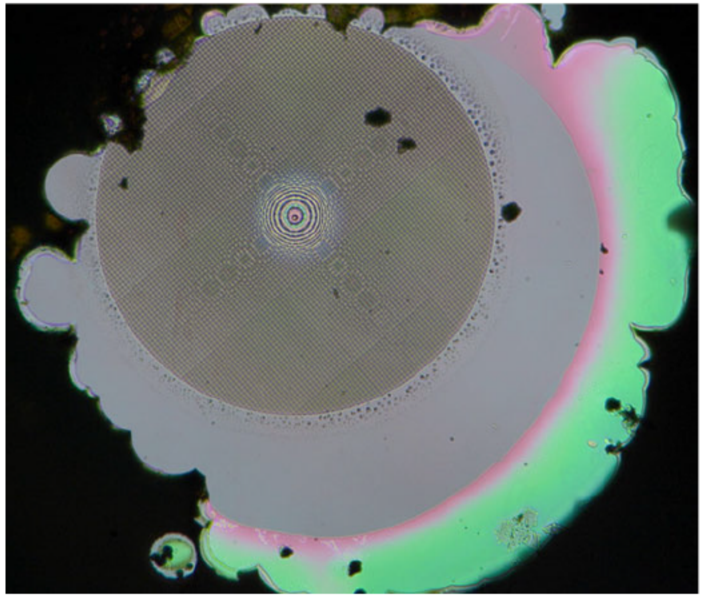
Focussing of XUV radiation

- transmitting metaoptics
  - wavelength-scale structures made of Si
  - optimized for 50 nm radiation:

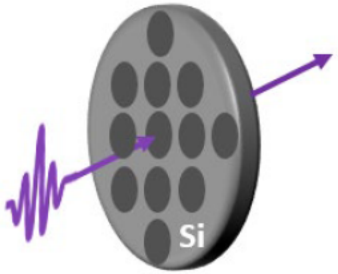
Hana Hampel
Martin Schultze



Sample preparation:
Maryna Meretska
Soon Wei Daniel Lim

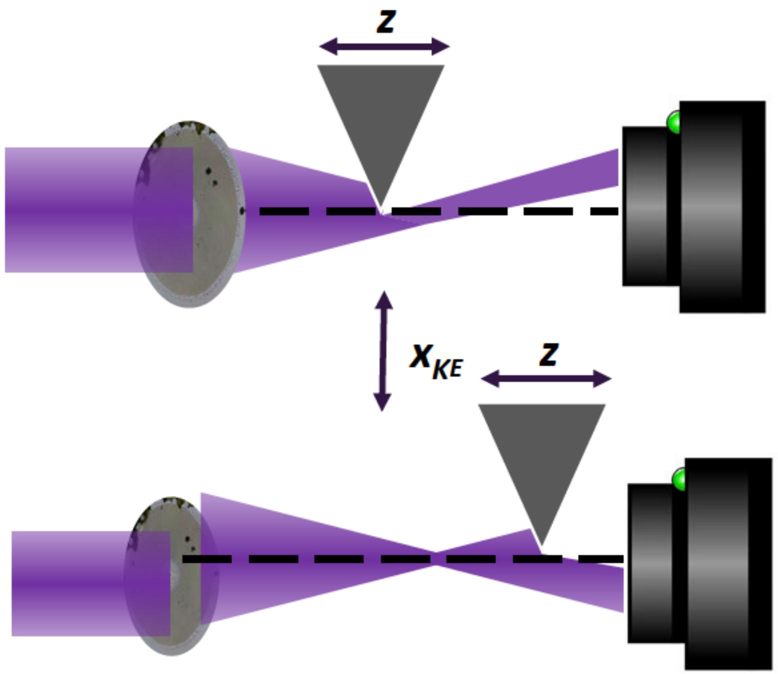


Numerics and concept:
Marcus Ossiander



Measurement – knife edge

How do we measure a beam waist without optics?

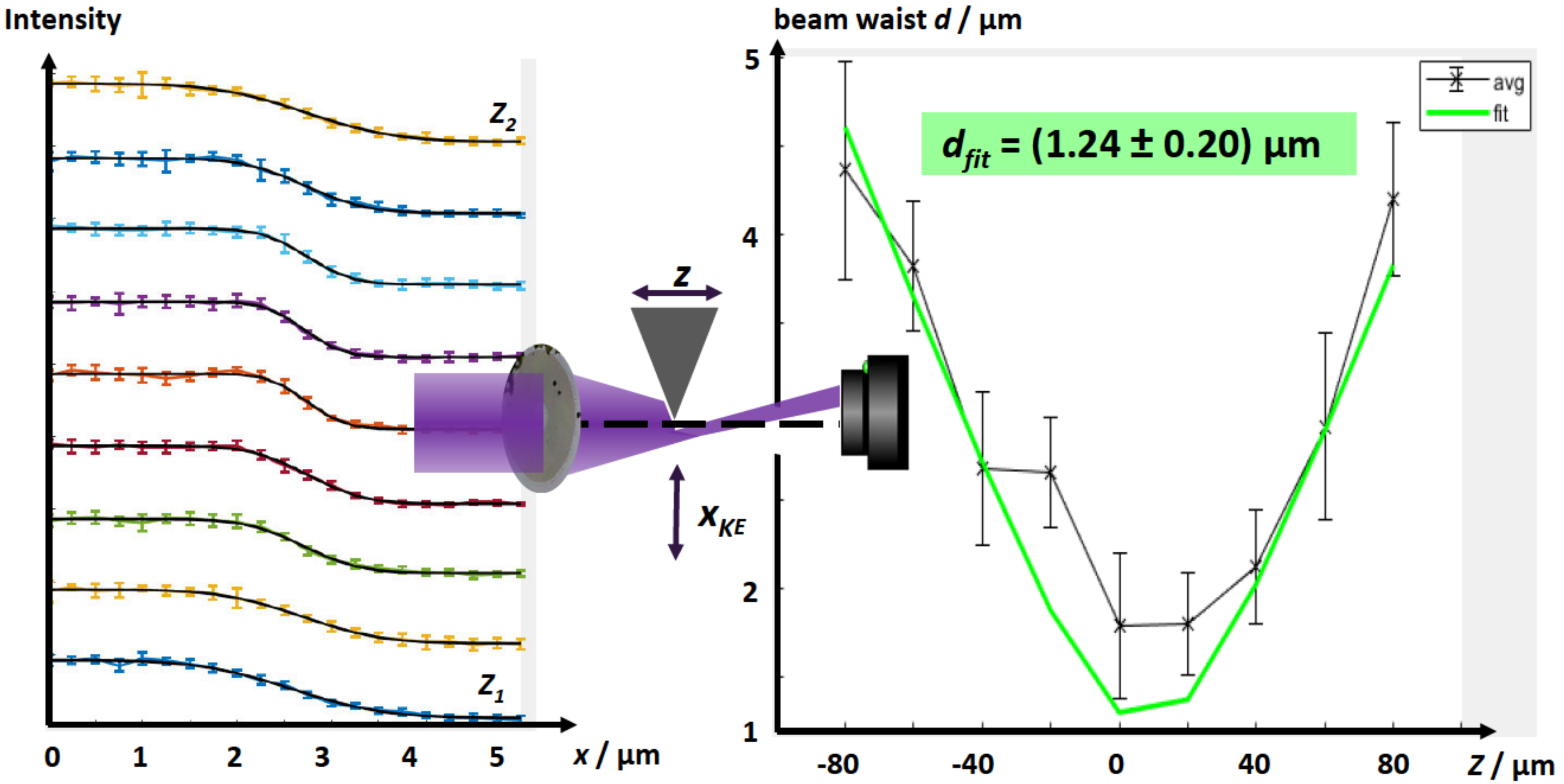


Gaussian

$$I(x_{KE}) \approx \int_{X_{KE}}^{\infty} I(x)dx$$

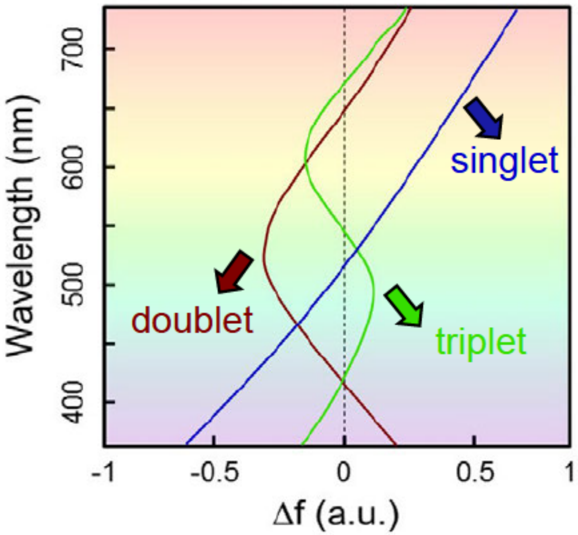
$$I(x_{KE}) \approx C \cdot (1 - erf\left(-\frac{c(x_{KE} - x_0)}{w}\right)$$

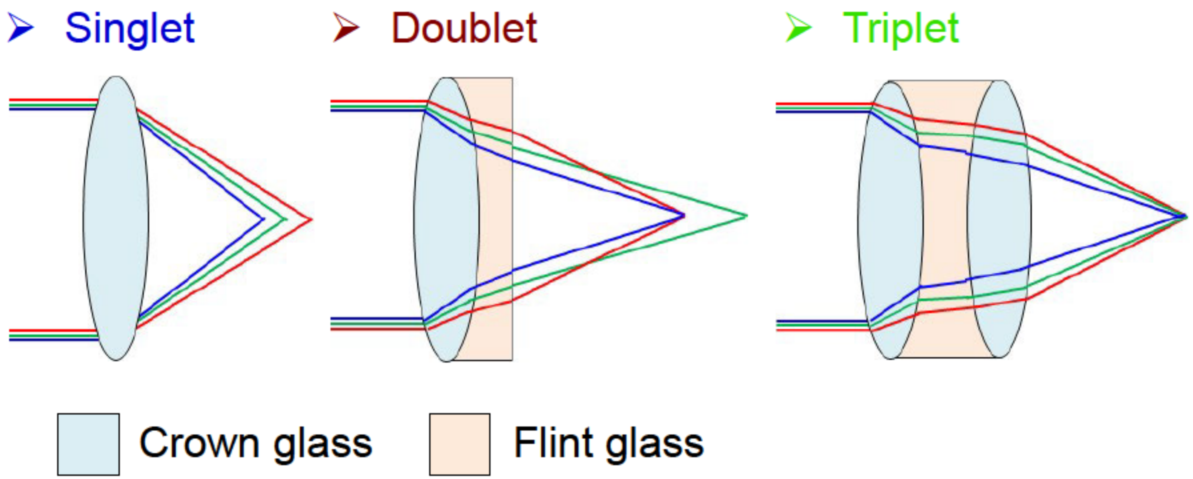
Measurement



Complexity of Achromatic Lens Design

➢ Conventional approaches for reducing chromatic aberration





➢ Limited choices of glass

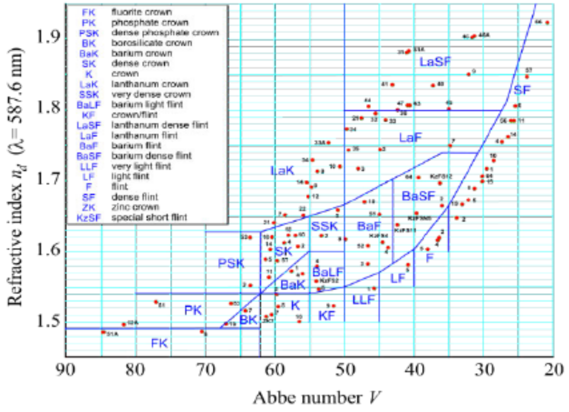
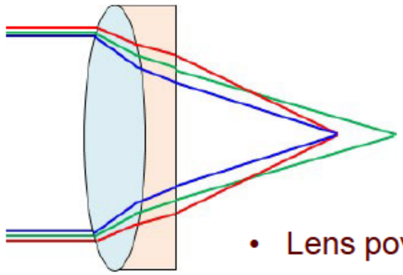


Image resource: Wikipedia

➢ Conventional design approaches (doublets for example)

Under thin lens approximation, lack of clear physical insights



$$\begin{cases} \phi_1 + \phi_2 = \phi_{total} \\ \dfrac{\phi_1}{V_1} + \dfrac{\phi_2}{V_2} = 0 \end{cases}$$

- Lens power $\phi = \frac{1}{f}$ Abbe number $V = \frac{n_{598nm} - 1}{n_{486nm} - n_{656nm}}$

Inverse design of metasurfaces

Inverse design: Defining and solving a physics problem in a mathematical way

Objective functions

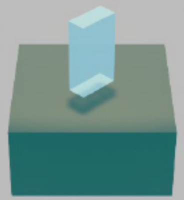
$$\max_{p} f(\boldsymbol{E},\boldsymbol{H})$$

$$f_i(p,\lambda,s)=0,\ \ i=1\cdots N_1$$

$$f_j(p,\lambda,s)\le 0,\ j=1\cdots N_2$$

$$f_k(\boldsymbol{E},\boldsymbol{H})=0,\ \mathrm{k}=1\cdots N_3$$

Meta-atom library (Optional)



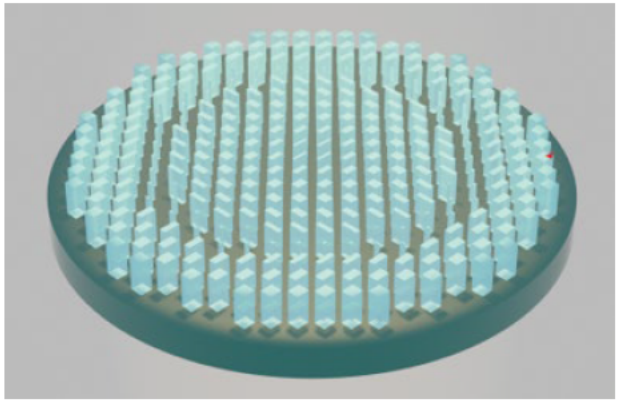
$$\boldsymbol{E}(p,\lambda,s)$$

$$\boldsymbol{H}(p,\lambda,s)$$

Mathematical tools (e.g., Optimizer)

p: design parameters
λ: wavelength
s: polarization state

Metasurface design



- The desired function cast as a Figure of Merit: during each iteration, the permittivity distribution,ϵ(r), is modified in a manner that improves the FOM.
- Compute the gradient of FOM with respect to ϵ(r), which is used to update ϵ(r), (structure shape).
- Gradient computed very efficiently using only two simulations per iteration, forward and adjoint

Zhaoyi Li, collaboration with Steve Johnson's group MIT

Inverse design of large-scale metalenses

Harvard John A. Paulson School of Engineering and Applied Sciences

Design flow

1. Determine objective function

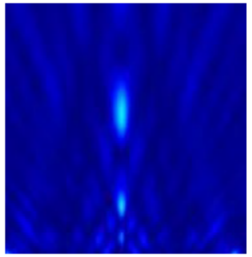
$$max\left(\min_{\lambda\in\lambda_s}(I_\lambda(\vec{\boldsymbol{x}}_{target},\vec{\boldsymbol{p}}))\right)$$

2. Initial random design

Fast approximate solver

3. Objective function evaluation

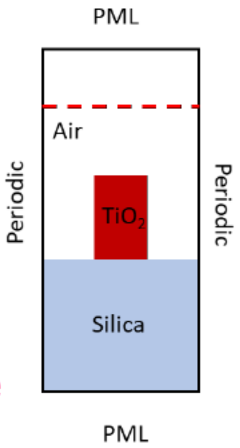
$$|\vec{\boldsymbol{E}}(\vec{\boldsymbol{x}}_{target})|^2$$



Adjoint method

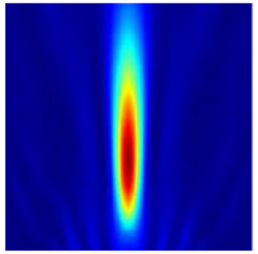
4. Re-design unit-cell parameters for the whole lens simultaneously

$$\nabla_{\mathbf{p}}\boldsymbol{I}(\vec{\boldsymbol{r}}_{target})$$

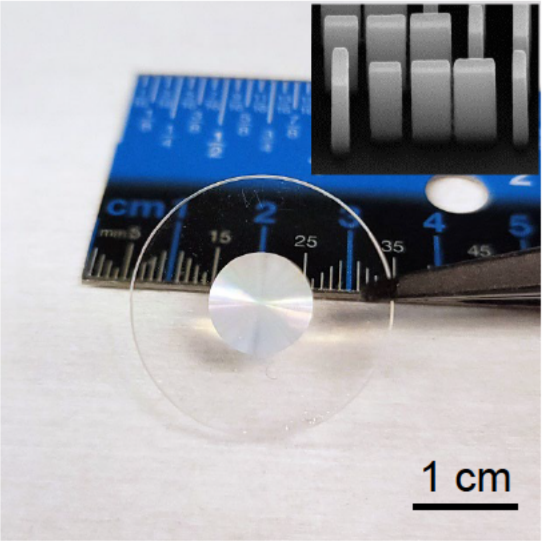


Fast approximate solver

5. Final design: validation/ fabrication

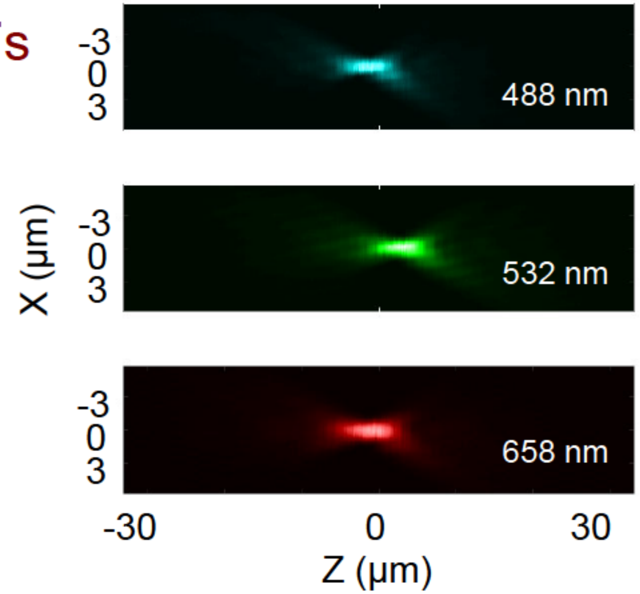


Device image



- Diameter: 1 cm
- NA: 0.3
- TiO_2 on fused silica
- Polarization insensitive
- Contains ~ $5\mathrm{x}10^8$ meta-atoms

PSFs



- RGB-achromatic
- Maximum focal shift: 4.5 μm (0.03% of design focal length)
- Diffraction-limited focusing

Capasso Group

Zhaoyi Li, collaboration with R. Pestourie and Steve Johnson MIT

Meta-atom roadmaps: from cubism to surrealism

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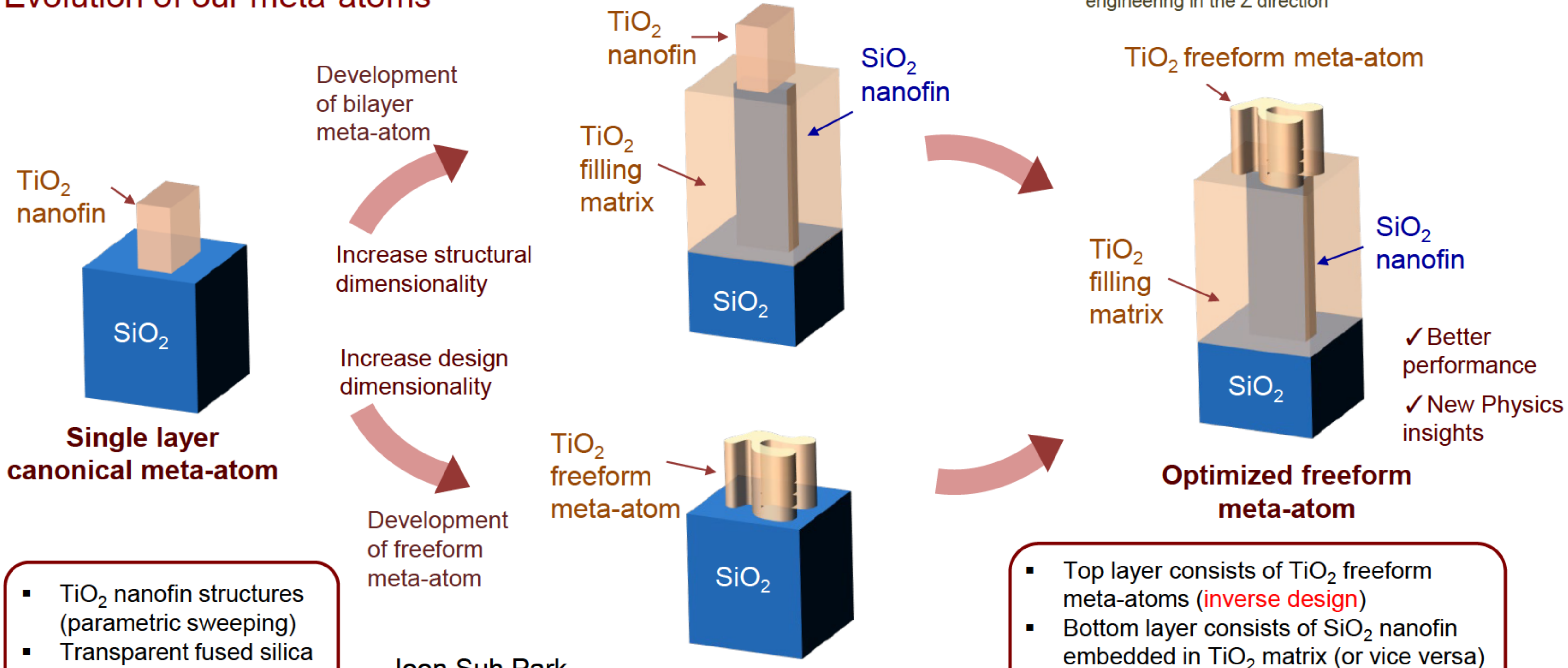
Evolution of our meta-atoms

* 2.5D: full design freedom in the XY plane, multilayer engineering in the Z direction"



Single layer canonical meta-atom

- TiO_2 nanofin structures (parametric sweeping)
- Transparent fused silica substrate

Joon Suh Park
Zhaoyi Li

Optimized freeform meta-atom

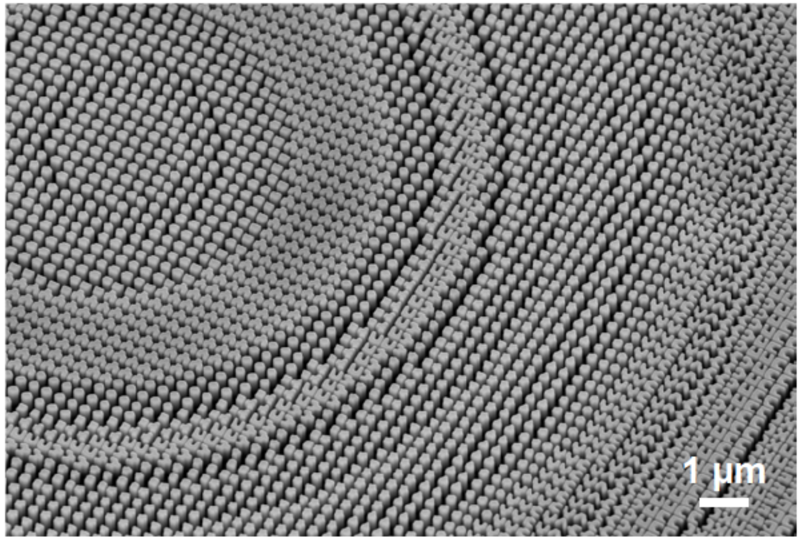
- Top layer consists of TiO_2 freeform meta-atoms (inverse design)
- Bottom layer consists of SiO_2 nanofin embedded in TiO_2 matrix (or vice versa)
- Transparent fused silica substrate

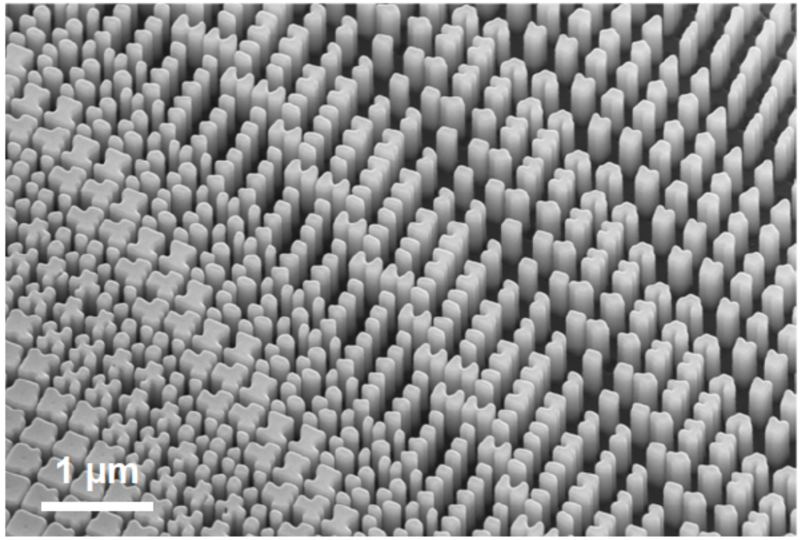
Bilayer freeform meta-atoms adventure

Harvard John A. Paulson School of Engineering and Applied Sciences

SEM images:

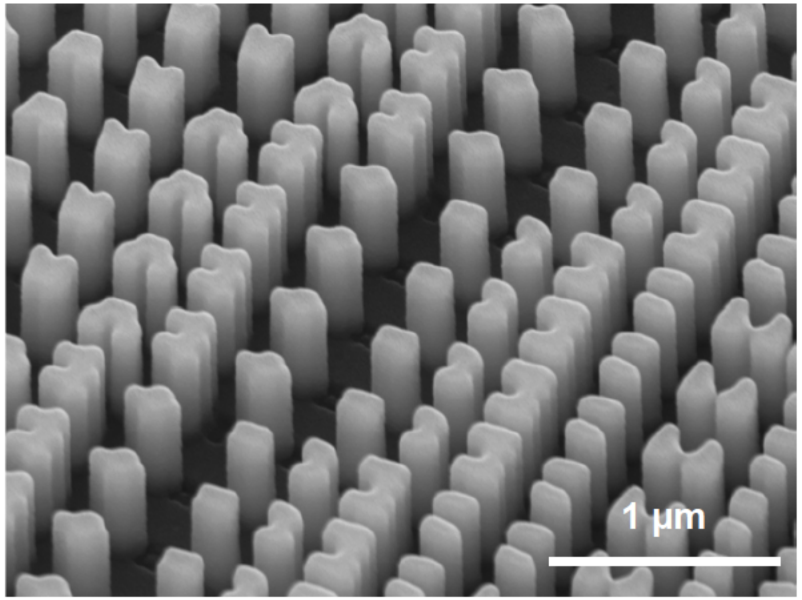
- freeform meta-atoms and meta-device (fabrication techniques has been developed ~3 years)

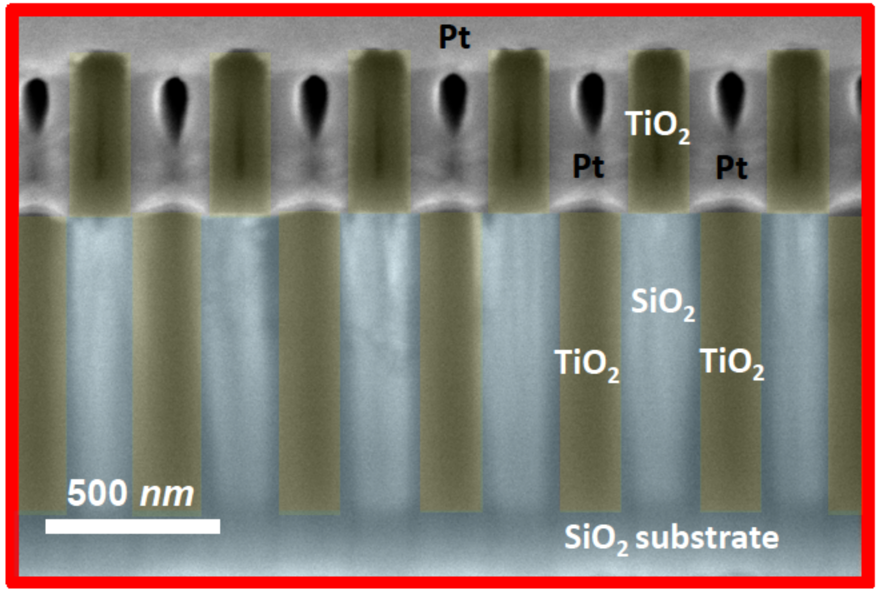




Meta-atoms material platform:

- TiO_2
- Fused silica

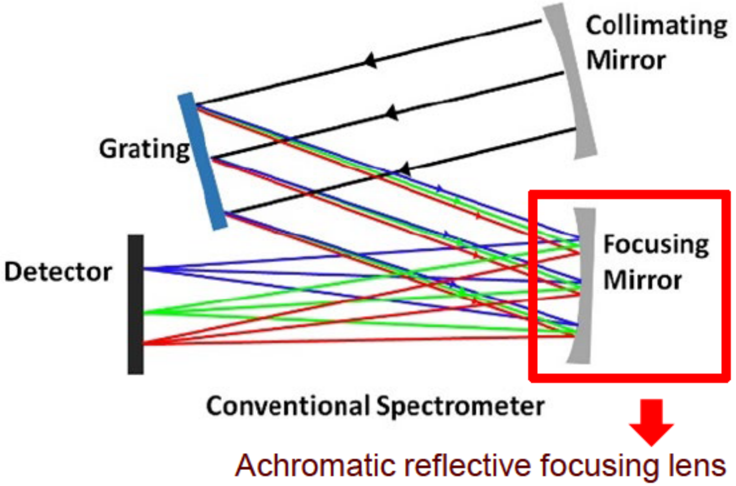




Joon Suh Park
Zhaoyi Li

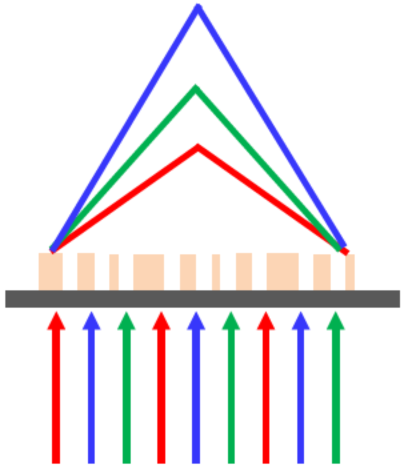
Meta-spectrometers: Making good use of Chromatic Effect

- Conventional grating-based spectrometers



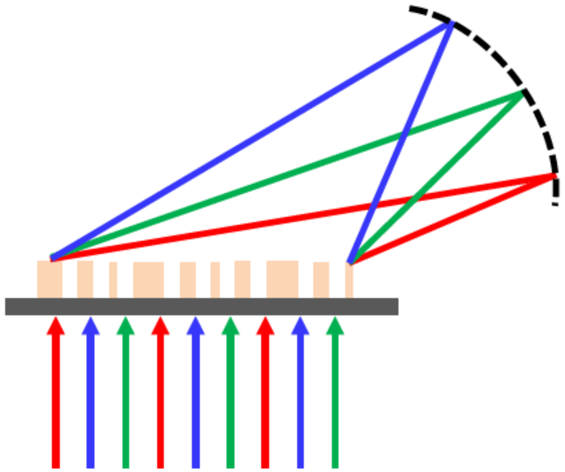
- angular dispersion

- On-axis focusing metalens



- longitudinal dispersion

- Off-axis focusing metalens

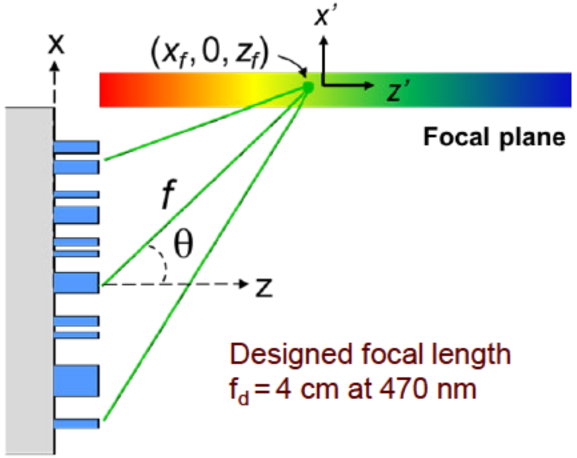


- angular dispersion + longitudinal dispersion

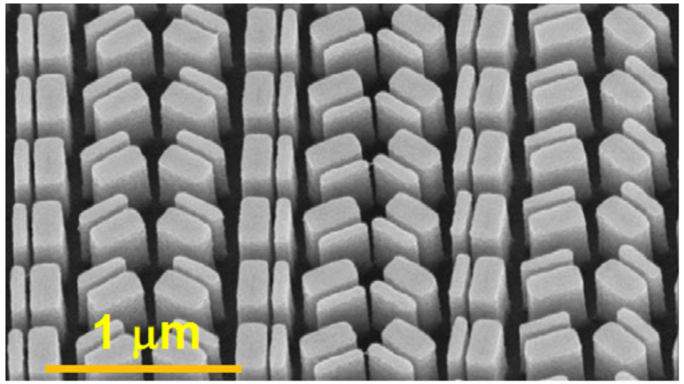
- Off-axis metalens has better spectral resolution because of angular and longitudinal dispersions.
- Off-axis metalens suffers two major aberrations (field curvature and astigmatism), which limite its spectral resolution and range in a narrow bandwidth.

Aberration-corrected metalens spectrometer

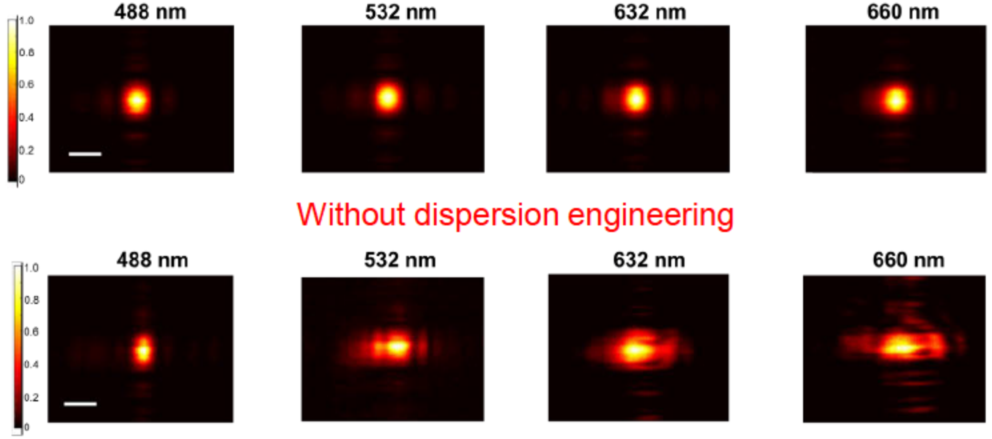
- Flat and perpendicular focal plane realized by dispersion-engineered metalens



- Coupled TiO_2 waveguide for fine tuning dispersion

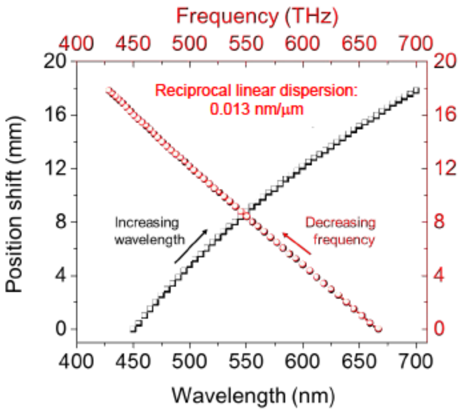


- Measured focal spots (FWHM ~ 56 μm)



- Metalens dispersion and spectral resolution

• Dispersion



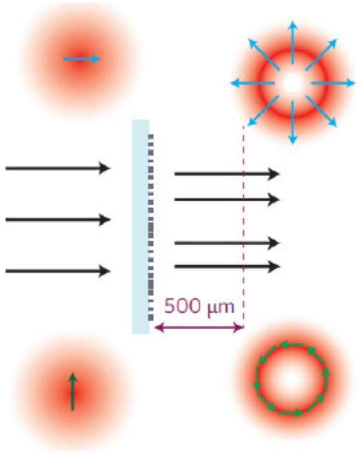
• Spectral resolution

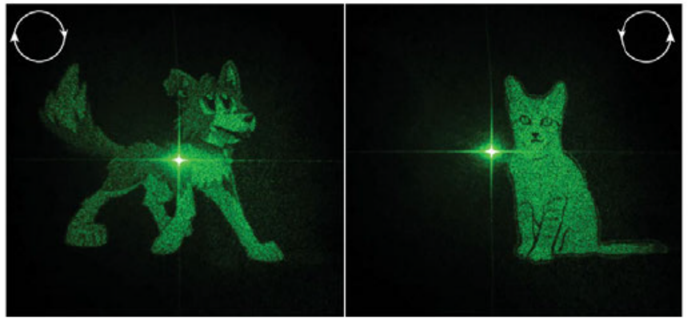
(Reciprocal linear dispersion × Focal spot size)

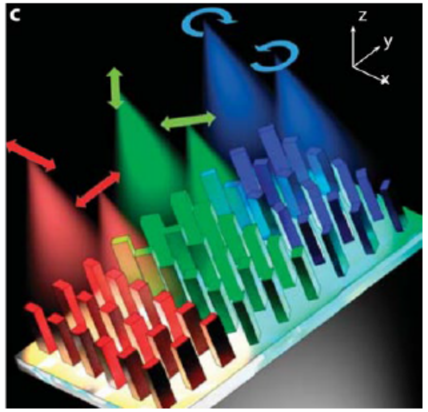
0.013 nm/μm   56 μm

~ 0.73 nm spectral resolution from 470 to 660 nm in the visible

Metasurface polarization optics





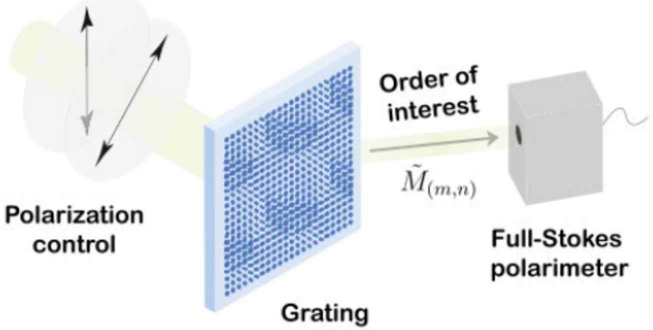


A. Arbabi, Y. Horie, M. Bagheri, and A. Faraon, *Nature Nanotechnology* **10**, p. 937–943 (2015).

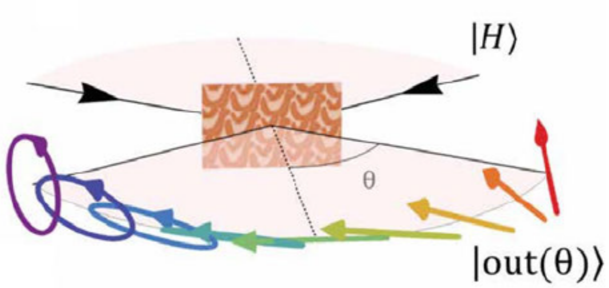
S. M. Kamali, E. Arbabi, A. Arbabi, and A. Faraon, *Nanophotonics* **7** (6), 1041-1068 (2018) [review].

J. P. B. Mueller, N. A. Rubin, R. C. Devlin, B. Groever, and F. Capasso, Phys. Rev. Lett. **118**, 113901 (2016)

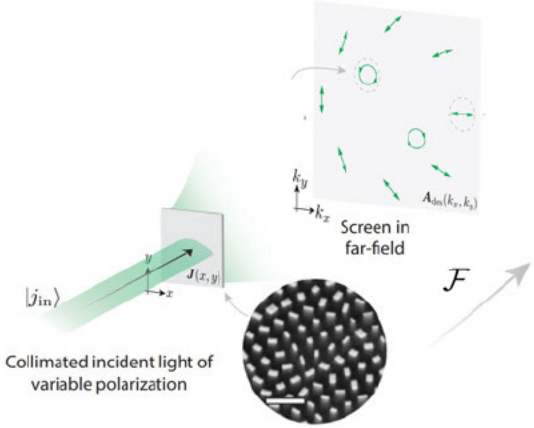
E Arbabi, SM Kamali, A Arbabi, and A Faraon, *ACS Photonics* **5**, 3132−3140 (2018)



N. A. Rubin, G. D'Aversa, P. Chevalier, Z. Shi, W. T. Chen, and F. Capasso, *Science* **365**, eaax1839 (2019)



Z. Shi, A. Y. Zhu, Z. Li, Y.-W. Huang, W.-T. Chen, C.-W. Qiu, and F. Capasso, Science Advances **6** (23), eaba3367 (2020)

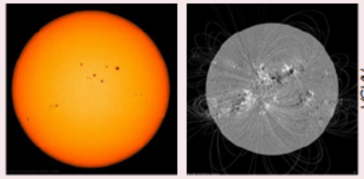


N. A. Rubin, A. Zaidi, A. H. Dorrah, Z. Shi, and F. Capasso, arXiv:2012.14874 (2021)

Why care about seeing polarization?

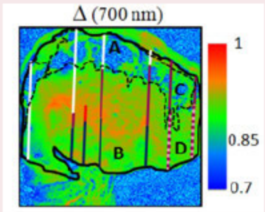
Science

Astrophysics



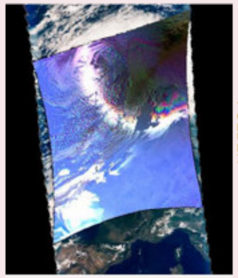
NASA

Medicine



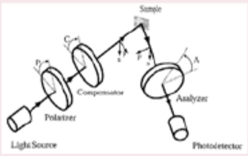
Opt. Express (2013)

Atmospheric science



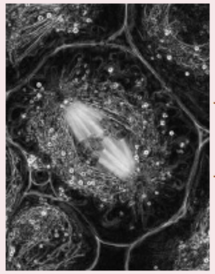
POLDER

Materials science



Appl. Opt.

Biology



OpenPolScope

Technology

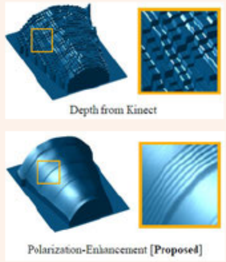
Remote sensing

Proc. SPIE

Autonomous vehicles

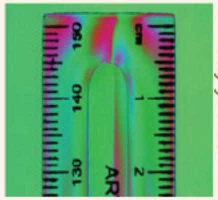
Aust. Natl. Univ.

3D reconstruction



MIT Media Lab

Machine vision



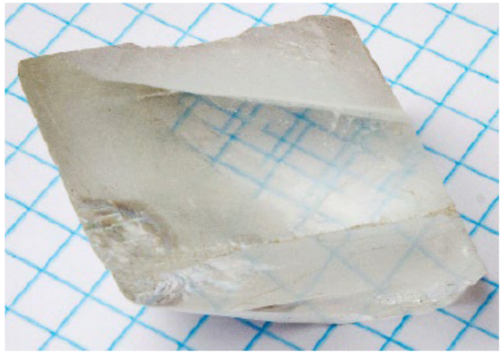
Teledyne DALSA

Security

Apple, Inc.

Polarization optics

~1650:



"Iceland spar"
(calcite)

Today:

Polarizing prisms

Waveplates

Rhombs

Polarizing sheet

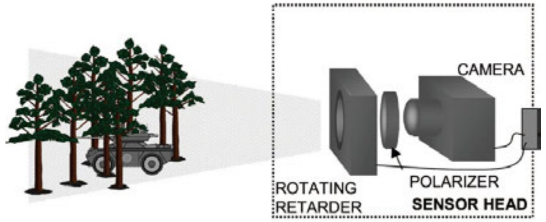
Polaroid, Inc.

In free space, we still rely on the same tools whose discovery prompted the first investigations into polarization optics 350 years ago.

What new polarization optics and physics can we explore?

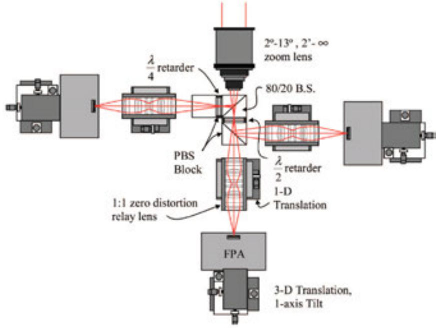
Polarization imaging: techniques and hardware

Division of time:



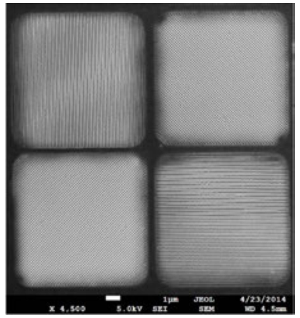
-Minimum of componentry ✓
-Limited time resolution ×
-Moving parts ×

Division of amplitude:



-No real limit to time-resolution ✓
-No moving parts ✓
-Complex, expensive systems ×
-Lots of polarization optics needed ×

Division of focal plane:



-No real limit to time-resolution ✓
-No moving parts ✓
-Difficult fabrication, sensitive alignment ×
-Expensive ×
-Usually only sensitive to linear polarization ×

Since different filters (analyzers) are needed to determine the state of polarization present polarization sensitive cameras are very complex

Can we have a single metasurface replace all this componentry?

Polarization of light: Stokes Polarimetry

- Encapsulated in the Stokes vector
  - $s_0 = I_x + I_y = I_{total}$
  - $s_1 = I_x - I_y$
  - $s_2 = I_{45} - I_{135}$
  - $s_3 = I_{RCP} - I_{LCP}$

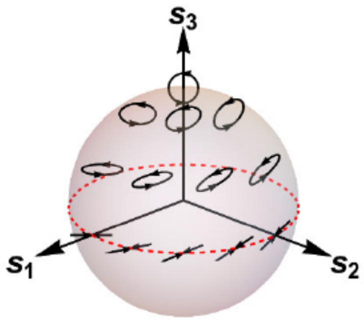
$$\vec{S} = \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix}$$

$s_0 = \sqrt{s_1^2 + s_2^2 + s_3^2}$ *Fully polarized*

$s_0 > \sqrt{s_1^2 + s_2^2 + s_3^2}$ *Partially polarize S d*

$\sqrt{s_1^2 + s_2^2 + s_3^2} = 0$ *Totally unpolarized*

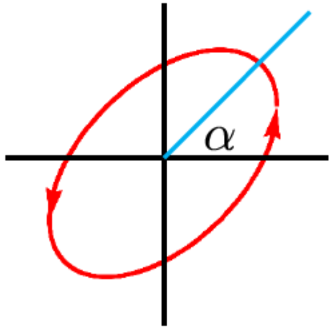
$DOP = \frac{\sqrt{s_1^2 + s_2^2 + s_3^2}}{s_0}$ *"Degree of polarization"*



Poincare' Sphere

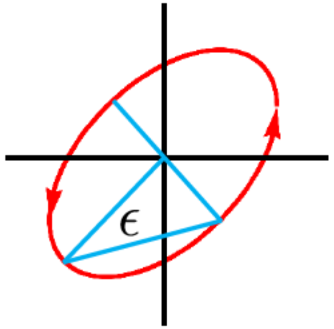
Four Intensity measurements with analyzers uniquely characterize polarization

The Stokes vector S correspond to physical properties of the polarization ellipse.



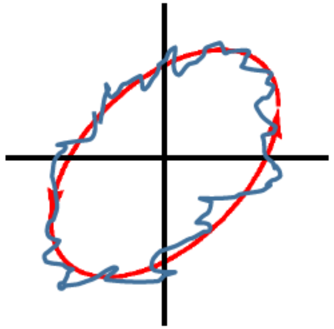
Azimuth

$$\alpha(\vec{S}) = \arctan \frac{S_2}{S_1}$$



Ellipticity

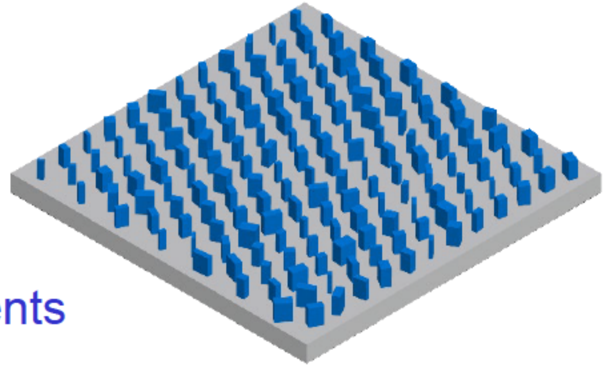
$$\epsilon(\vec{S}) = \arctan \frac{S_3}{\sqrt{S_1^2 + S_2^2}}$$

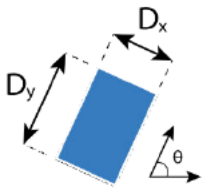

Degree of polarization

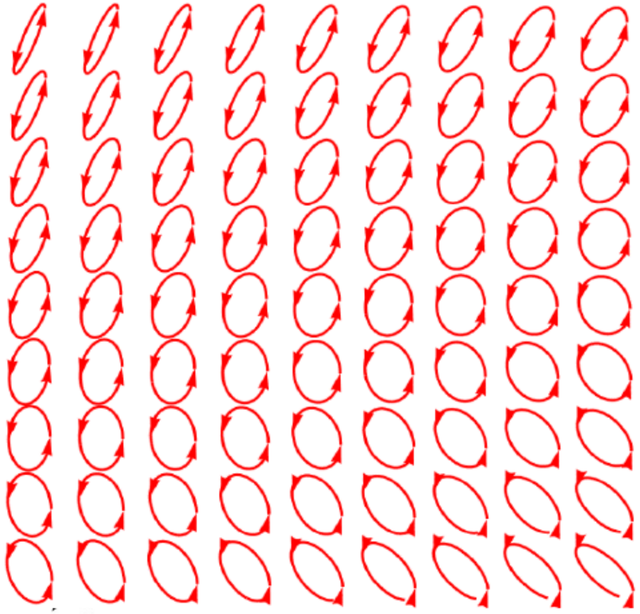
$$p(\vec{S}) = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

Metasurfaces and polarization optics

- Subwavelength arrays of shape-birefringent elements – custom waveplates on a subwavelength scale
- Engineered polarization-dependent behavior
- Spatially-varying polarization







Linearly birefringent elements
Liner eigen polarizations

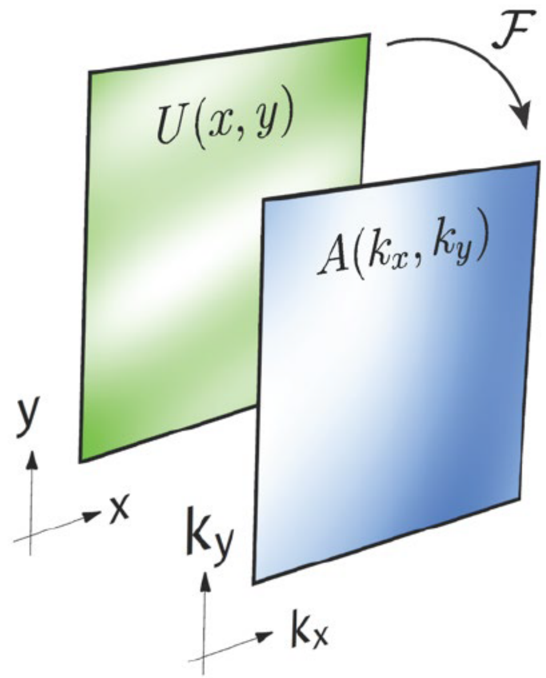
Jones Matrix $$J = R(-\theta)\begin{bmatrix} e^{i\phi_x} & 0 \\ 0 & e^{i\phi_y} \end{bmatrix} R(\theta)$$

Z. Bomzon, G. Biener, V Kleiner, and E Hasman, *Opt. Lett.* **27**, 13 (2002)

A. Arbabi et al., *Nat. Nanotech.* **10,** 11 (2015)

J. P. Balthasar et al., *Phys. Rev. Lett.* **118,** 113901 (2017)

Jones matrix Fourier optics



Scalar obstacle, scalar far-field.

The two are linked by Fourier transform.

With metasurfaces, we should think about a plane wave decomposition over *Jones matrices:*

$$\tilde{J}(x,y) = \begin{bmatrix} J_{11}(x,y) & J_{12}(x,y) \\ J_{21}(x,y) & J_{22}(x,y) \end{bmatrix}$$

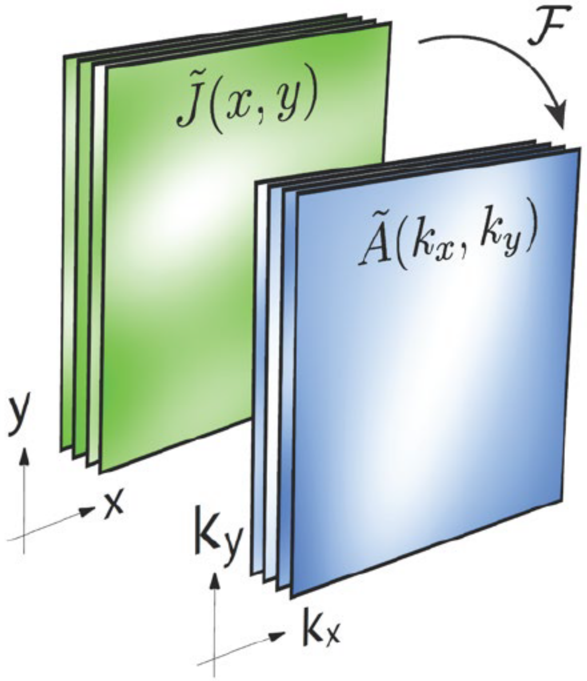
Spatially-varying Jones matrix

Describes a metasurface

$$\Big\downarrow \mathcal{F}$$

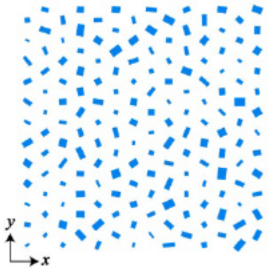
$$\tilde{A}(k_x,k_y) = \begin{bmatrix} A_{11}(k_x,k_y) & A_{12}(k_x,k_y) \\ A_{21}(k_x,k_y) & A_{22}(k_x,k_y) \end{bmatrix}$$

Jones matrix describing polarization-dependent **behavior** of the far-field the metasurface creates, irrespective of the polarization of illumination.

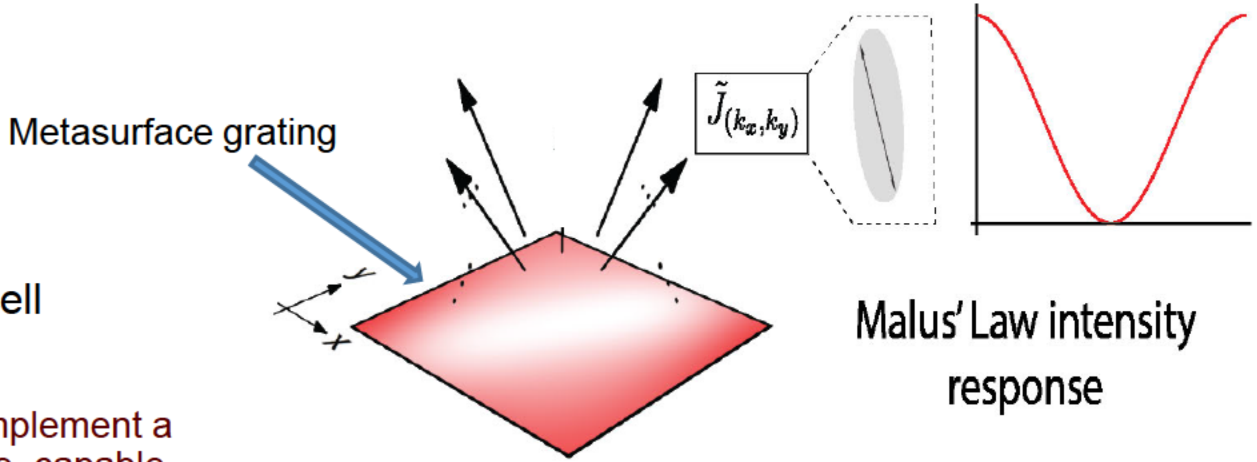


N.A. Rubin, G.A. D'Aversa, P. Chevalier, Z. Shi, W.T. Chen, and F. Capasso, "Matrix Fourier optics enables a compact full-Stokes polarization camera", *Science* **365** (6445), 2019

Polarization imaging with metasurfaces



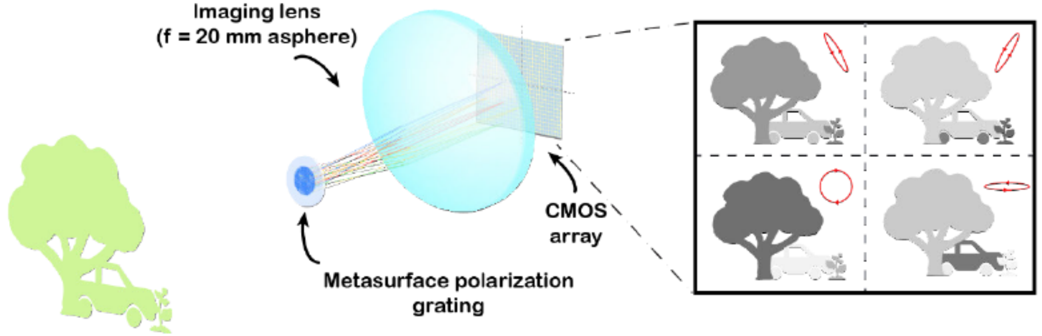
Metasurface unit cell



- Each diffraction order of a metasurface grating can implement a different polarization device ,capable of analyzing an arbitrary state of polarization (elliptical)

- These orders can act as polarizers with a Malus' Law intensity response

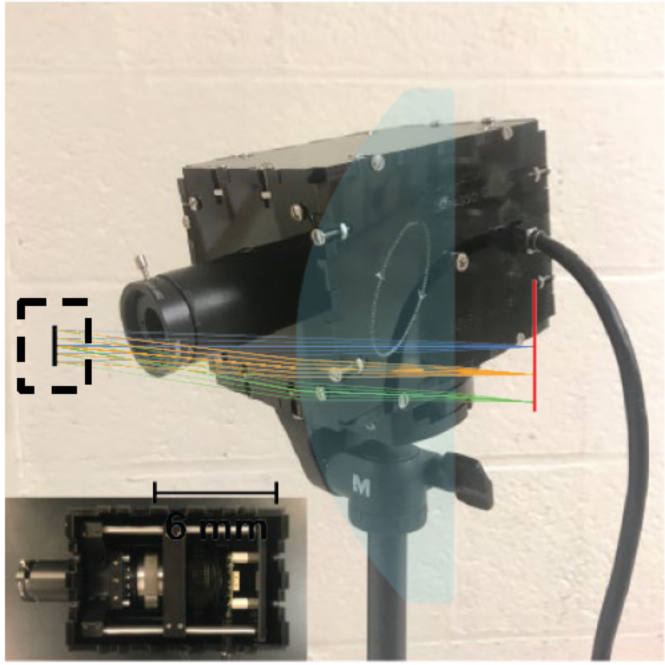
- This grating can be used to construct a polarization camera with a minimum of componentry



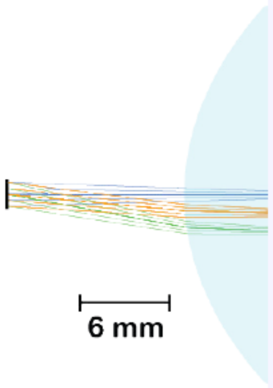
Each point of the scene is analyzed by 4 polarizers and projected in 4 corners: 4 copies of the scene Are then overlapped to provide point by point polarization Information (Stokes parameters)

N.A. Rubin et al. , Matrix Fourier optics enables a compact full-Stokes polarization camera, *Science*, **365**, 6448 (2019)

Metasurface polarization camera

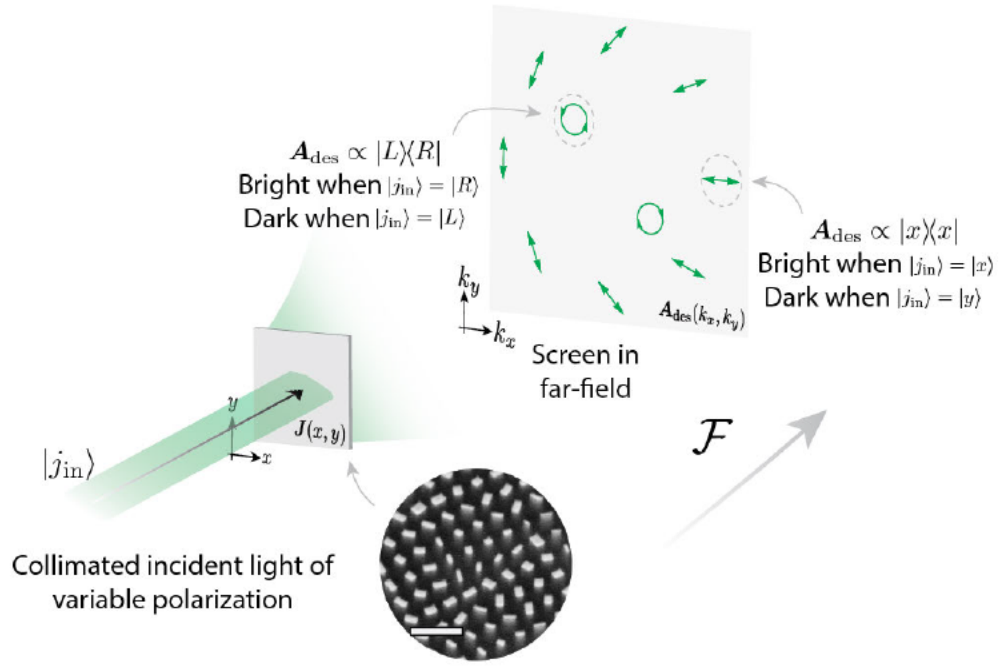


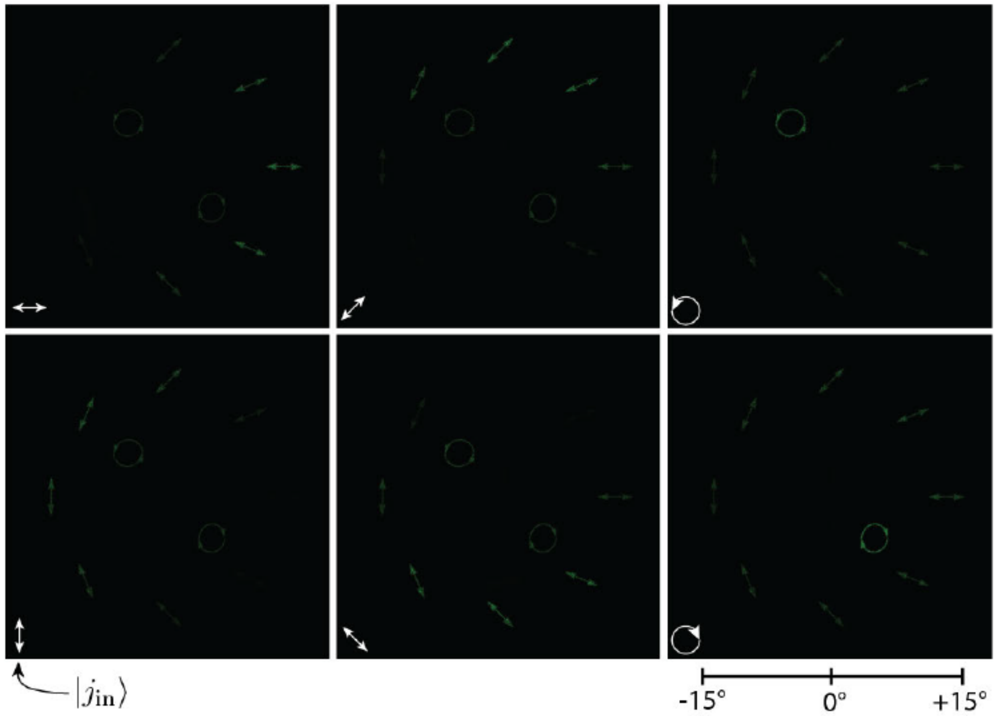
Packaged prototype with user interface for real-time polarization imaging indoor and outdoor.



Part-3: Jones-matrix metasurface holography

A single polarization-switchable metasurface device that analyzes for arbitrarily many polarization states in parallel at the far field





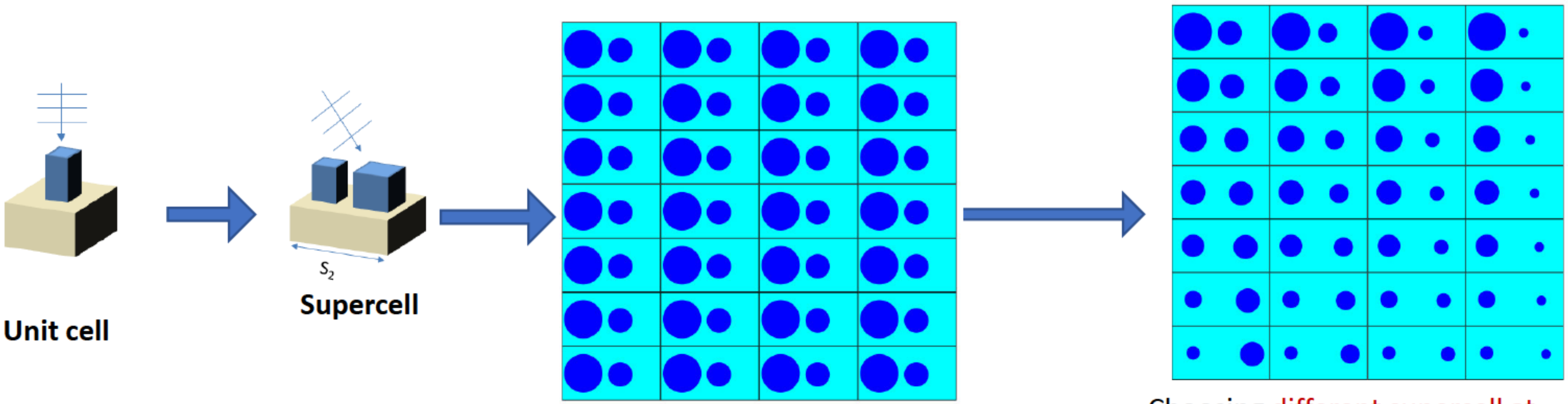
Paper 11833-7

Jones matrix holography with metasurfaces

On demand starting 1 August 2021

NA Rubin, A Zaidi, AH Dorrah, Z Shi, and F Capasso, arXiv:2012:14874, 2020.
In press: *Science advances*

Supercell metasurfaces

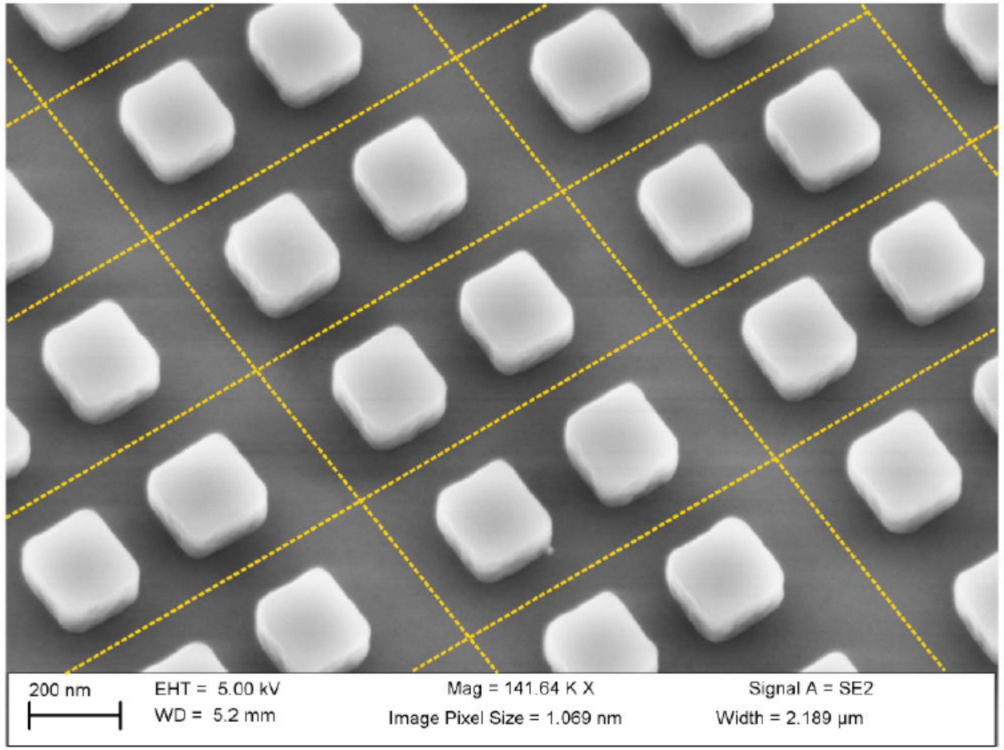


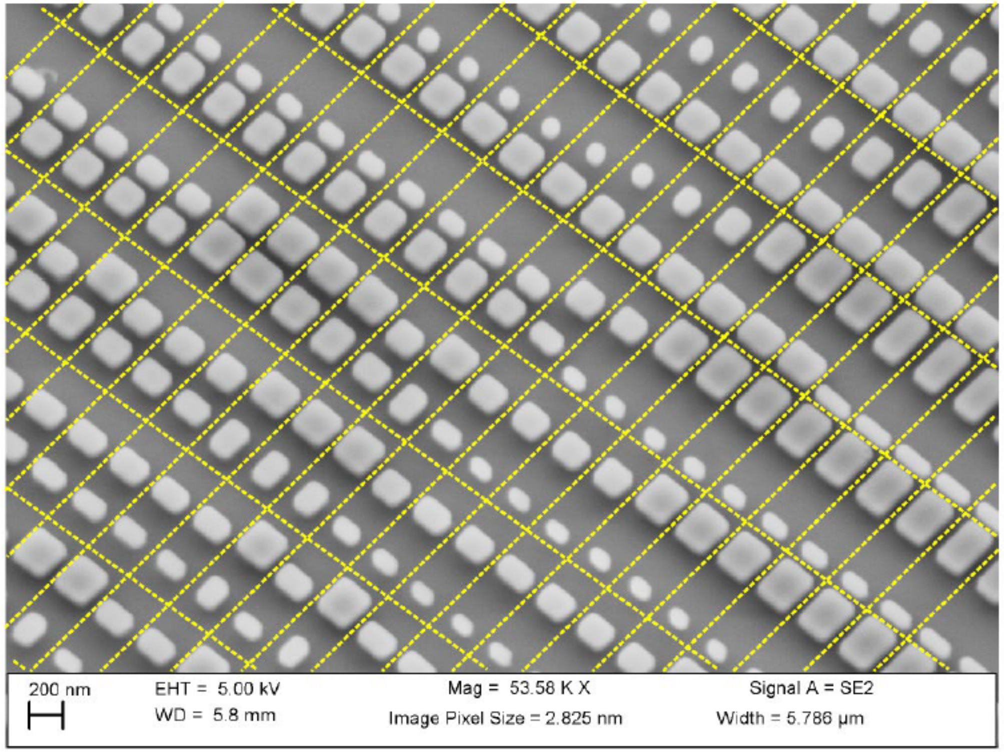
Meta-grating
the simplest type
of supercell metasurface

Choosing different supercell at different positions leads to independent phase control on each order using a supercell library

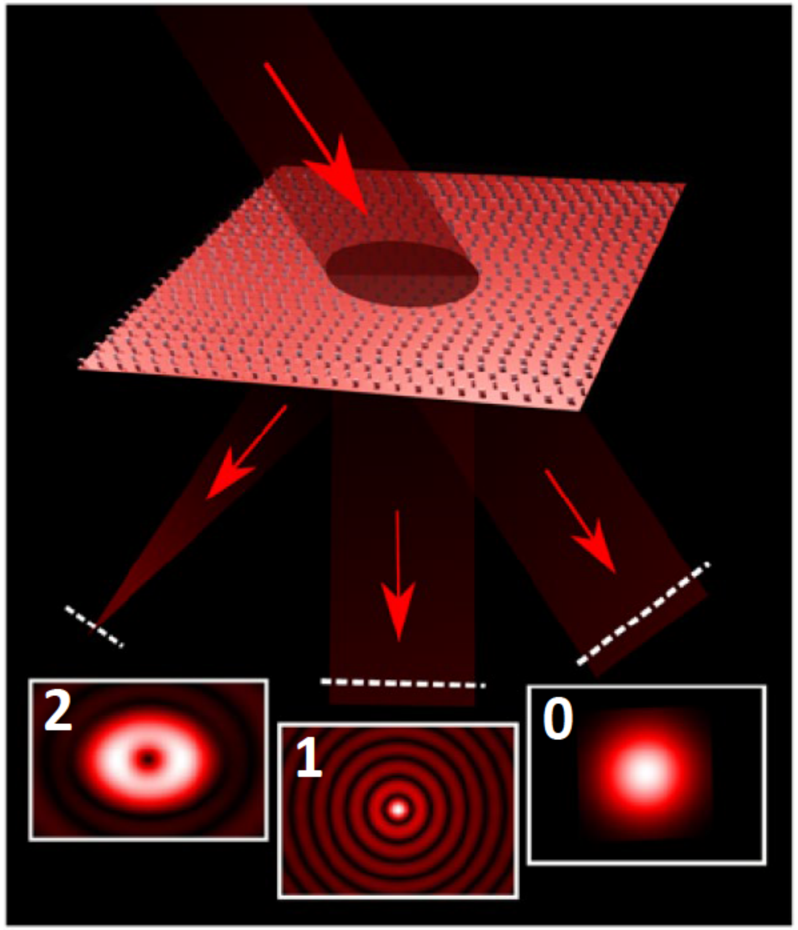
- Christina Spägele, Michele Tamagnone, Dmitry Kazakov, Marcus Ossiander, Marco Piccardo, and Federico Capasso. "Multifunctional wide-angle optics and lasing based on supercell metasurfaces." Nature Communications 12, 3787 (2021)

Micrograph of supercell metasurfaces





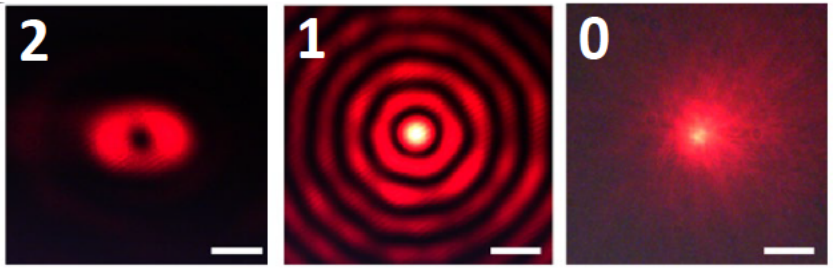
Multifunctional wide-angle optics based on supercell metasurfaces



Simulations

This device operates in transmission and was used as a test and demonstration of the key idea. An incident gaussian beam is split in three beams with different functions:

- *The 0th order is left unchanged*
- *The 1st order is shaped as a Bessel beam*
- *The 2nd order is shaped as a focused vortex beam*



Experiment

➢ Christina Spägele, Michele Tamagnone, Dmitry Kazakov, Marcus Ossiander, Marco Piccardo, and Federico Capasso. "Multifunctional wide-angle optics and lasing based on supercell metasurfaces." Nature Communications 12, 3787 (2021)

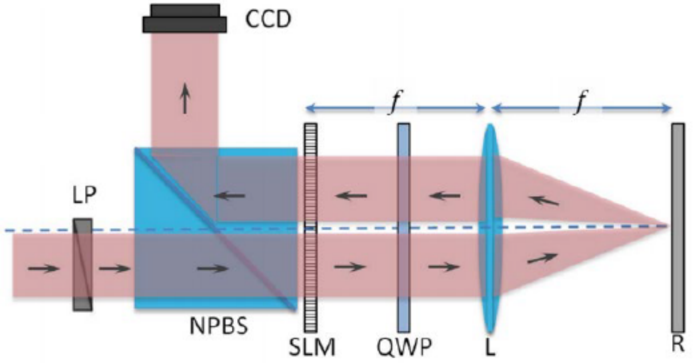
Challenges in digital holography

Spatial light modulators (SLMs)

SLM pixel

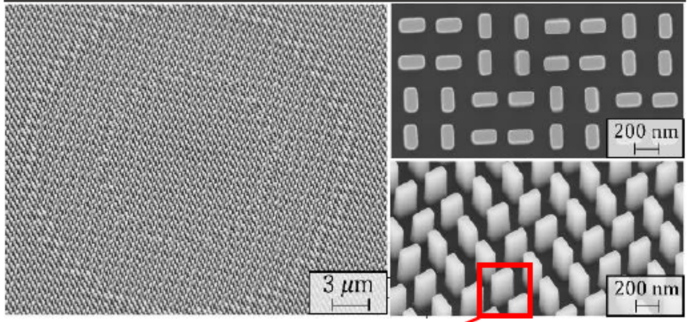
- Operates on one polarization at a time
  → either $\hat{x}$ or $\hat{y}$
- Modeled by a scalar value: $e^{i\theta}$

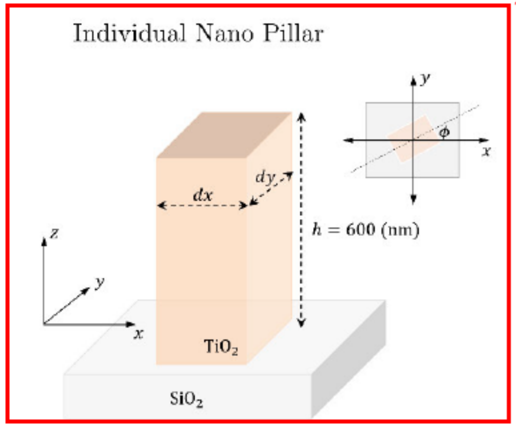
We need 2 SLMs (+ polarization optics) to generate vector beams!



I. Moreno, J. A. Davis, M. M. Sánchez-López, K. Badham, and D. M. Cottrell, *Optics Letters* **40**, 23 (2015)

Metasurface





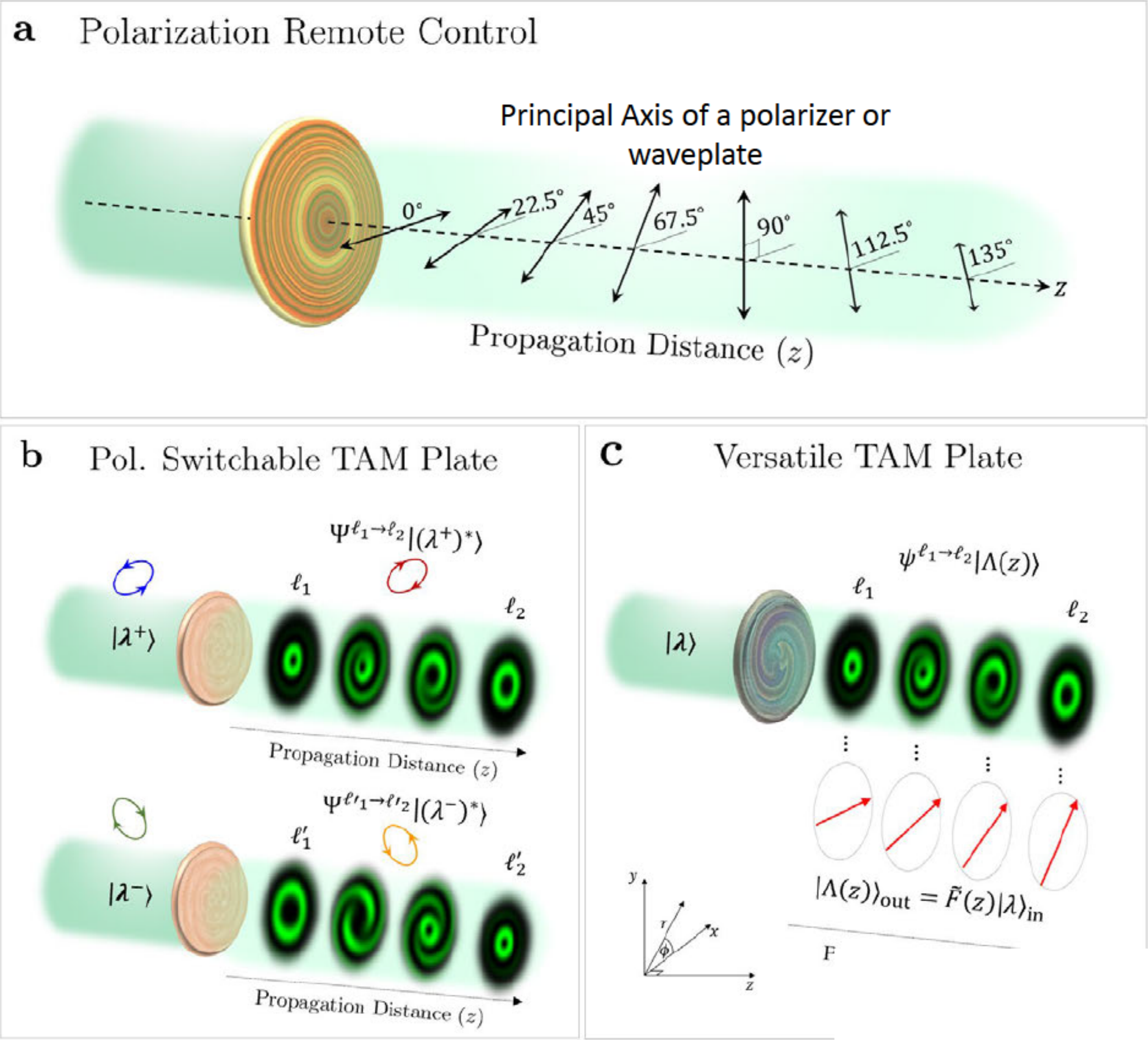
Metasurface unit-cell:

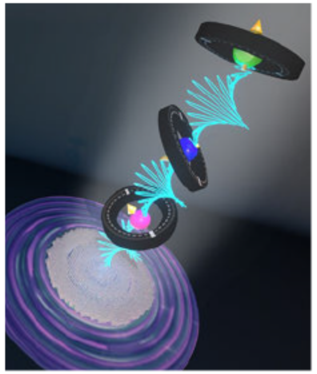
- 2 independent phases for $\hat{x}$ and $\hat{y}$ polarizations by varying the nanofin dimensions.
- A geometric phase by rotating the nanofin.

Each pixel modeled by 2×2 Jones matrix

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

Structuring light in the propagation direction
OAM/SAM control in 3D with metasurfaces





Novel optical elements that modify the polarization behavior along the propagation direction of a waveform (e.g., a z-dependent linear polarizer or waveplate)

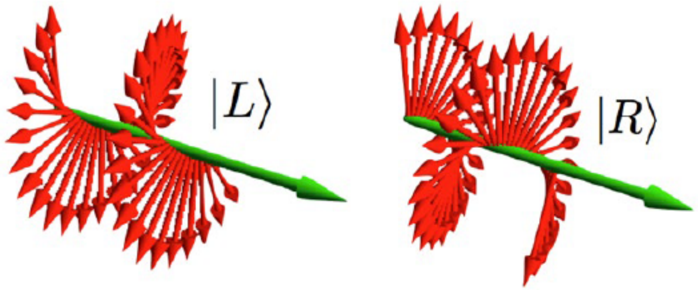
Meta-optics which control OAM/SAM along the optical path

The evolution occurs only locally while keeping both the global OAM and SAM conserved across the transverse plane

- **Micromanipulation and colloid sorting in 3D**
- **Novel communication schemes**

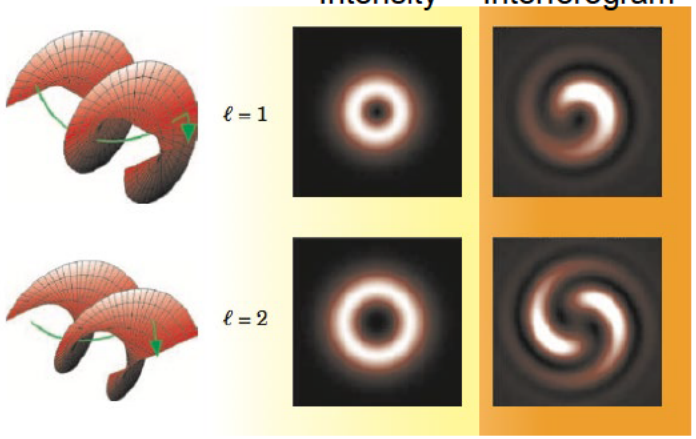
Spin and Orbital Angular Momentum of Light

Spin angular momentum (SAM)



- Circularly polarized light (RCP or LCP)
- $S = \sigma\hbar$ per photon, $\sigma = \pm 1$

Orbital angular momentum (OAM)



- Independent of the beam's polarization
- Helical phase front $\exp(i\ell\phi)$
- Spiral path of Poynting vector
- $L = \ell\hbar$ per photon, ℓ is integer

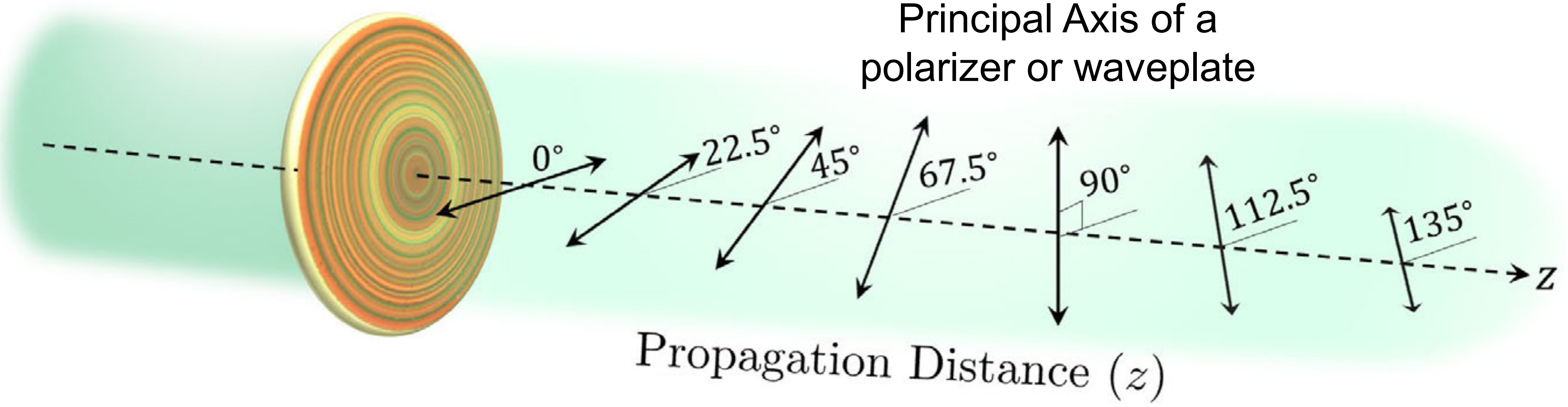
Total angular momentum (TAM)

- $J = (\ell + \sigma)\hbar$ per photon

valid for paraxial beams

Change of polarization along the propagation direction

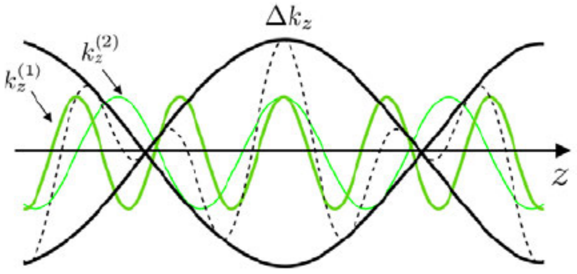
A new class of optical elements that modify the polarization behavior along the propagation direction of a waveform (e.g., a z-dependent linear polarizer or waveplate)



Ideally, we require a Bessel-like beam that propagates for long distance while overcoming diffraction

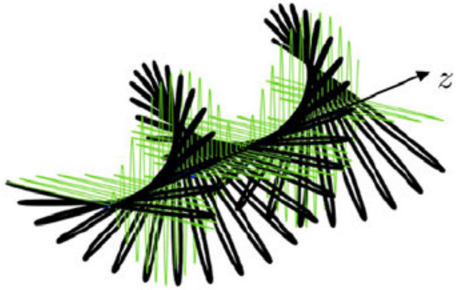
Concept: Spatial harmonic beating

Intensity Beating (Scalar case)



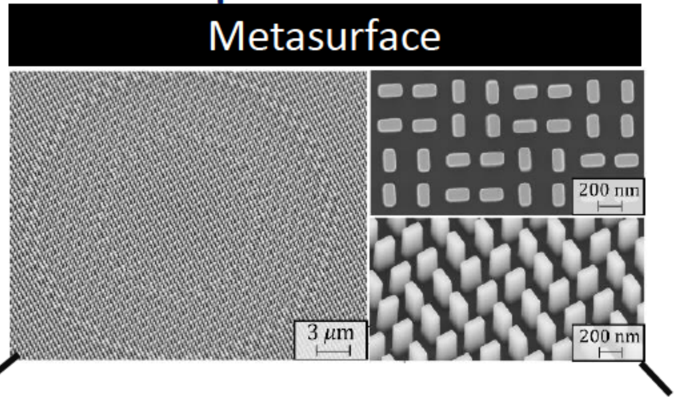
Interfering 2 plane waves with same frequency and polarization but different k_z

Polarization Beating (Vector case)



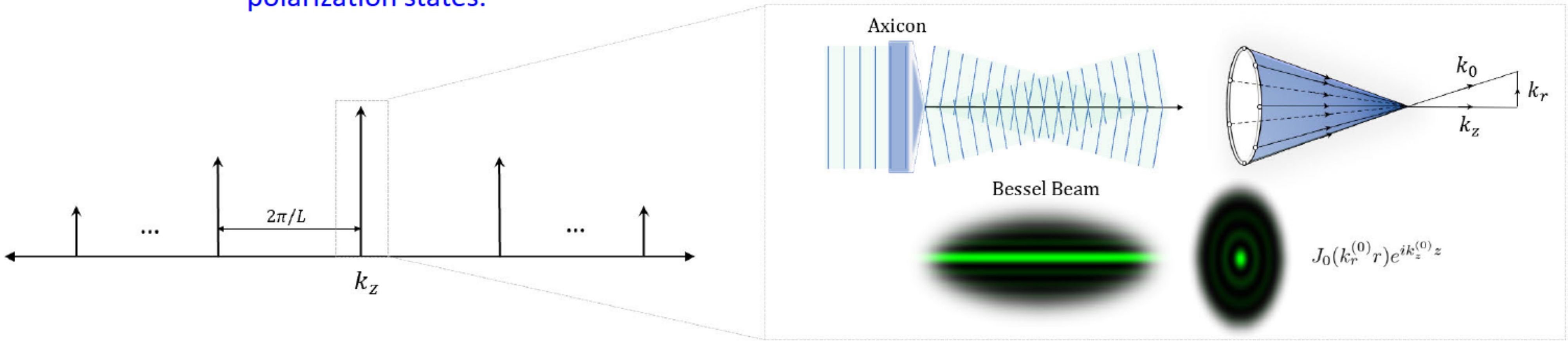
Interfering 2 plane waves with opposite circular polarization but different k_z

Metasurface Implementation*



The metasurface implements a superposition of pencil-like Bessel beams with different k_z (cone angles) and polarization states.

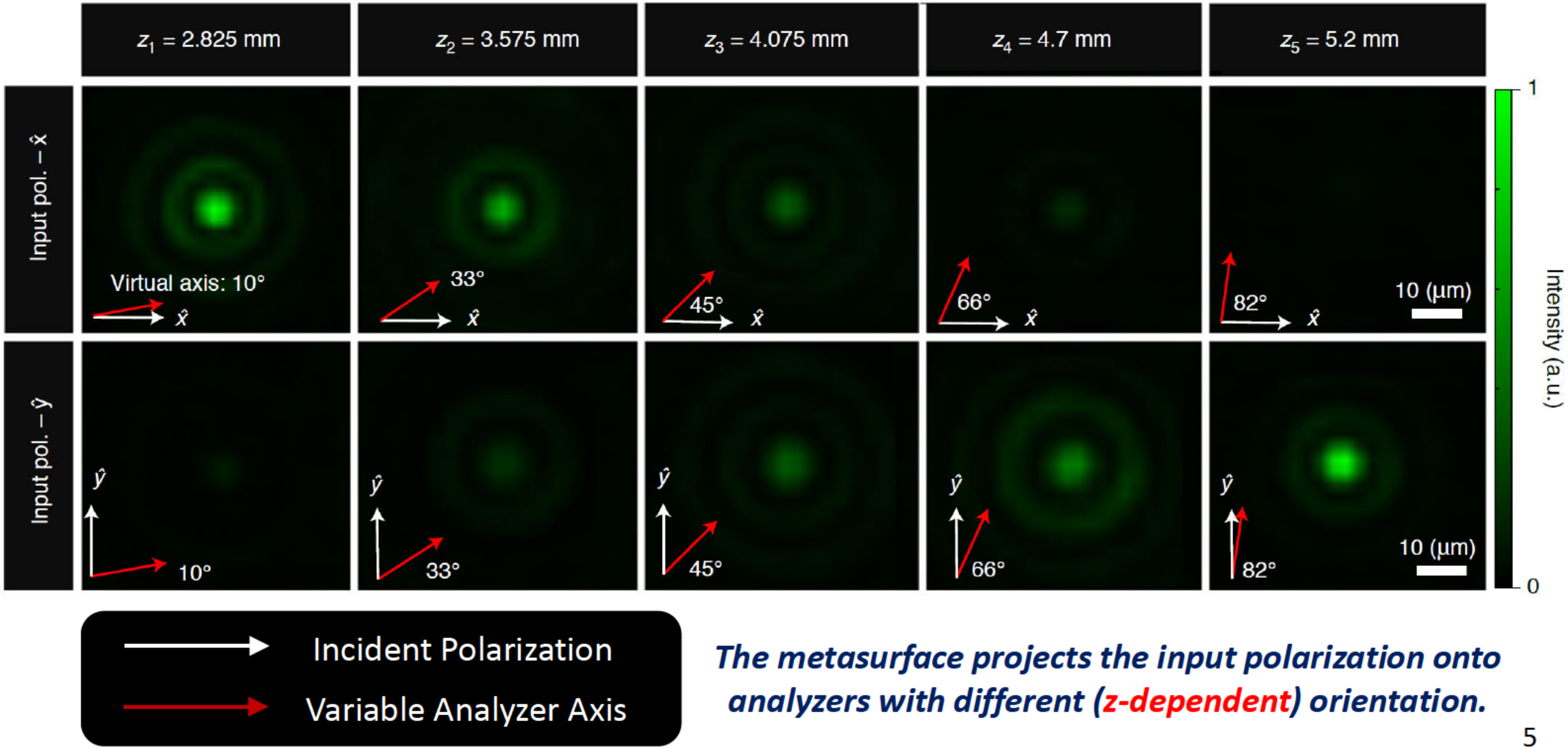
The device produces a non-diffracting beam over a distance L



*NA Rubin, G D'Aversa, P Chevalier, Z Shi, WT Chen, and F Capasso, *Science*, Vol. 365, Issue 6448, eaax1839 (2019).
*AH Dorrah, NA Rubin, A Zaidi, M Tamagnone, and F Capasso, *Nature Photonics* (2021).
https://doi.org/10.1038/s41566-020-00750-2

z-dependent polarizer: measured transverse profiles

A single multifunctional device that analyzes for different polarization states in parallel depending on the propagation distance, z.



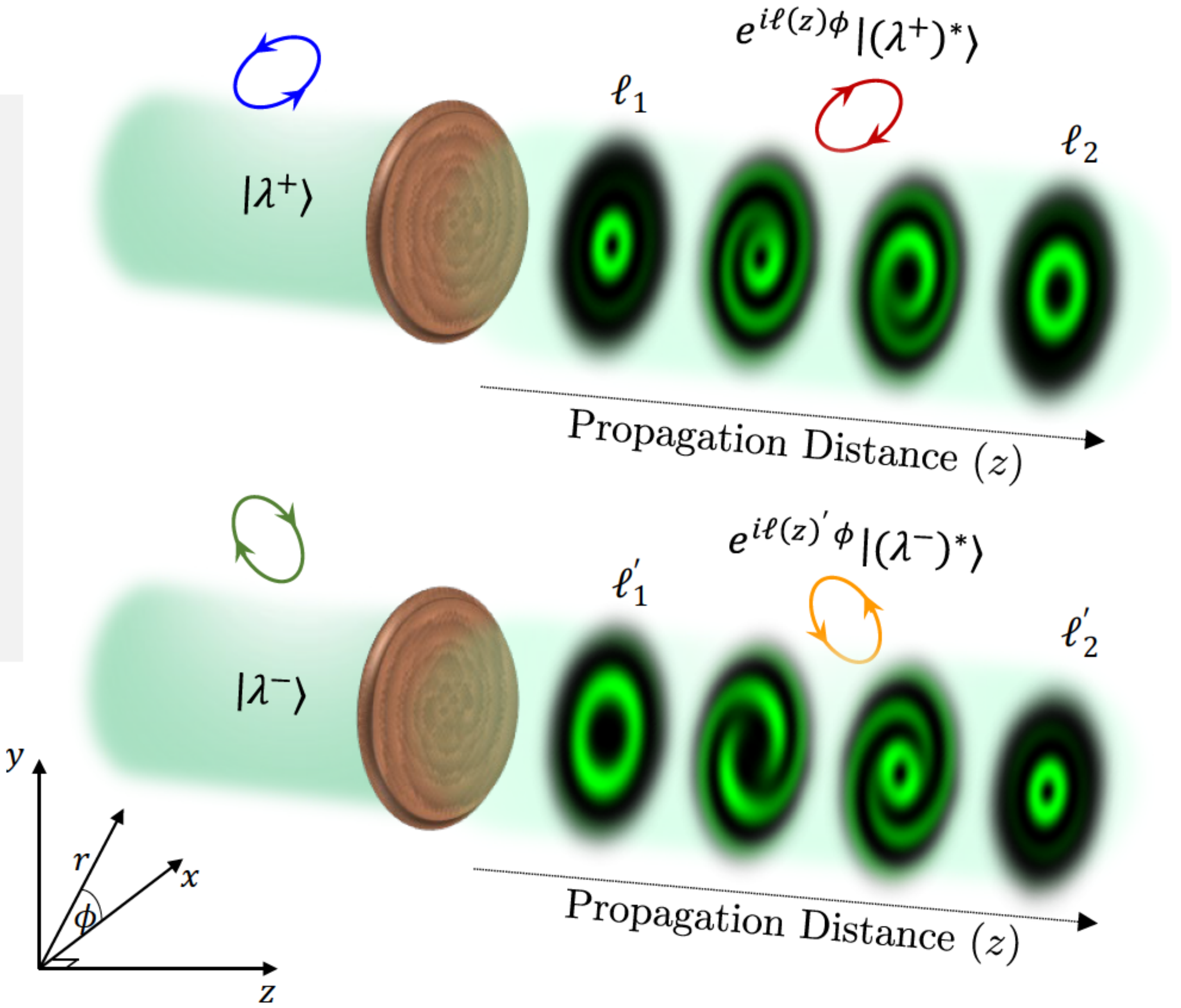
The metasurface projects the input polarization onto analyzers with different (z-dependent) orientation.

Meta-optics for 3D OAM control

- Polarization-switchable Device
- Generates vortex beams with **locally** variable topological charge (ℓ) along the optical path depending on incident polarization
- Global OAM always conserved!
- ℓ can be designed **independent of λ**

? **Can these different OAM states be launched into fibers?**

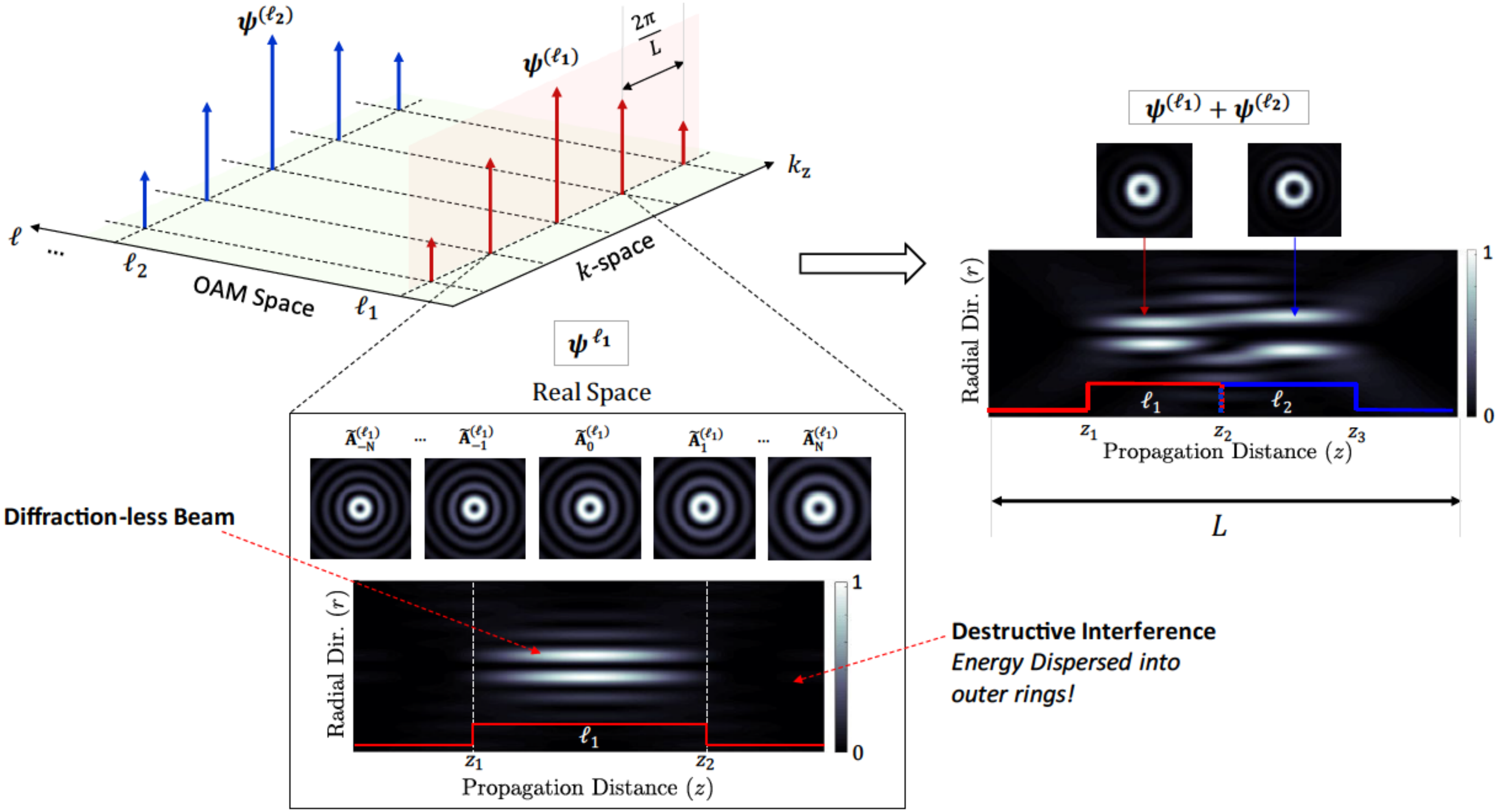
? **Applications**
Micromanipulation and sorting colloids?



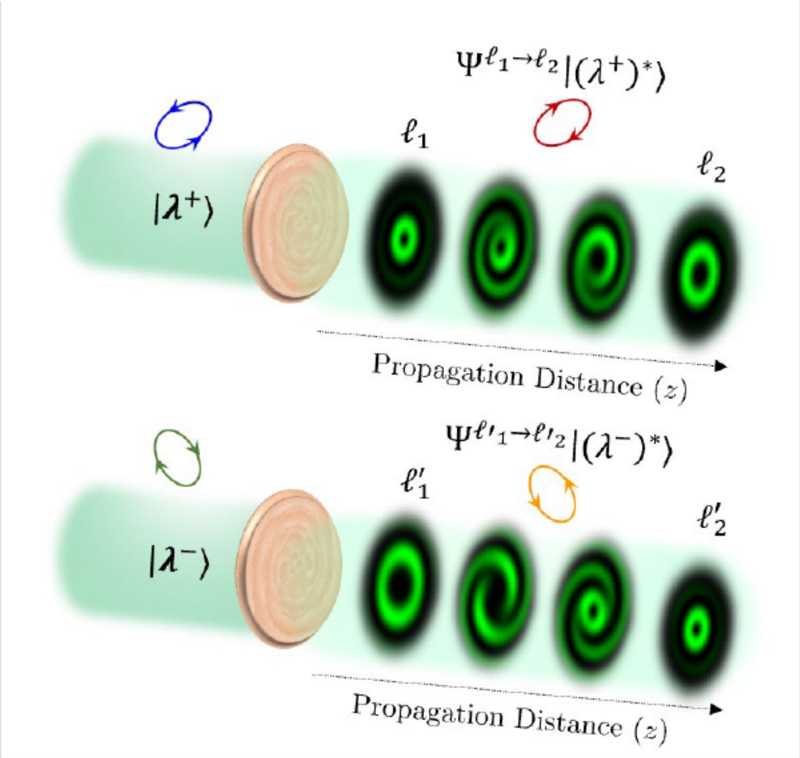
Design Strategy

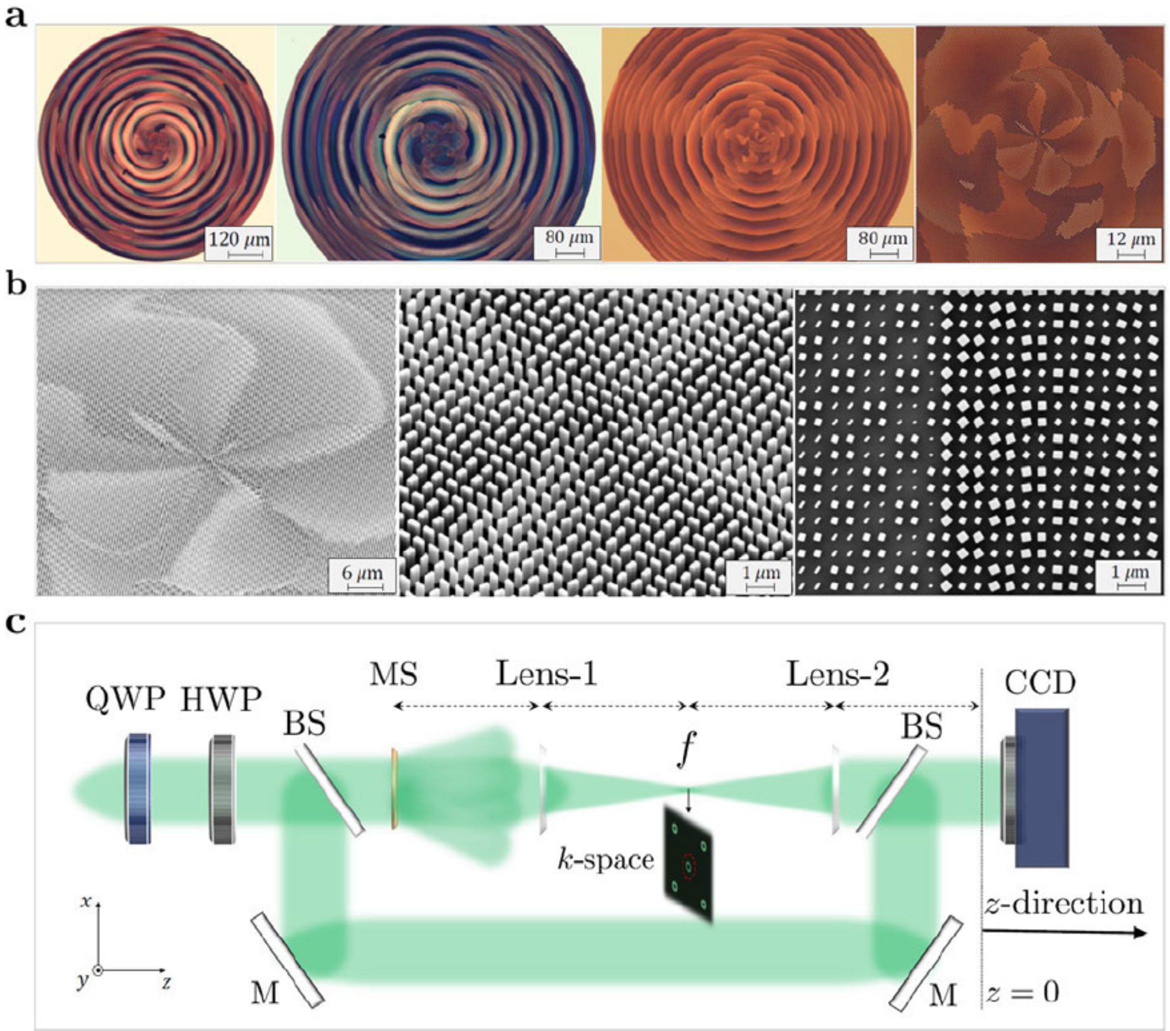
The OAM plate implements a series of OAM modes equally separated in k-space
("OAM combs" in **spatial frequency domain**)

⇨ **Spatial beating yields an envelope in which the ℓ value is modulated with propagation distance**



Polarization switchable Plate

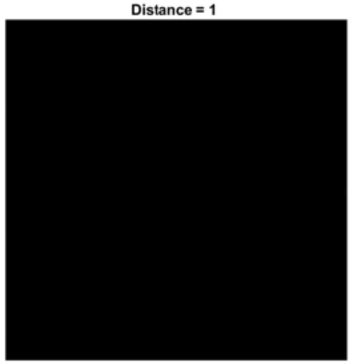




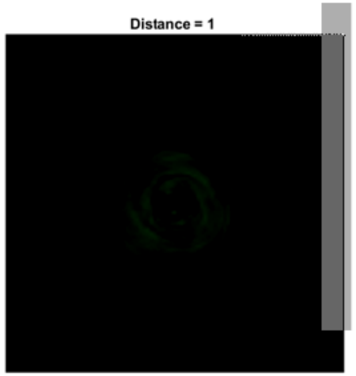
A device that creates optical vortices with propagation-dependent OAM. Output can switch depending on the incident polarization!

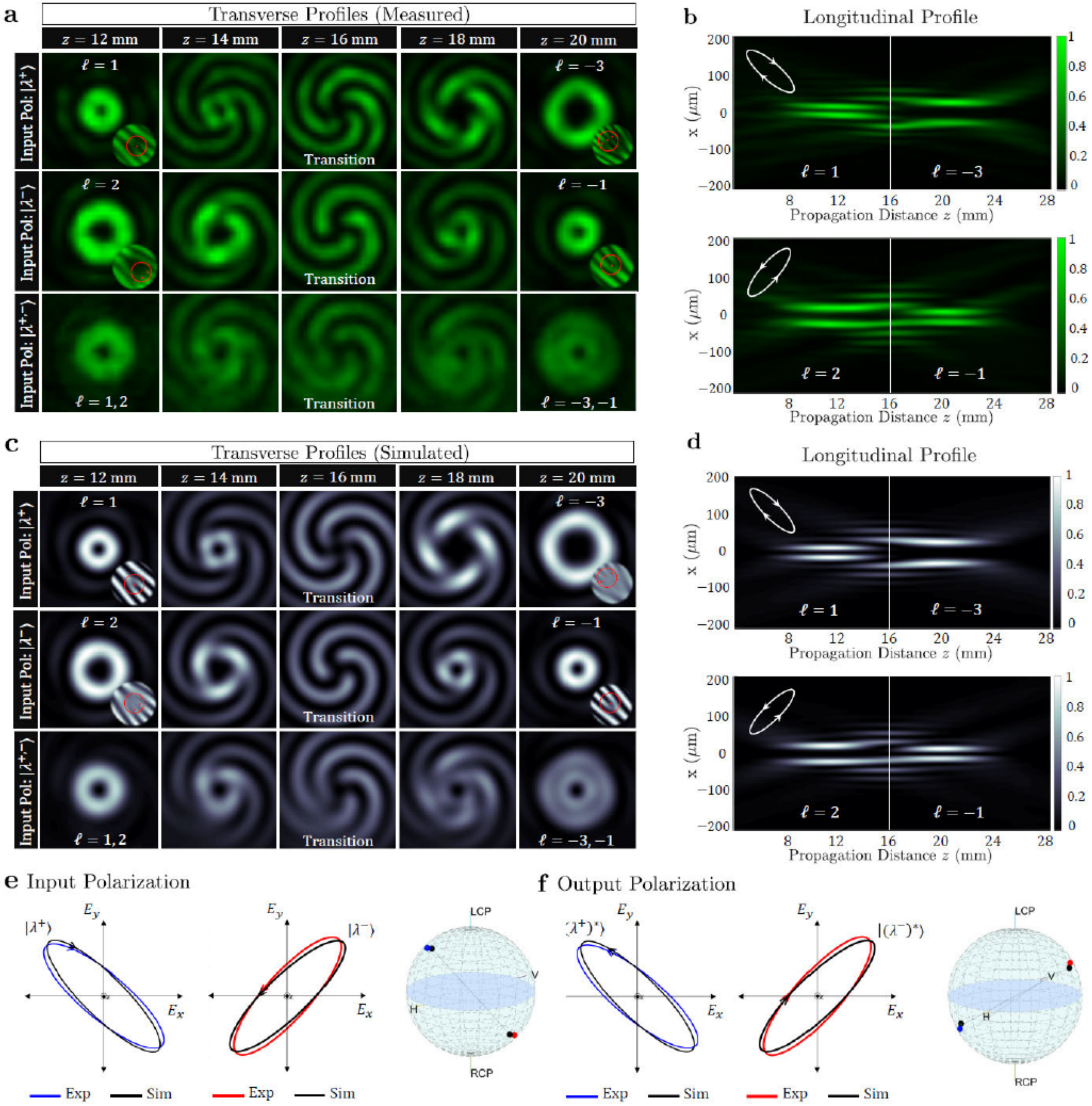
Elliptical eigen-polarizations

λ^+



λ^-

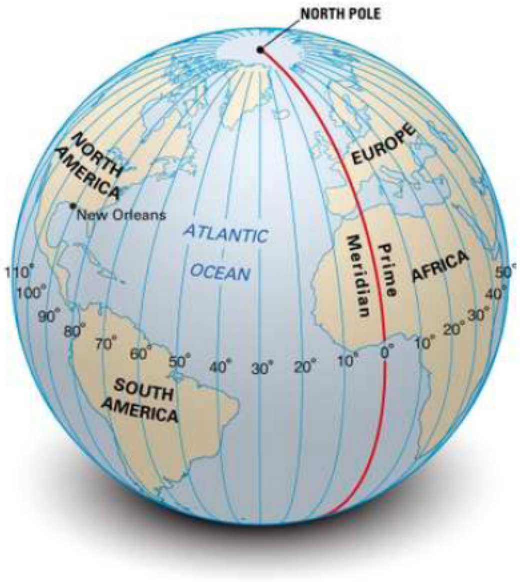




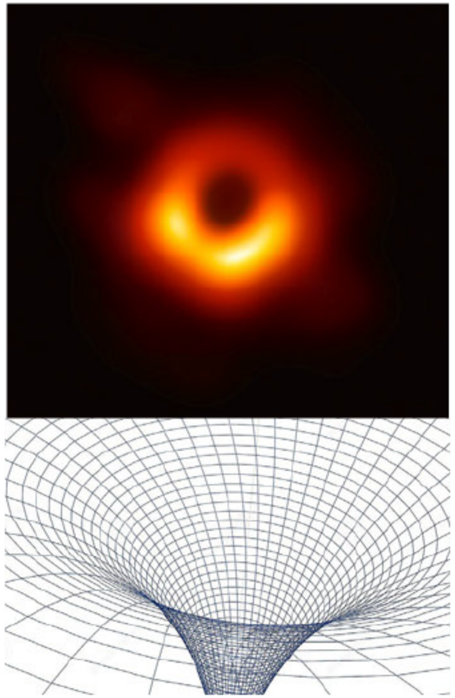
The dark side: Optical singularities

- Singularities occur when a parameter is not defined.

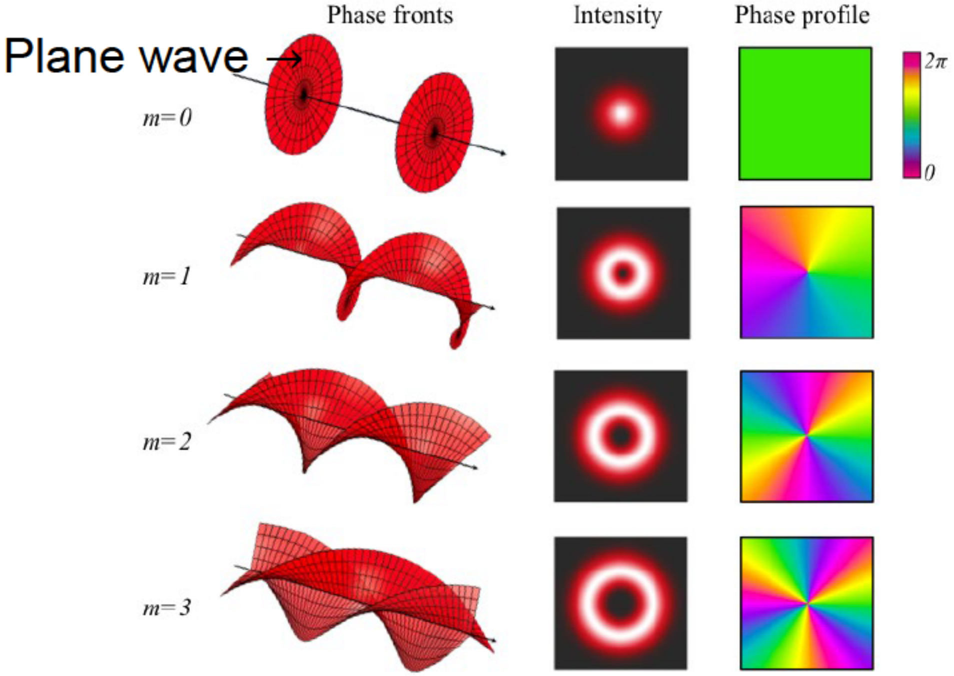
Coordinate singularity:
longitude not defined at the North/South Poles



Gravitational singularity:
gravitational field not defined at black hole center



Optical singularity:
One or more field parameters not defined

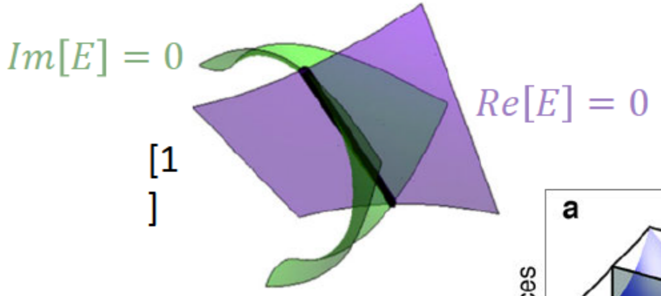


Orbital angular momentum (OAM) modes have **on-axis singularities** with **undefined phase**

Image sources:
- Event Horizon Telescope, https://www.eso.org/public/images/eso1907a/
- Encyclopedia Britannica, https://www.britannica.com/science/longitude
- *Computational Nonlinear & Quantum Optics Group*, University of Strathclyde http://cnqo.phys.strath.ac.uk/research/quantum-theory-of-light/optical-angular-momentum/oam-examples/

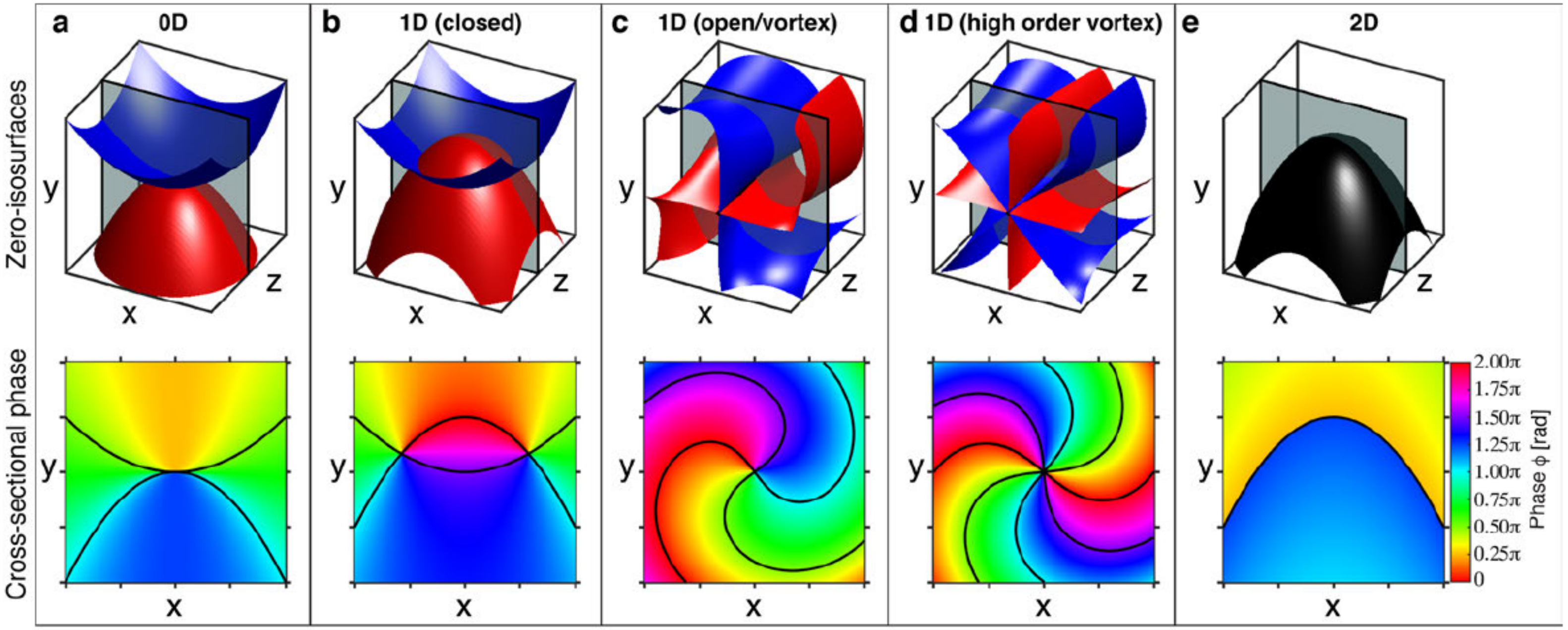
Structuring Dark via Phase Singularity Sheets

Concept: Singularity shapes depend on the intersection of zero-surfaces



- Consider complex scalar field $E(\boldsymbol{r}) = Re[E(\boldsymbol{r})] + i \cdot Im[E(\boldsymbol{r})] = 0$
- Intersection of surfaces $Re[E(\boldsymbol{r})] = 0$ and $Im[E(\vec{\boldsymbol{r}})] = 0$ gives singularity.
  - Two surfaces typically intersect on a line.

- 1D first-order singularities are robust against small field perturbations.
- 1D first-order singularity existence is preserved under small deformations or displacements of the zero-surfaces (topologically-protected).



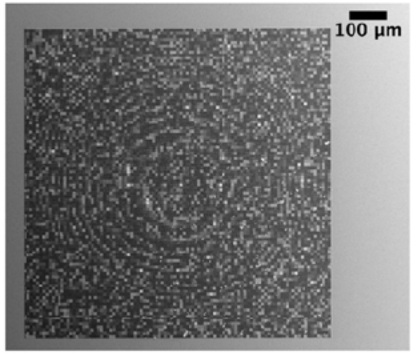
Our Recipe for sheet singularities: *maximize phase gradient orthogonal to desired sheet!*

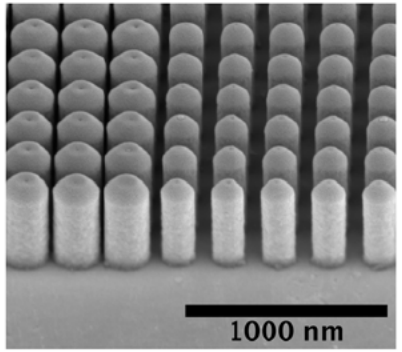
[1] Dennis, M, O'Holleran, K & Padgett, M. Chapter 5 Singular Optics: Optical Vortices and Polarization Singularities, *Progress in Optics* **53**, 293-363 (2009)
[2] Nye, J.F. & Berry M. Dislocations in Wave Trains, *P. Roy. Soc. A-Math. Phy.* **336**, 165-190 (1974)

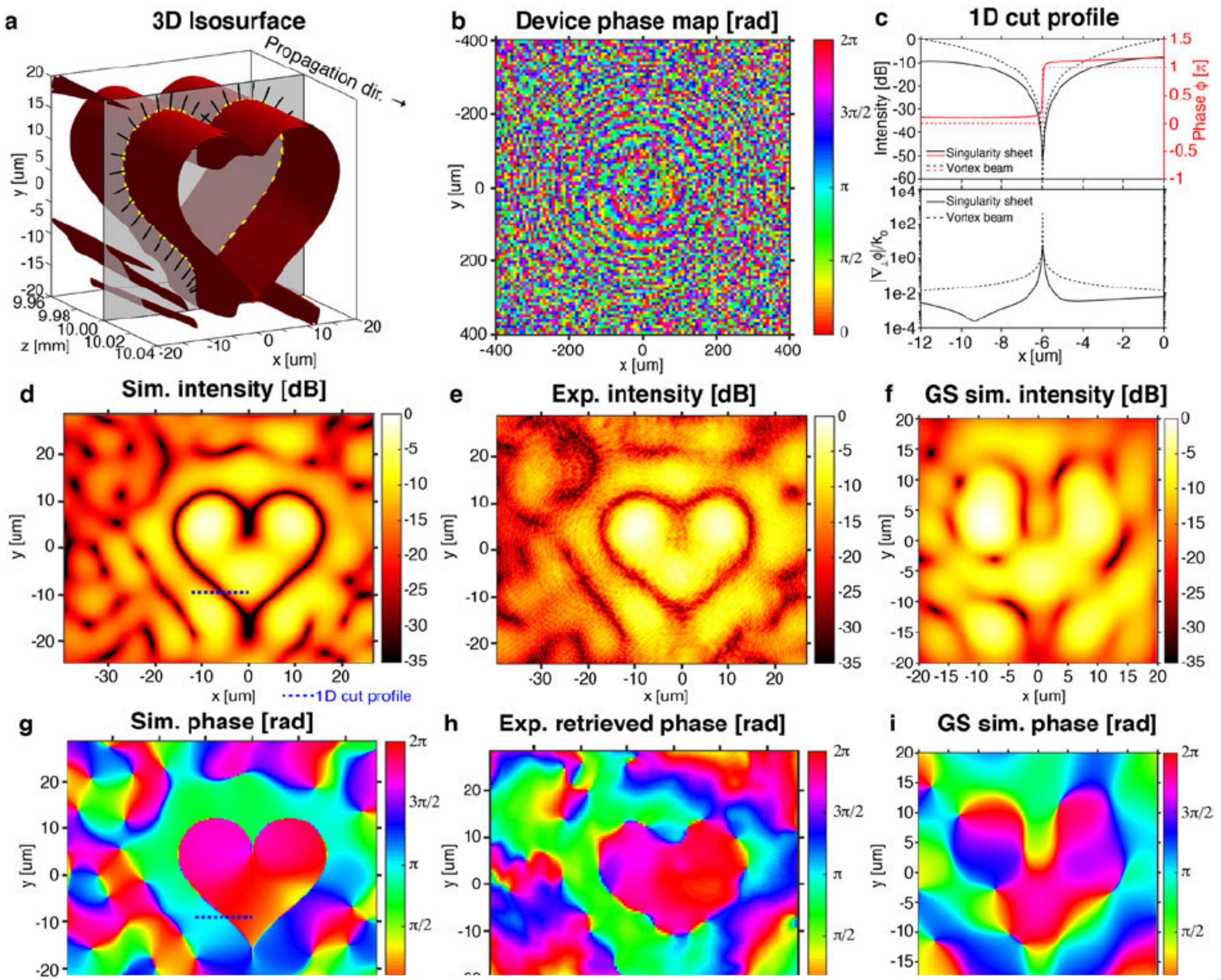
Heart-shaped phase sheet singularity

- Sheet singularity with heart-shaped cross-section designed using phase gradient maximization and fabricated.
  - For 532 nm wavelength.
  - Metasurface platform: TiO_2 nanopillars on SiO_2
- Fidelity and contrast attained is superior to that obtained using the Gerchberg-Saxton (GS) algorithm.

Full metasurface *Superpixel zoom in*

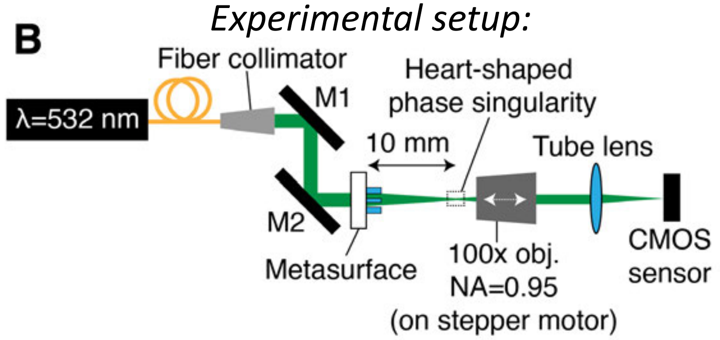






3D singularity sheet structure flythrough

Experimental setup:

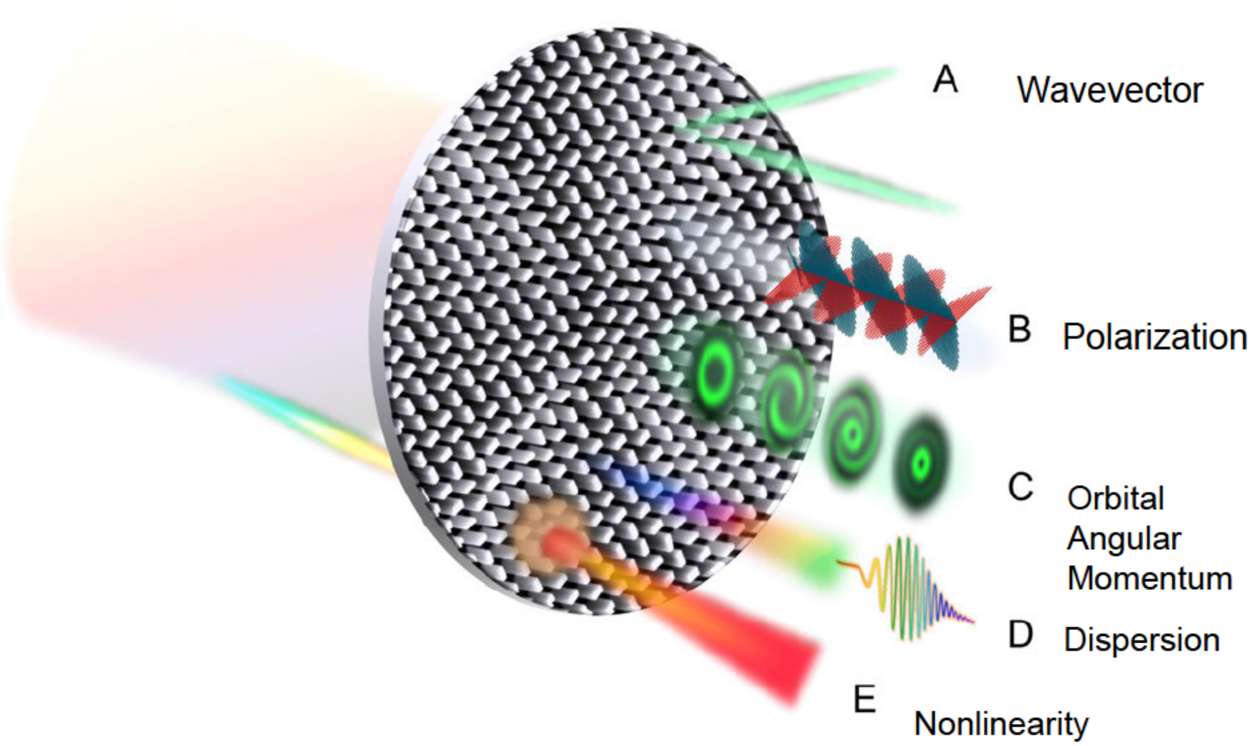


- Close correspondence between simulated and experimental intensity and phase profiles as a function of axial position (z).
- This sheet singularity is unstable with propagation, like fractional topological charge vortices [1-2] and high-order vortices.
  - But some highly symmetric sheet singularities are stable: e.g., 1D diffraction fringes, Bessel beam nodes.

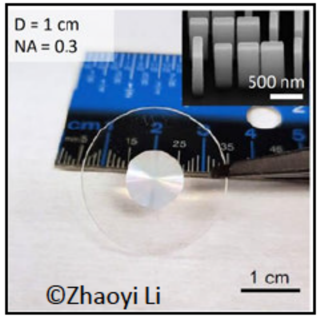
[1] Basistiy, I. V., Pas'ko, V. A., Slyusar, V. V., Soskin, M. S. & Vasnetsov, M. V. Synthesis and analysis of optical vortices with fractional topological charges. *Journal of Optics A: Pure and Applied Optics* **6**, S166–S169 (2004).
[2] Berry, M. v. Optical vortices evolving from helicoidal integer and fractional phase steps. *Journal of Optics A: Pure and Applied Optics* **6**, 259–268 (2004).

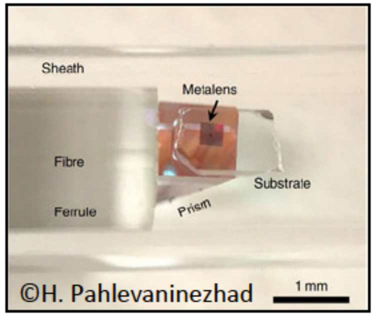
Capasso Group
Harvard School of Engineering and Applied Sciences

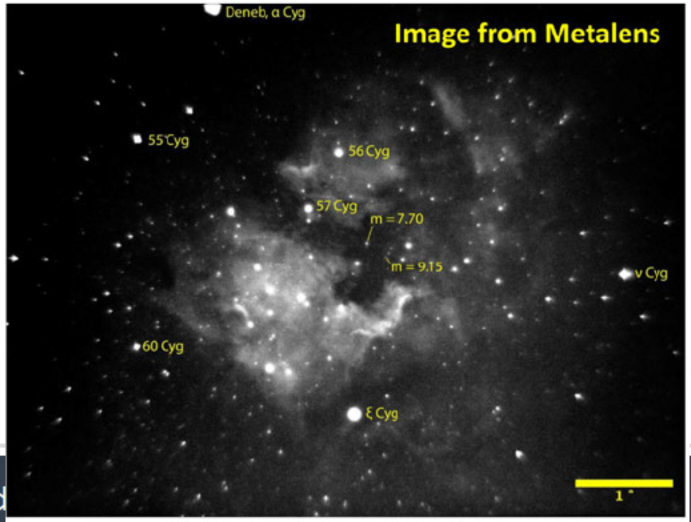
Multifunctional Metaoptics



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





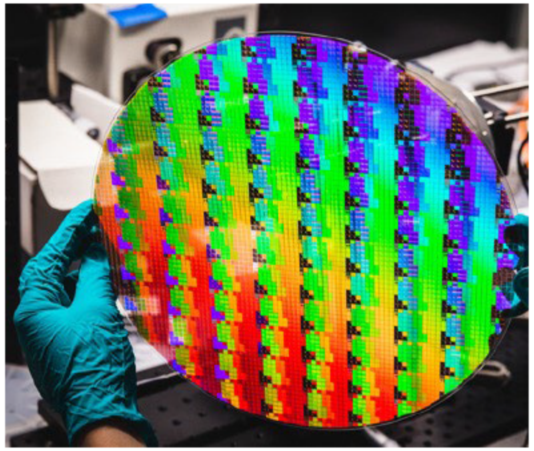


metalenz

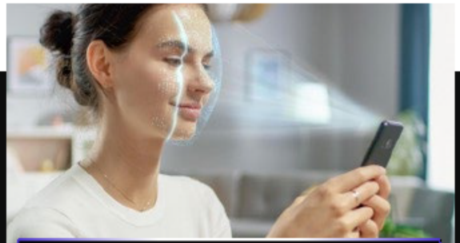
Enabling the next generation of sensing with **metasurface optics.**

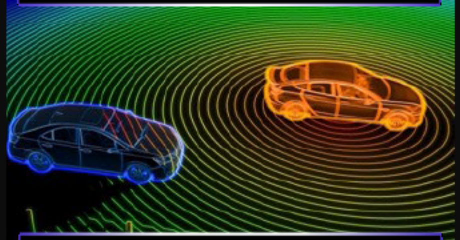
HARVARD UNIVERSITY

Harvard University spin out (Capasso Lab), commercializing foundational metasurface IP



- Fabless optical semiconductor company with multiple foundry partners.
- Introduced world's first metasurfaces to the consumer device market in 2022.
- Simplifying and proliferating advanced optical sensing
- Based in downtown Boston with >40 employees.





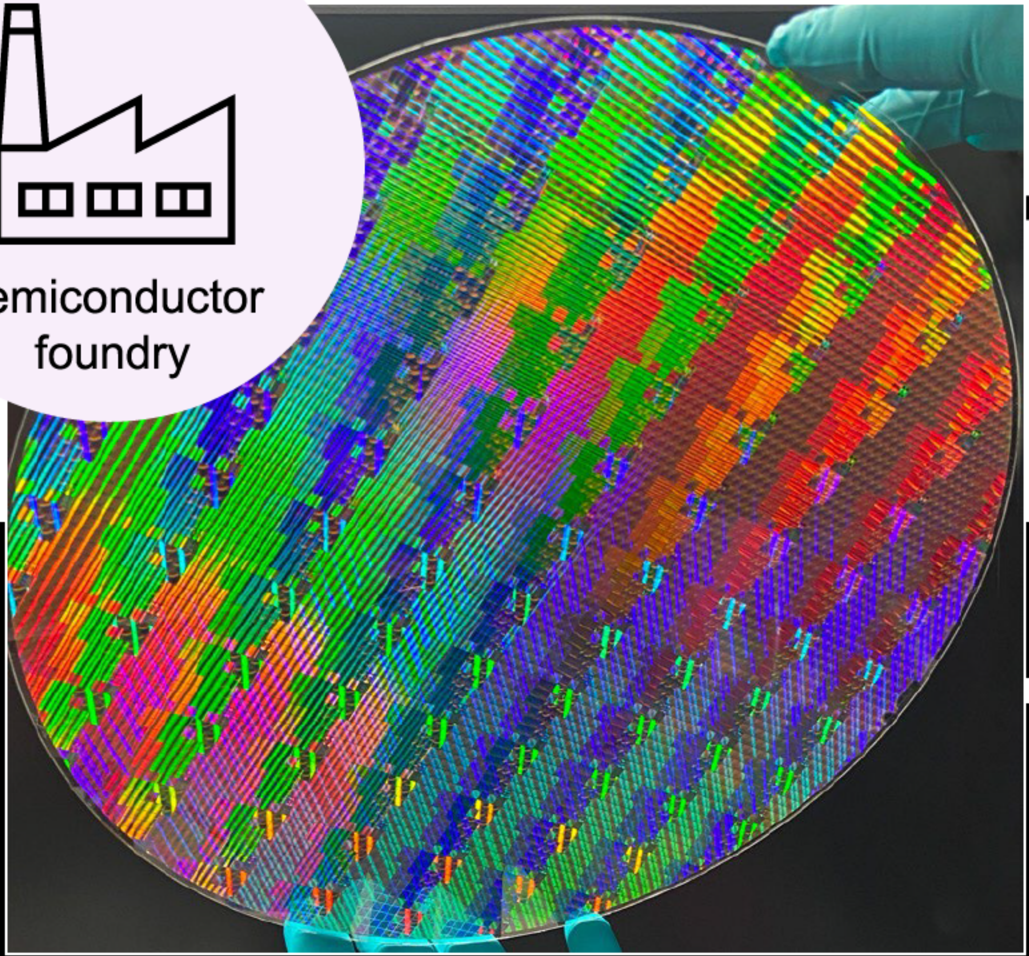
NEOTRIBE | 3M | TDK VENTURES | intel capital | APPLIED Ventures | foothill ventures | M. VENTURES | BRAEMAR ENERGY VENTURES | global brain | SGINNOVATE

Supply Chain Consolidation

Enabling the optical foundry

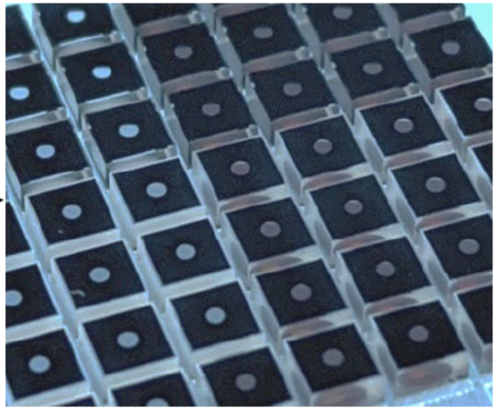
semiconductor foundry

optic design file



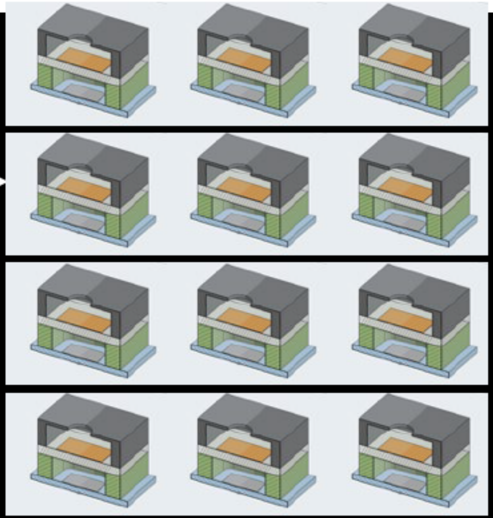
12-inch wafer ~7,000 meta-optics

Singulation



1000s of lens chips

Back-end integration

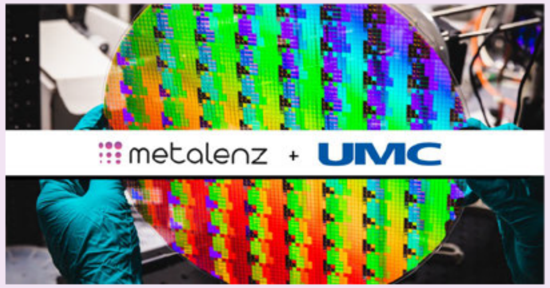


metalenz

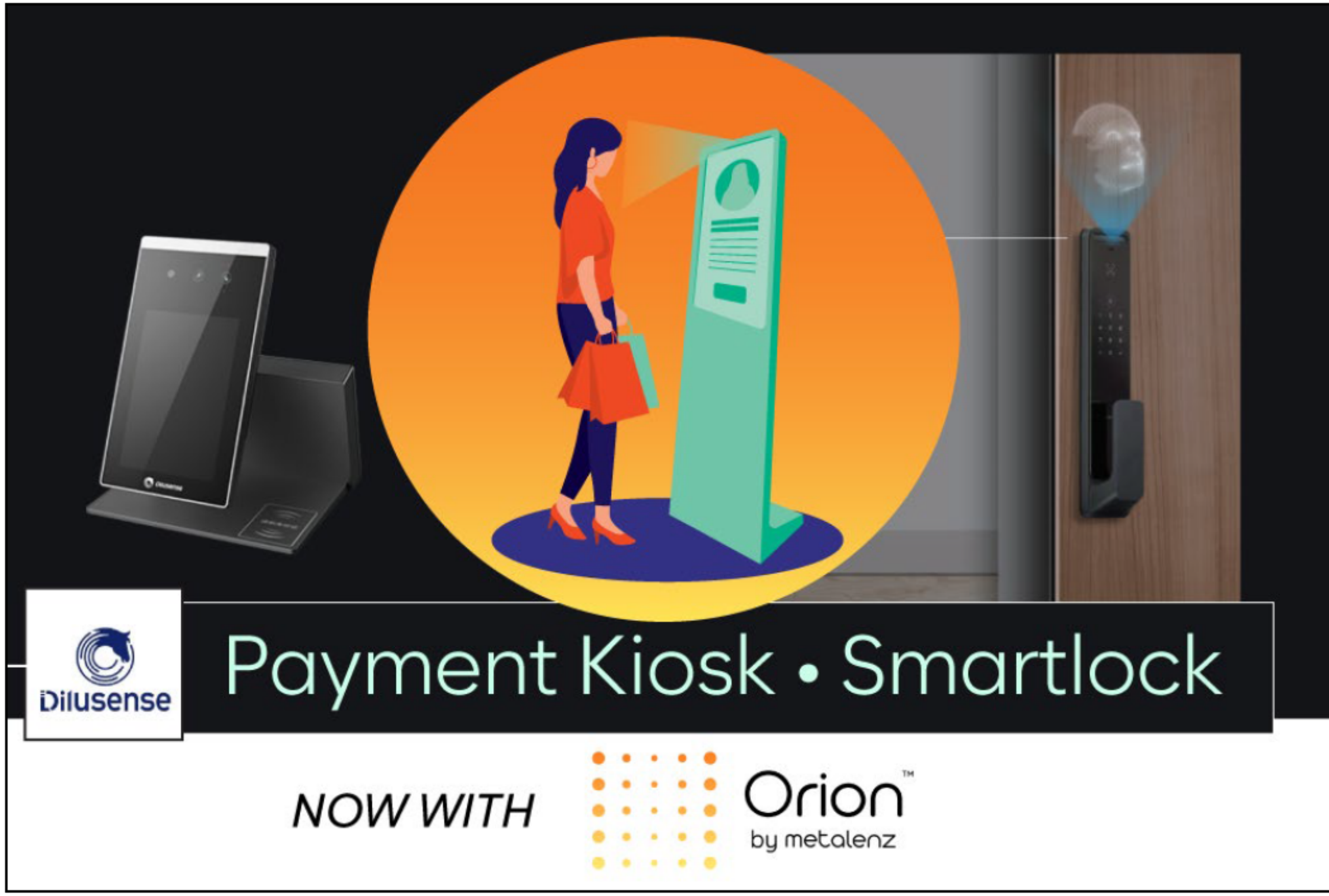
Partenrship with UMC (2023)

- **Metalenz optics released to production at UMC**
- **Dilusense adopts structured light meta-optics for facial authentication in Payment Kiosk and Smartlocks**

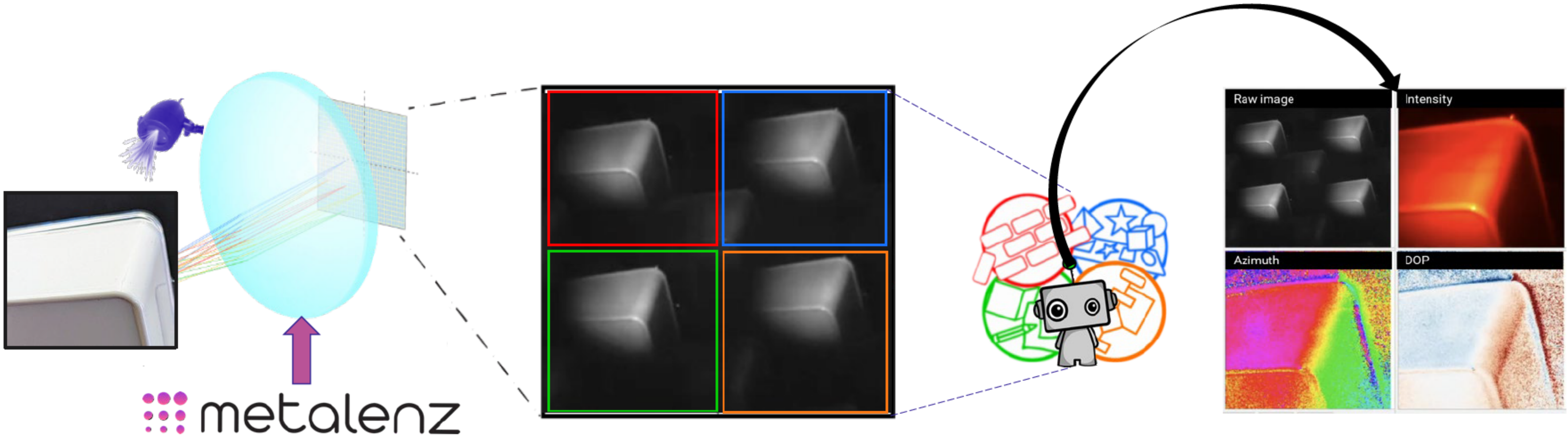
Forbes



Metalenz Pioneers High Volume Semiconductor Foundry-Based Lens Manufacturing



PolarEyes: Polarized Imaging Basics



- Light naturally gets polarized as it reflects from an illuminated scene and the PolarEyes metalens separates differently polarized light into 4 unique regions on the image sensor.
- Computational imaging can derive all Stokes Vectors of the polarized light from which 2D intensity images, 3D depth maps and surface classifications can be processed.

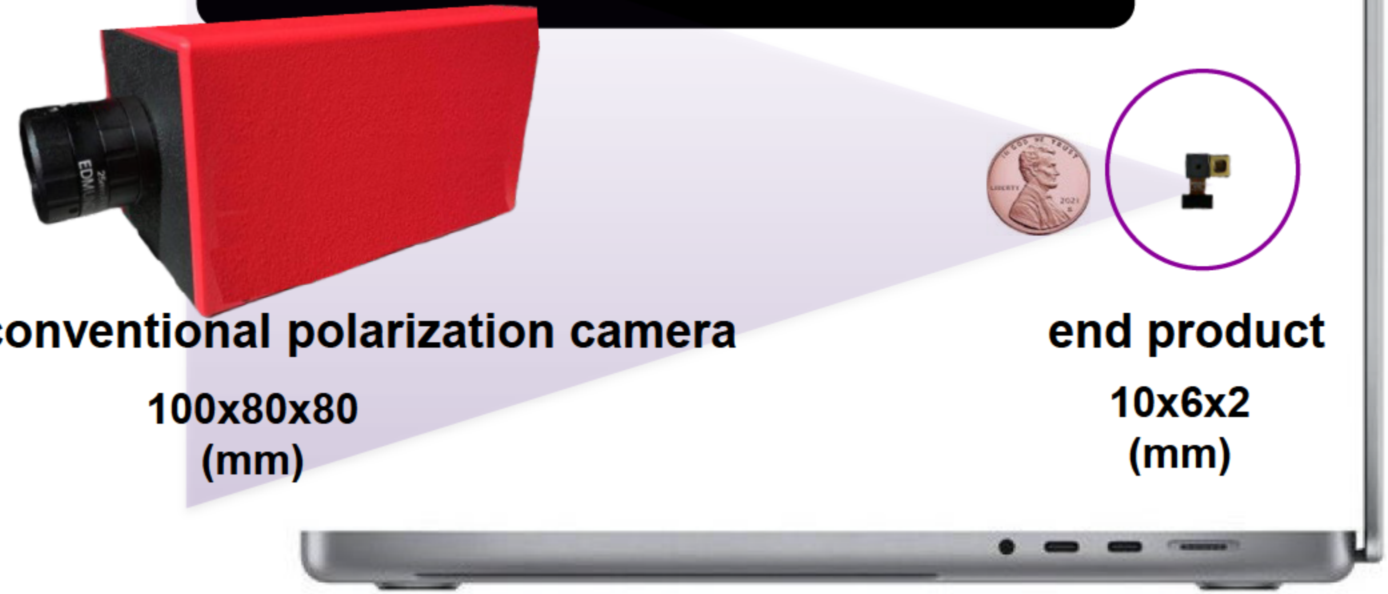
PolarEyes™

Fit for any form factor

Impact

Meta-optics enable complete control of polarized light.
Current optics cannot capture this information.
This enables better information to enter machine vision systems.

From laboratories to pockets

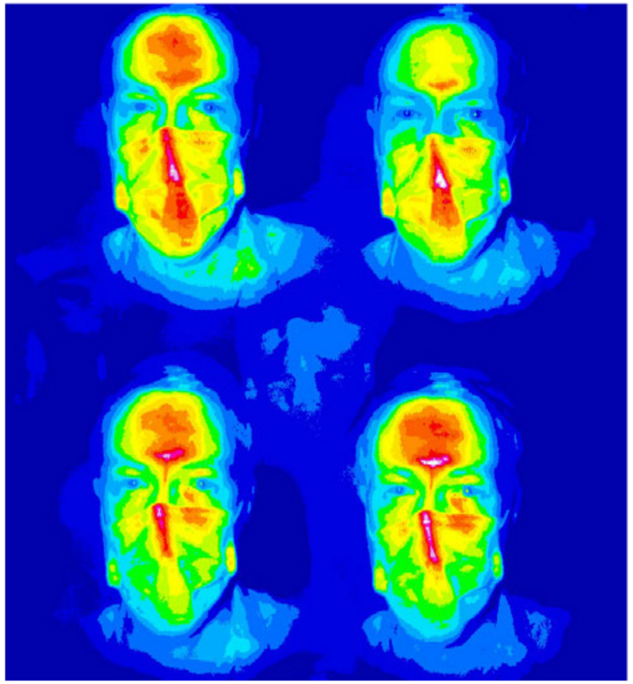


Polar ID

A single polarized image contains all information needed for secure biometrics

Applications

- **Biometric Authentication**
- Medical imaging
- Edge detection
- High resolution 3D shape reconstruction



Vision for Planar ("Flat") Optics based on Metasurfaces

F. Capasso, *Nanophotonics*, **6** 953 (2018)

- **Metasurfaces provide arbitrary control of the wavefront (phase, amplitude and polarization)**
- **Metasurfaces enable flat optics:** compact, thinner, easier fabrication and alignment
- **Multifunctionality: single flat optical components can replace multiple standard components**
- **Flat Optics for a wide range of optical components** (lenses, holograms, polarizers, phase plates, etc.) and applications: machine vision, biomed imaging, drones, polarimetry, polarization sensitive cameras
- **Same foundries will manufacture camera sensor and lenses using same technology (deep-UV stepper) CMOS compatible flat optics platform for high volume markets**:
  Examples: lenses in cell phone camera modules will be replaced by metalenses fabricated by DUV lithography (same foundry that makes the sensor chip)
  Displays, wearable optics (augmented reality).
- **Metasurfaces can generate arbitrary vector beams** (structured light) well beyond the capabilities of SLM
- **Importance of inverse design, co-design of hardware & software, impact of AI on optics**

Acknowledgments


Reza Khorasaninejad


Wei Ting Chen


Robert Devlin


Zhujun Shi


Alexander Zhu


Maryna Meretska


Paul Chevalier


Joon-Suh Park

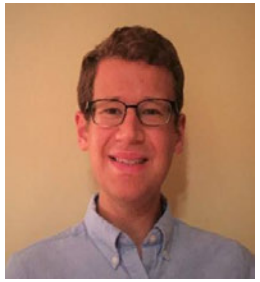

Zhaoyi Li


Christina Spaegele

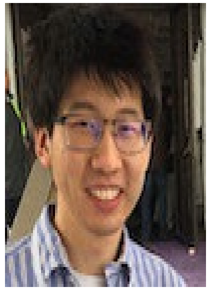

Ahmed Dorrah


Michele Tamagnone


Daniel Lim


Noah Rubin


Aun Zaidi

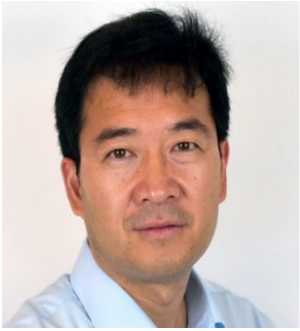

Alan She

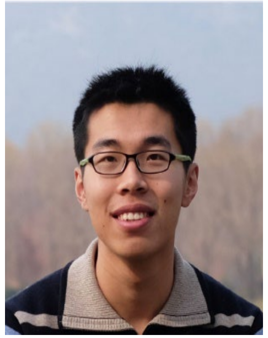

Shuyan Zhang


Raphael Pestourie


Steve Johnson, MIT


Peng Lin, BU


Ji-Xin Chen, BU


Qi Guo


Todd Zickler