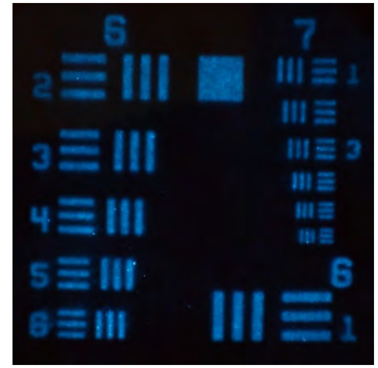
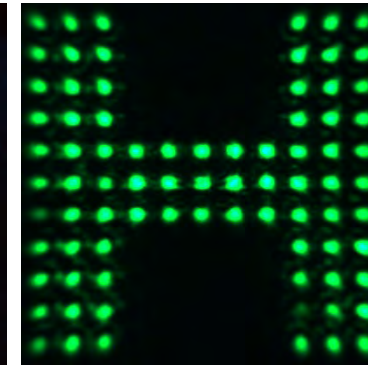
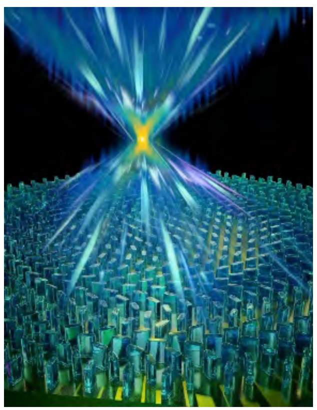
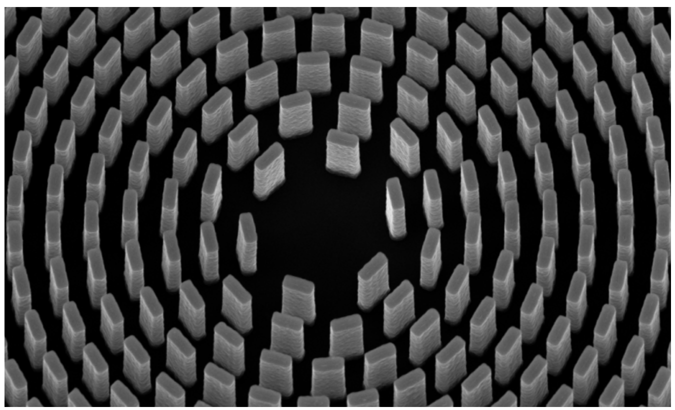
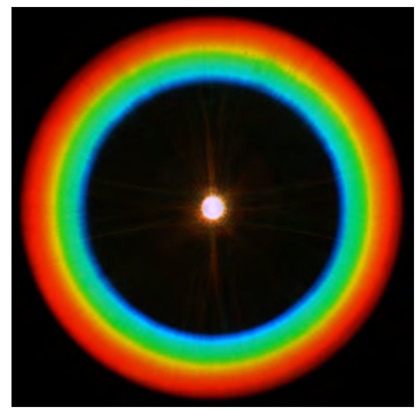
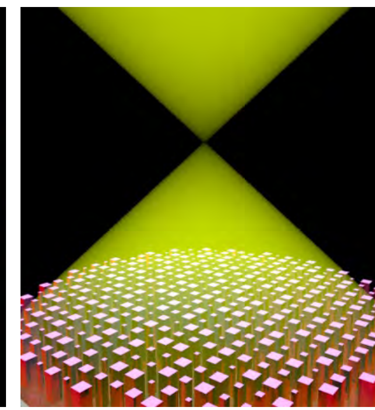
Broadband and Multifunctional Flat Optics: From High Performance Components to Cameras



OSA Webinar, August 17

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Capasso Group
Harvard School of Engineering and Applied Sciences

Funding: DARPA, AFOSR

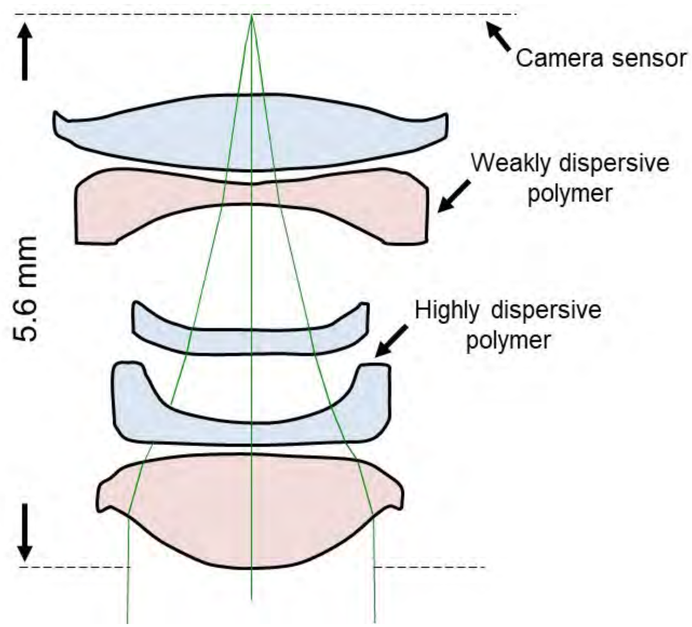
Our Vision for Planar ("Flat") Optics

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**

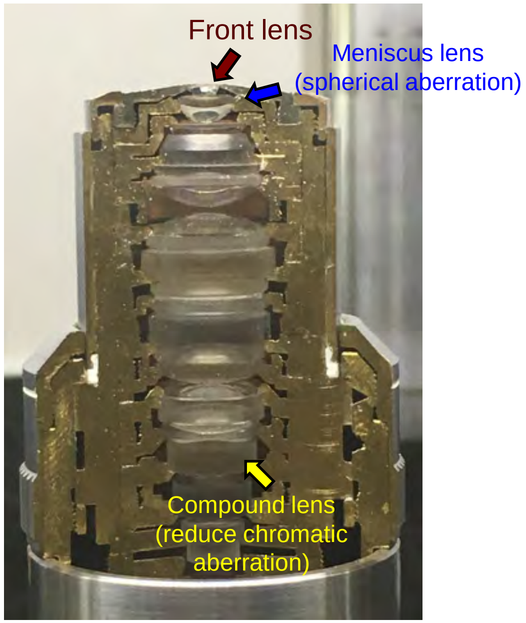
Conventional Lens Manufacturing

- Mobile phone camera (all plastic lenses)



Ref: U.S. Patent 0085059 A1, Mar. 24, 2016.

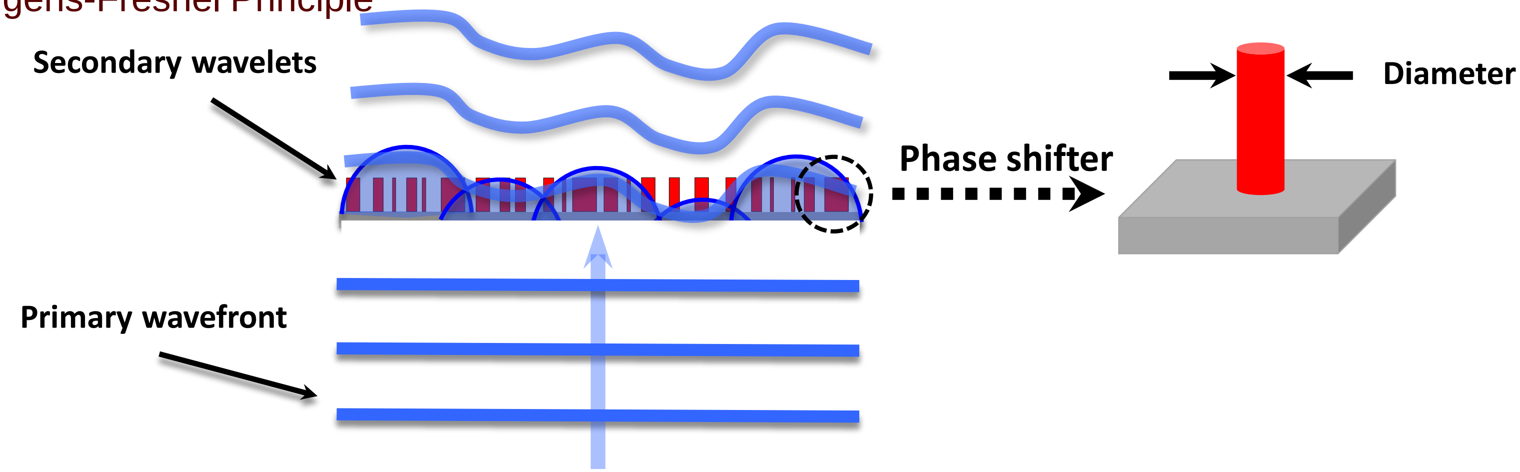
- Microscope objective lens



- All lenses suffer from distortions in the way they focus
- Focal point is blurred by aberrations (spherical, astigmatism, coma, etc.)
- Can be corrected by using multiple lenses, which however makes the optics much thicker, bulky and heavier

Metasurfaces: complete wavefront control

- Huygens-Fresnel Principle



Benefits

- **Straight-Forward Fabrication**
  - Lithographically defined: same technology of chip making
- **Compact**
  - Light weight, capability to be vertically integrated
- **Unprecedented Control of Dispersion**
- **Overcome Limitations of Conventional Optics**
  - Aberrations, multifunctionality

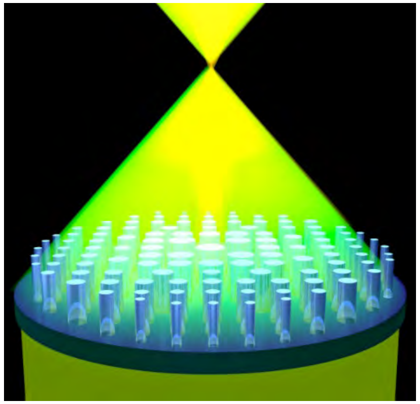
Diffraction limited metalens design

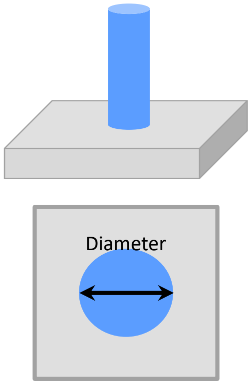
Propagation phase from lens to focus with respect to center ray

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

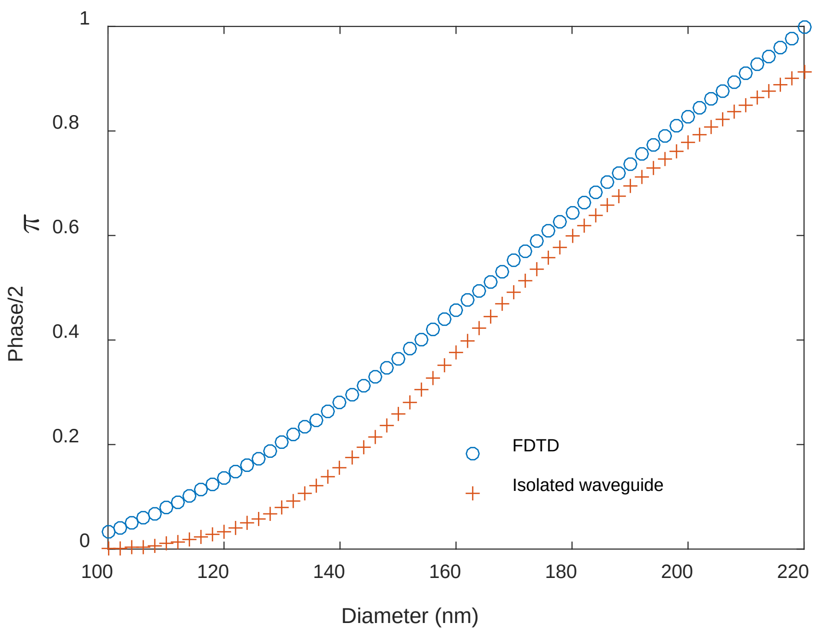
Phase imparted by the pillar at x,y must compensate for difference in propagation phase shifts

✓ **Uniform amplitude**
✓ **2π phase coverage**





Phase versus Diameter at design wavelength of 532 nm

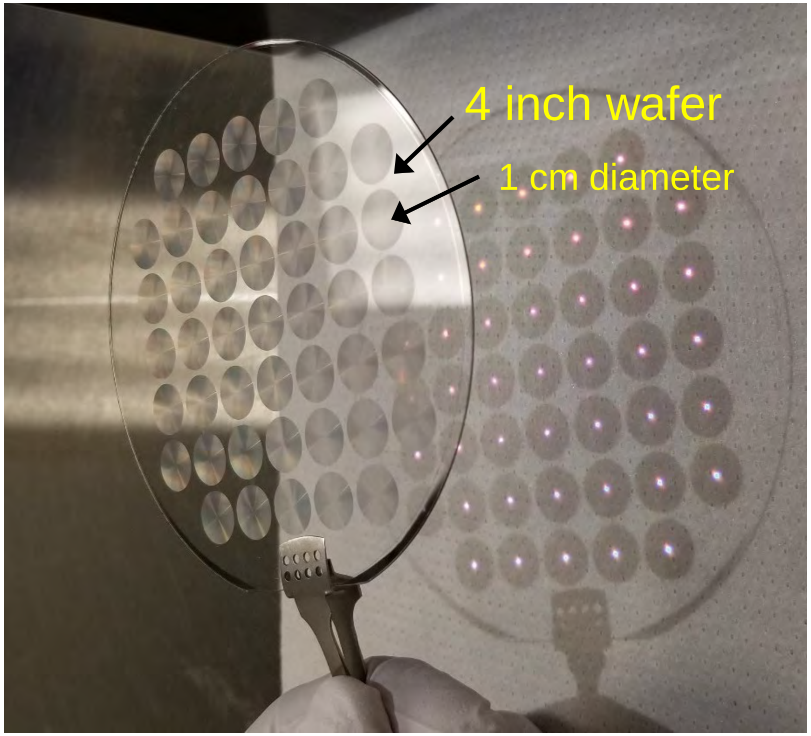


- **Numerical Aperture as High as 0.85**
- **<600 nm Tall TiO_2 Nanopillars**

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

Large Area Metalenses

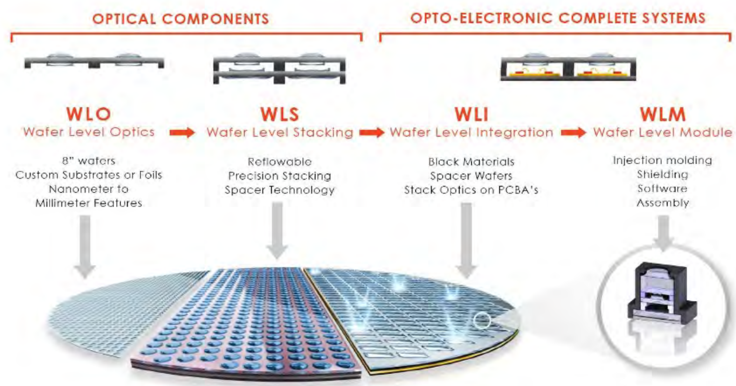
- Glass lens
- nano-meter precision with high throughput
  - ➢ 160 Million nanopillars per lens



Manufactured by deep ultraviolet (DUV) projection lithography: used in semiconductor IC chip manufacturing **Unification of two industries: ICs and Optics**

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

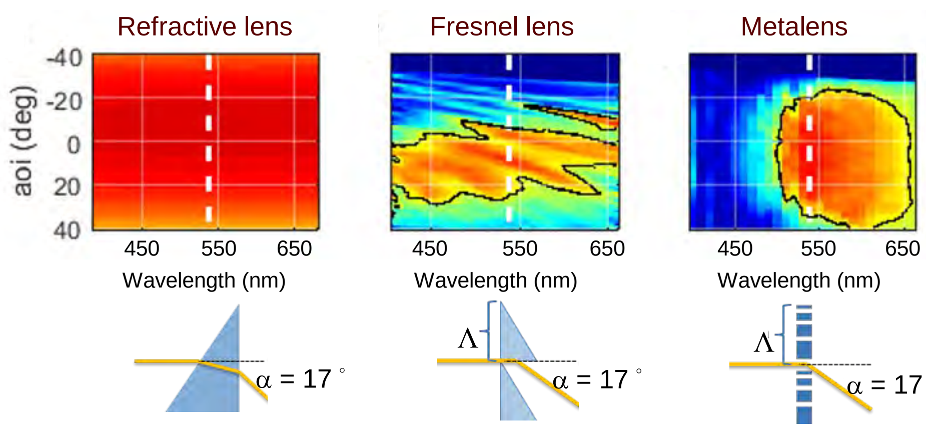
- Flat and Compact:
  compatible with wafer packaging



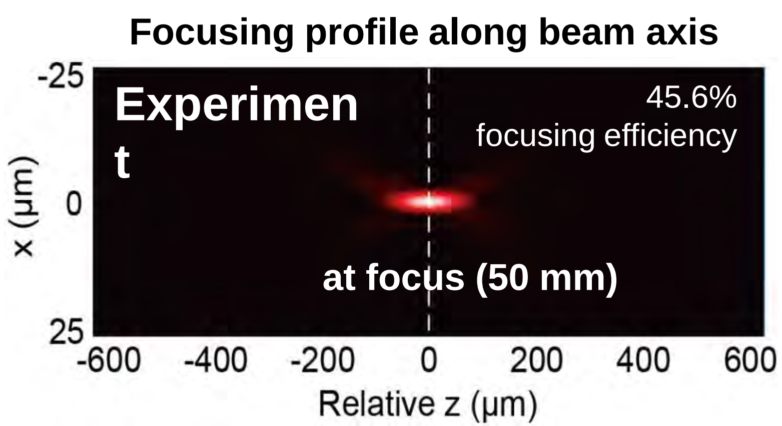
Ref: Heptagon Inc. (Wafer level optics packaging)

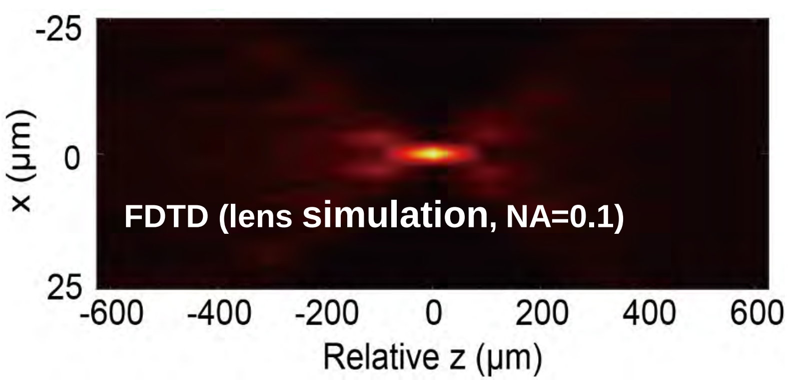
- Metalenses have larger angular bandwidth (collaboration with Zeiss)

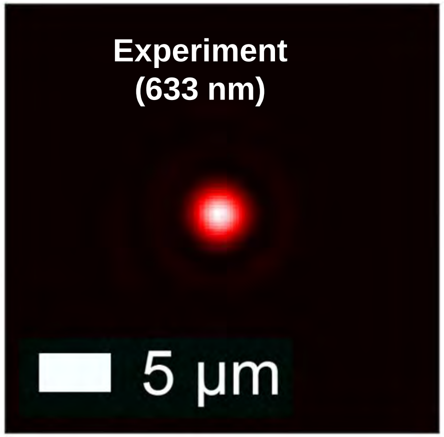
M. Decker et al., *ACS Photonics* **6**, 1493 (2019))

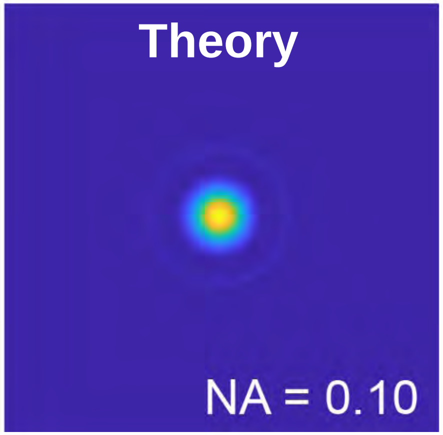


Focusing profile at design wavelength

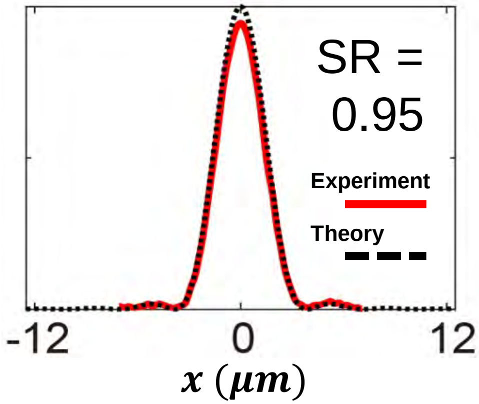








Strehl ratio (SR): Ratio of central intensity between aberrated and unaberrated focus.



Theoretical results are derived from Kirchhoff integral.

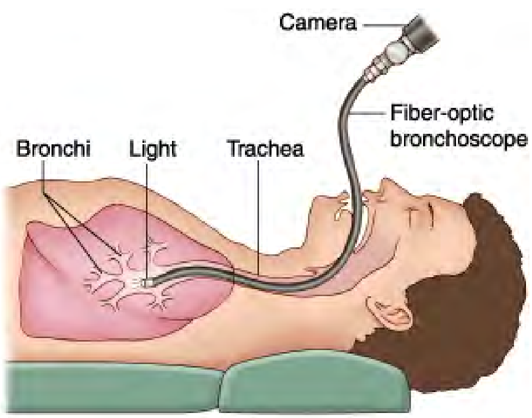
SR > 0.8 : "diffraction limited"

$$SR = \frac{I_{aberrated}}{I_{unaberrated}} = \frac{I_{aberrated}}{I_{Airy\ disk}}$$

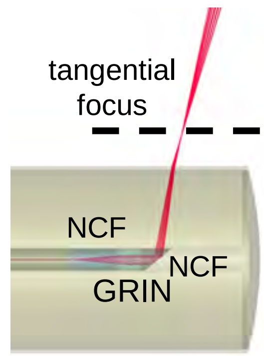
Metalens for High Resolution Endoscopes

Hamid Pahlevani et al. Nature Photonics https://doi.org/10.1038/s41566-018-0224-2

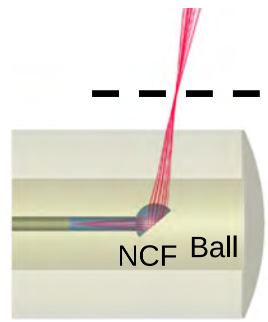
- Collaboration with Mass General Hospital, Prof. Melissa Suter



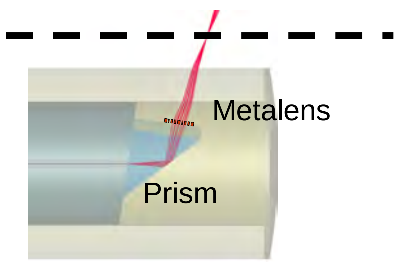
GRIN lens catheter

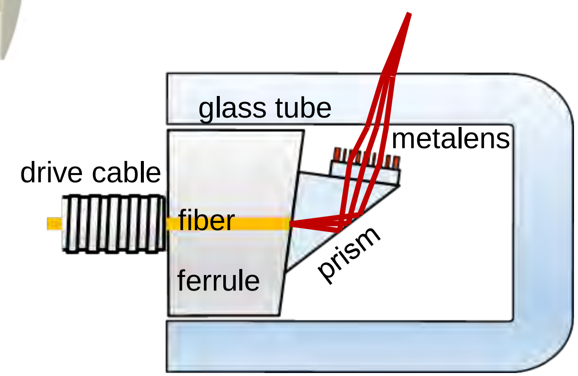


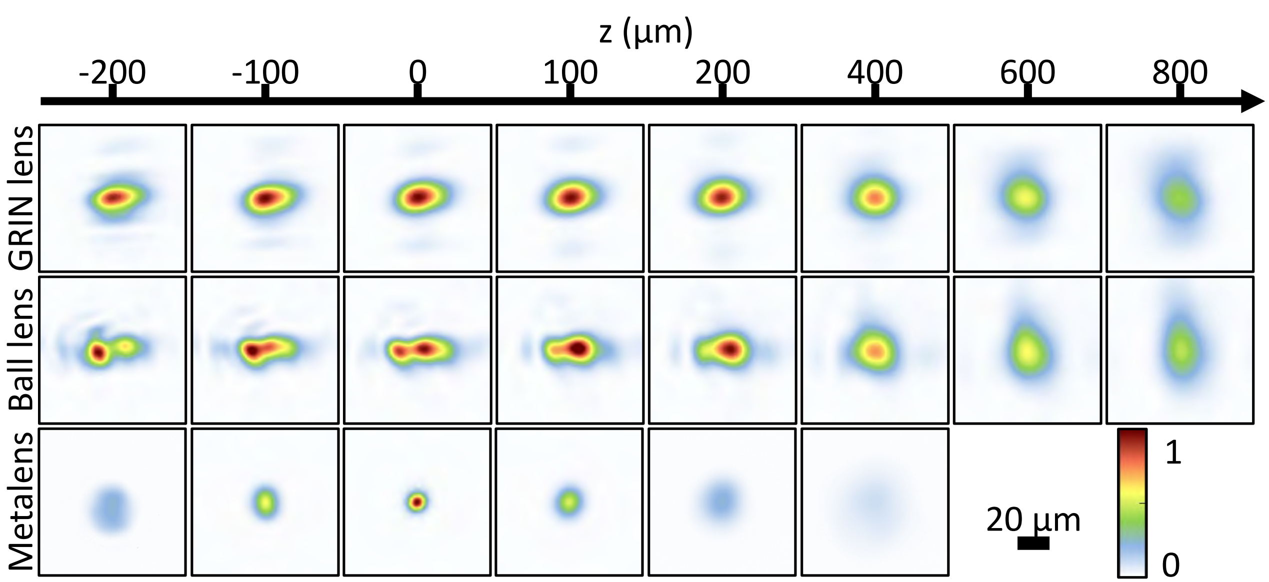
Ball lens catheter

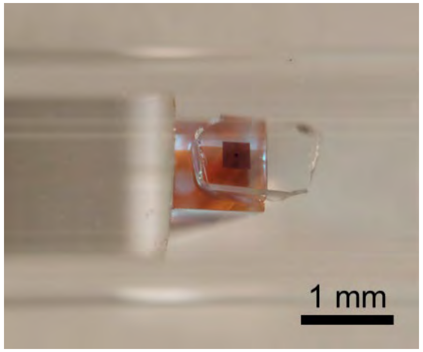


Metalens catheter

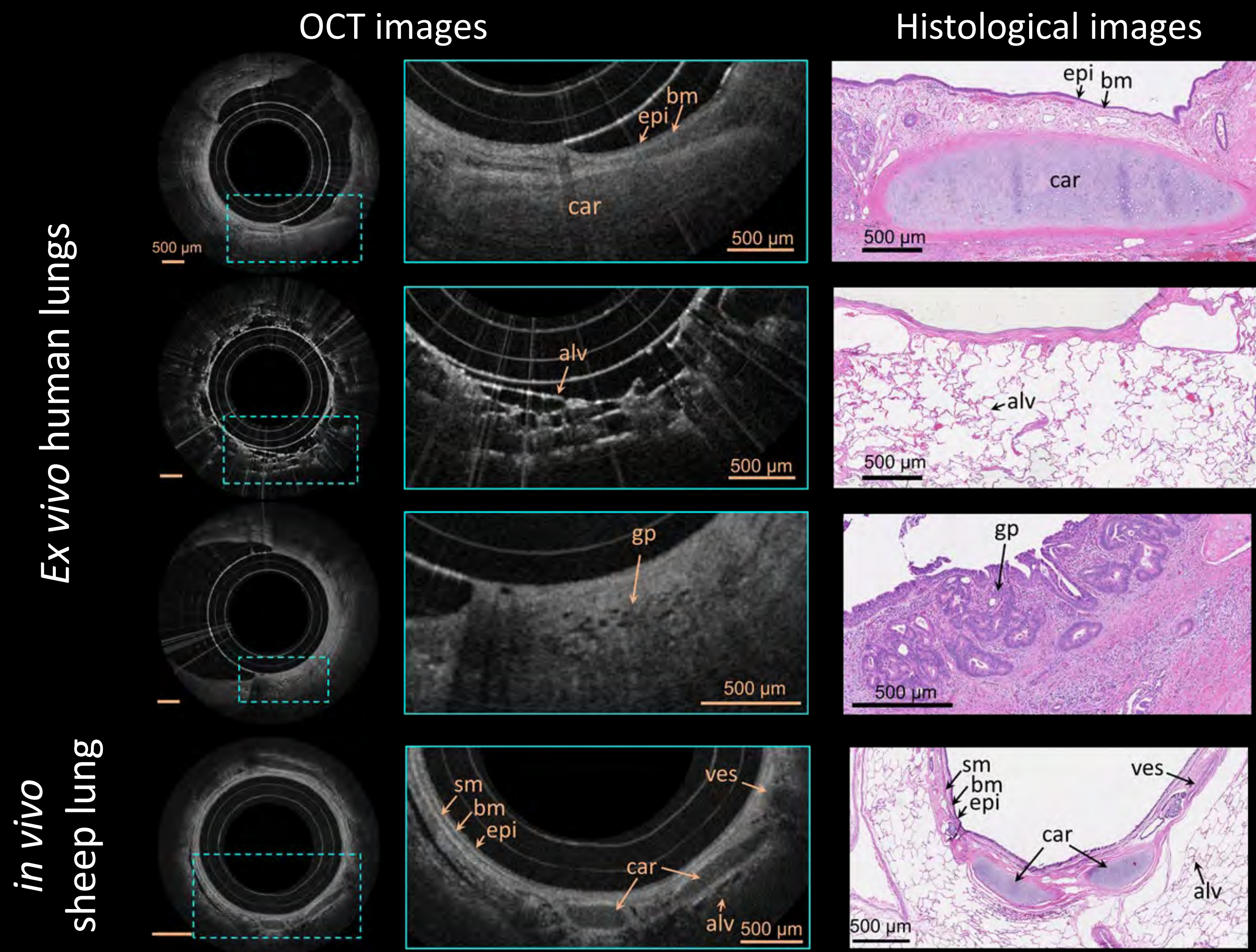








Endoscopic imaging using metalens catheter

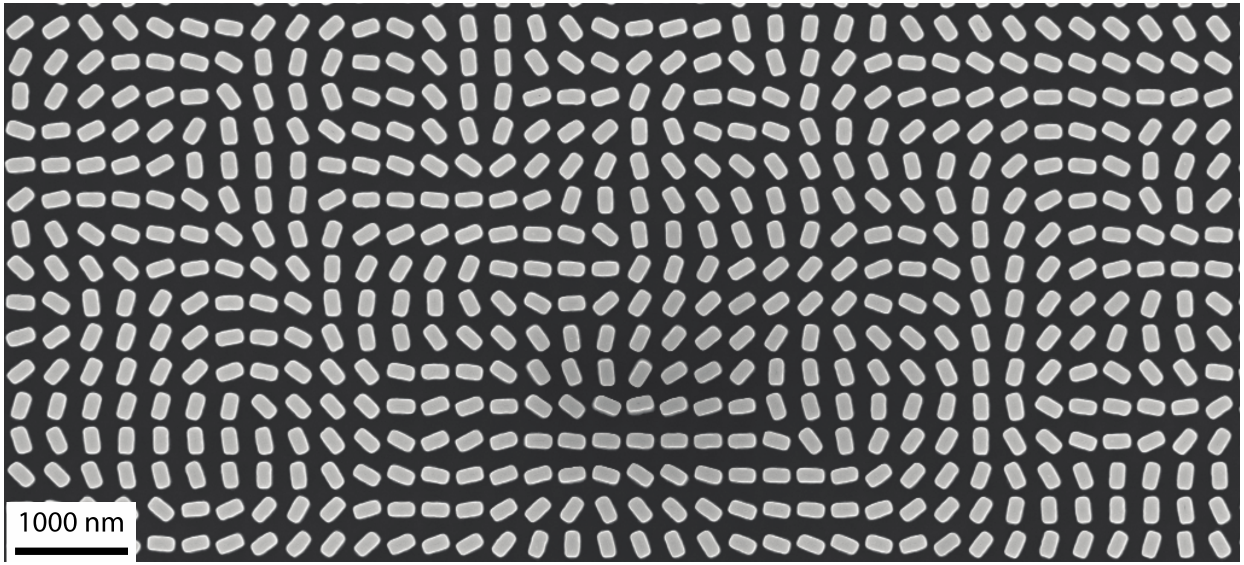


epi: epithelium; bm: basement membrane; car: cartilage
ves: blood vessels; alv: alveolar; gp: glandular patterns

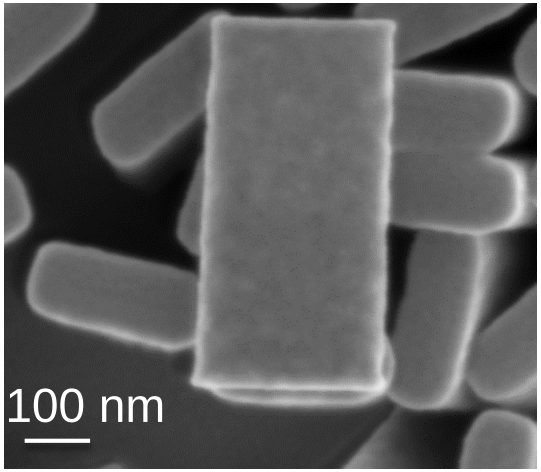
TiO2 Metasurfaces by Atomic Layer Deposition:

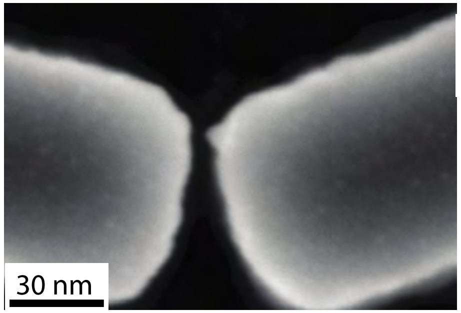
Completely transparent in the visible;

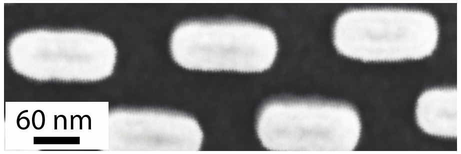
Negligible roughness, Vertical walls

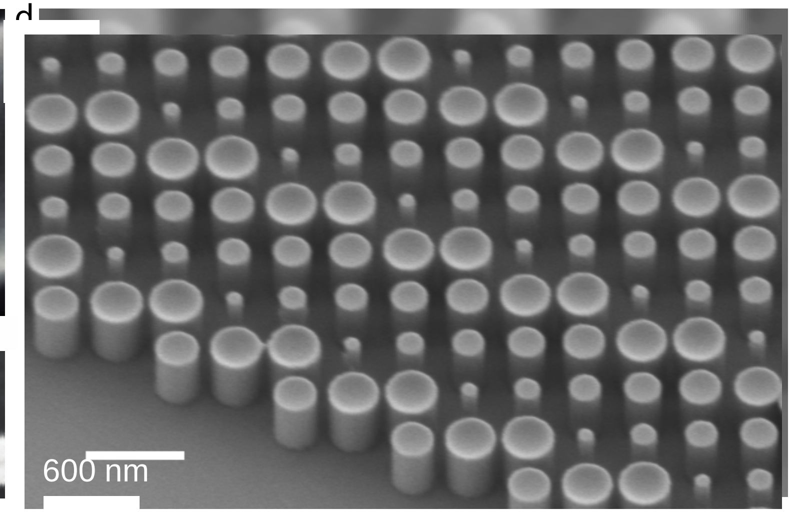


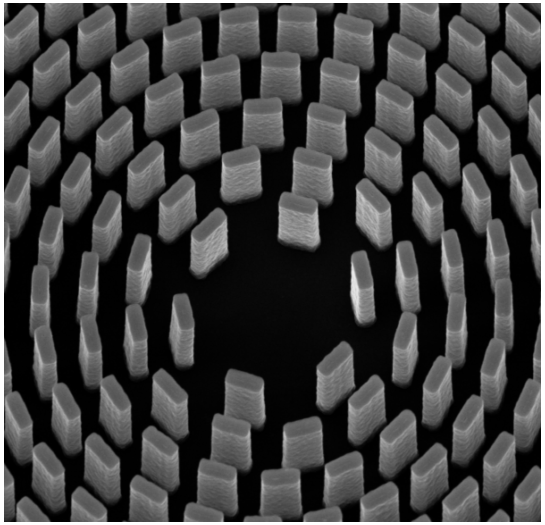
Side view







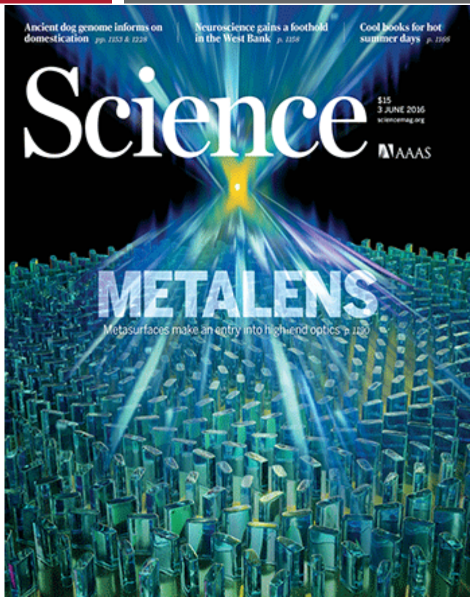


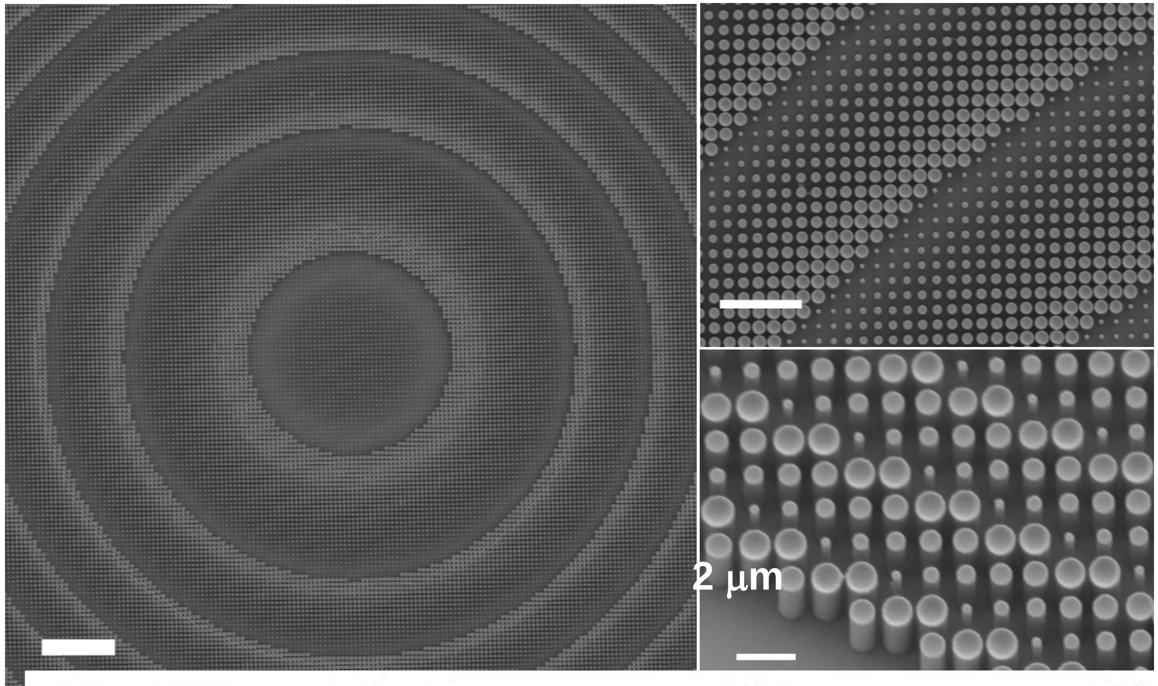


R.C. Devlin, *et al. Proc. Nat. Acad. Sci* .**113**, 10473 (2016)

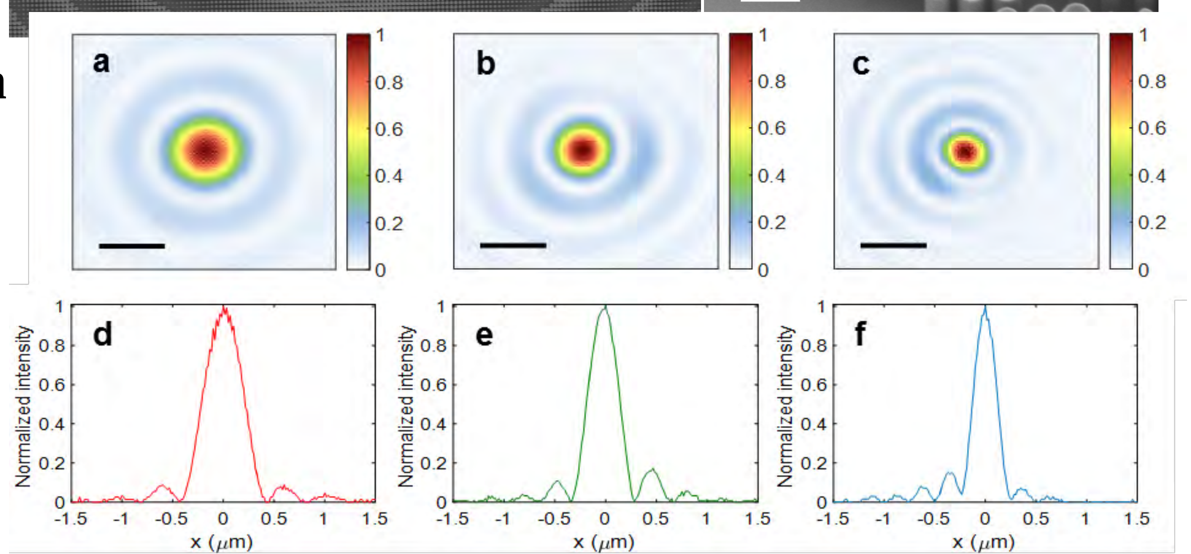
Diffraction Limited High NA Metalenses

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





Ø = 2 mm; f= 800µm
NA= 0.8

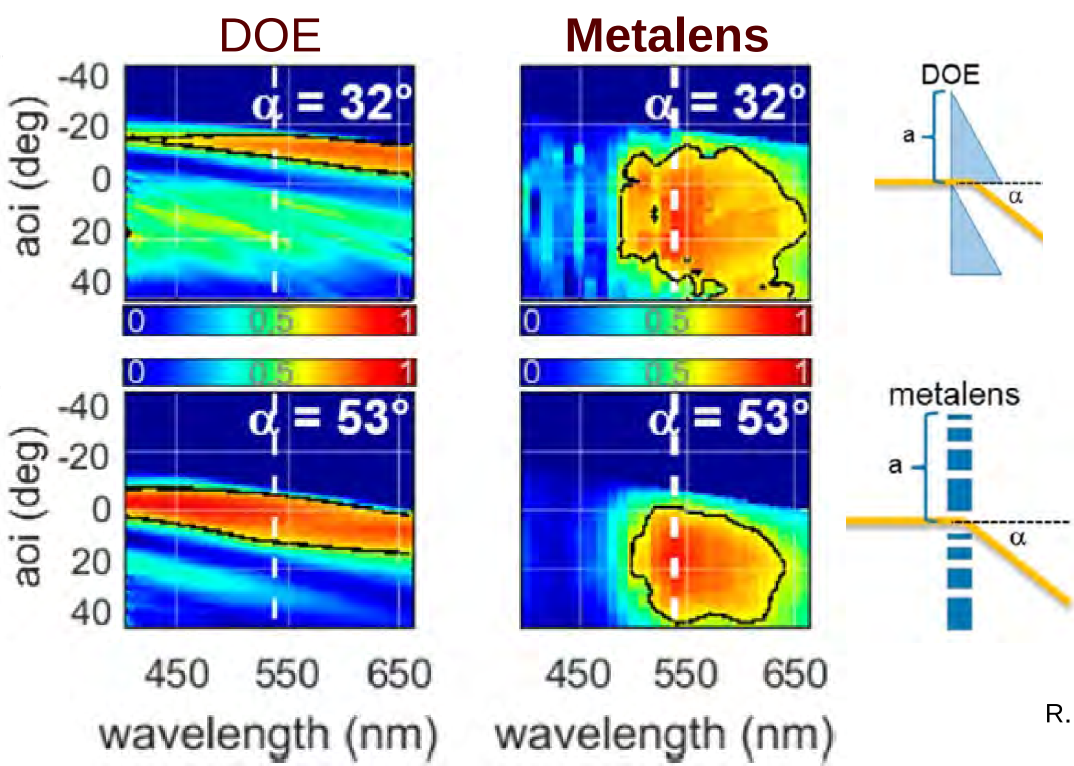


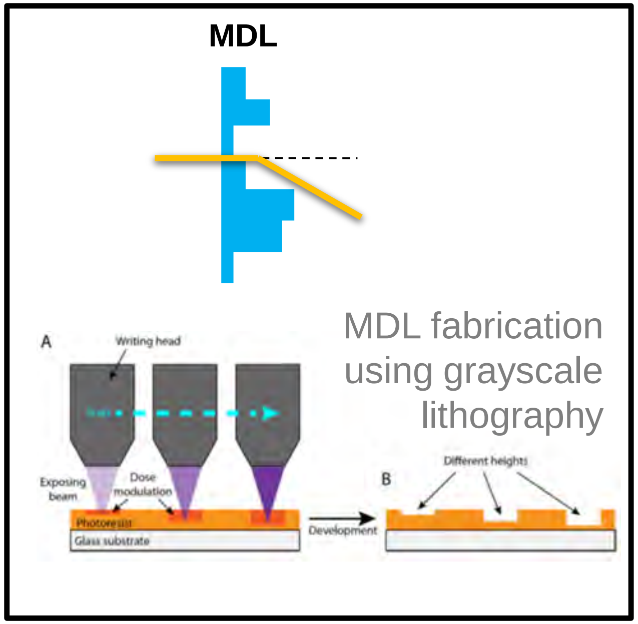
Focusing efficiency:
60% to 80 % depending
For NA in 0.8 to 0.6 range

Metalens vs Fresnel and Multi-level Diffractive Lens

Collaboration with Zeiss Inc. (M. Decker et al., *ACS Photonics* 6, 1493 (2019))

- The angular bandwidth (range of incidence angle with high deflection efficiency) is an important measure of how much light can be transported within an imaging optical system
- Angular bandwidth with DOEs (control of phase with different heights) including multi-level diffractive lenses (MDLs) is much lower compared to metalenses due to shadowing. This results in resolution and intensity losses (vignetting).
- The bandwidth of metalenses can be much improved by dispersion engineering, while the limitation of angular bandwidth MDLs is intrinsic



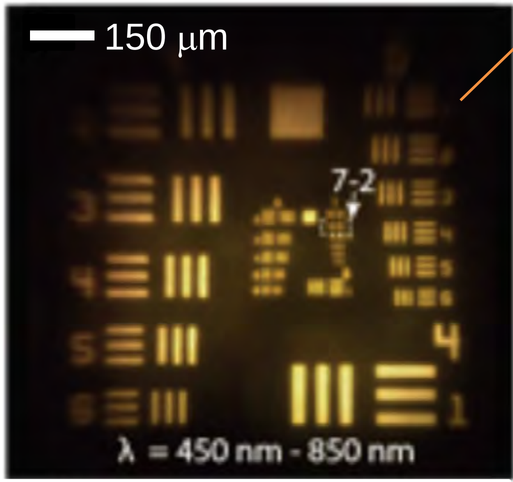


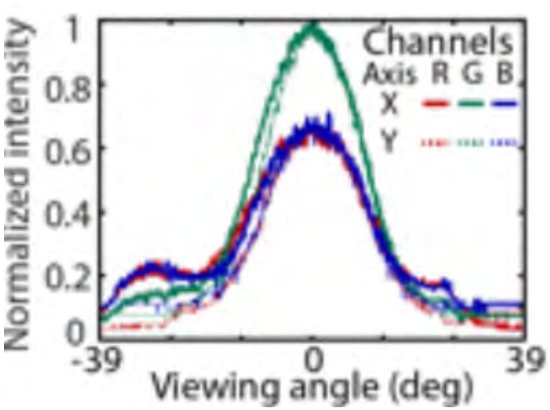
R. Menon's Group Appl. Phys. Lett. 117, 041101 (2020)

Vignetting: drawback of low angular bandwidth

➢ Multilevel diffractive lens
(NA = 0.075, Dia = 150 μm)

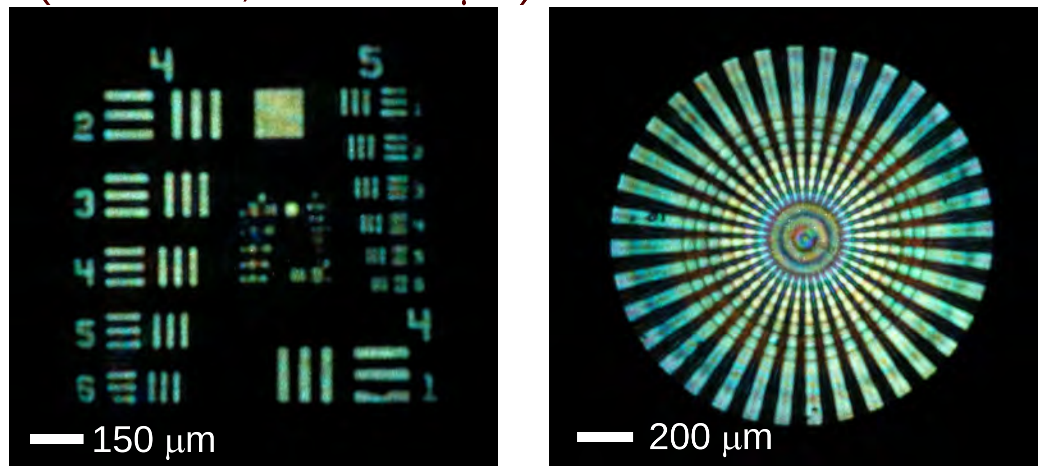
significant vignetting even in low NA lens





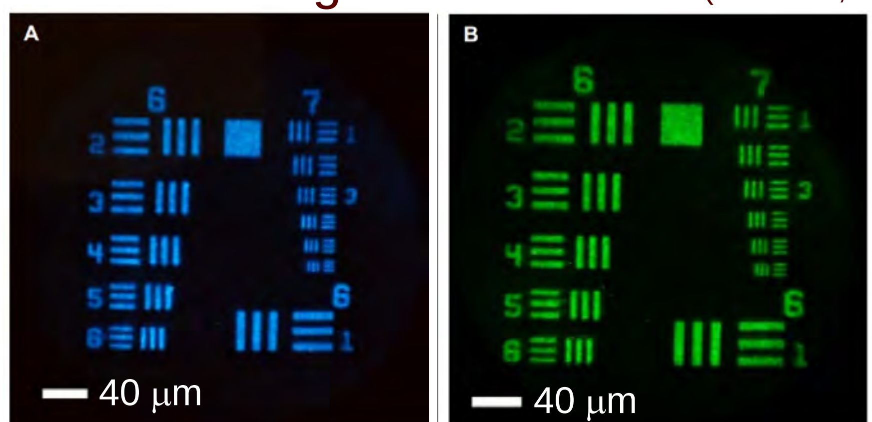
R. Menon's Group Appl. Phys. Lett. 117, 041101 (2020)

➢ Achromatic low NA metalens
(NA = 0.02, Dia = 220 μm)



Ref: W. T. Chen et al., *Nat. Nanotechnol*. **13**, 220-226 (2018).

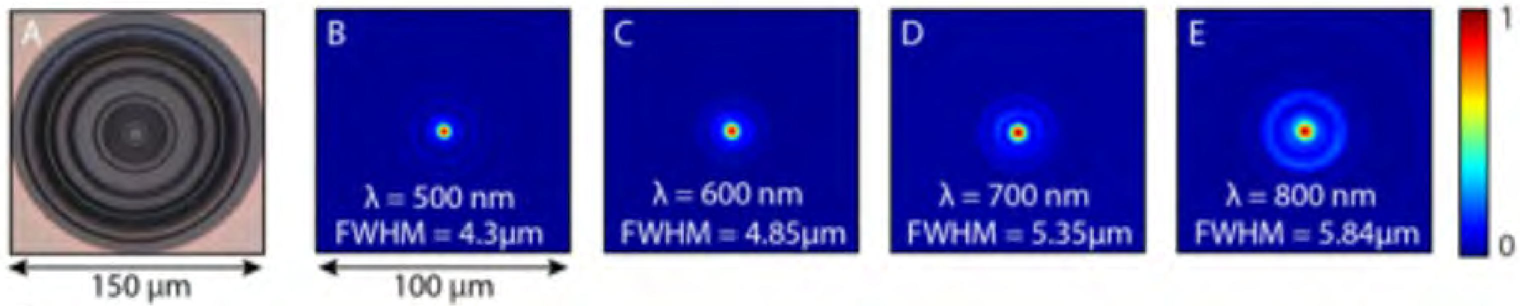
➢ Chromatic high NA metalens (NA = 0.8, Dia = 2 mm)



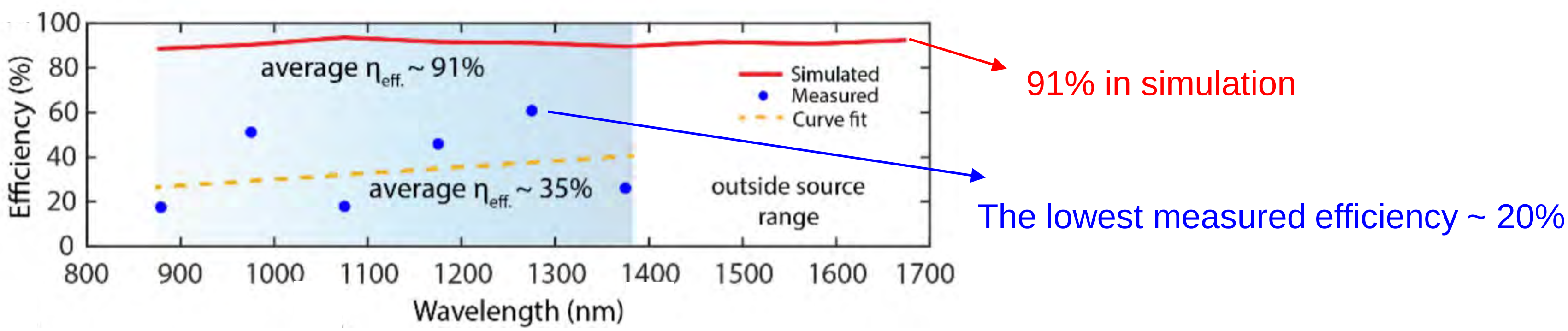
Ref: M. Khorasaninejad et al., *Science* **352**, 1190-1194 (2016).

Multi-level Diffractive Lenses (MDLs)

- Height is hard to control precisely, and therefore MDLs are challenging to reach diffraction-limited focusing and high efficiency.
  - Large aberrations and low efficiency in fabricated MDL (NA = 0.075, Dia = 150 um)
    Strong side lobes and low Strehl ratio



  - Large deviation of efficiency between measurement and design



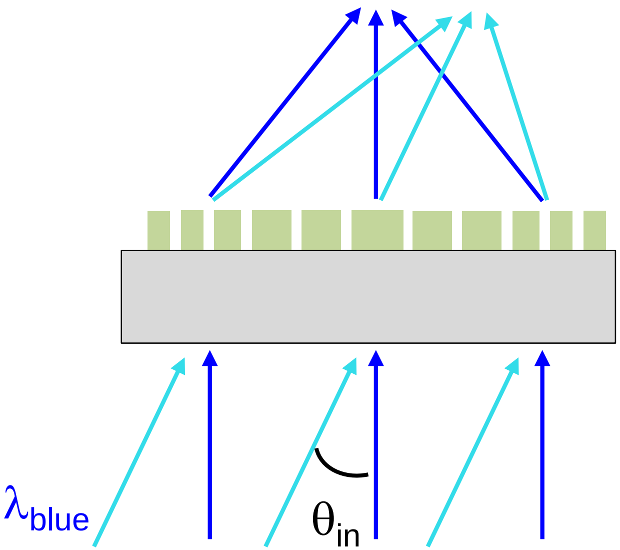
R. Menon's Group, OSA Continuum., 2, 2968 (2019) and Appl. Phys. Lett. 117, 041101 (2020)

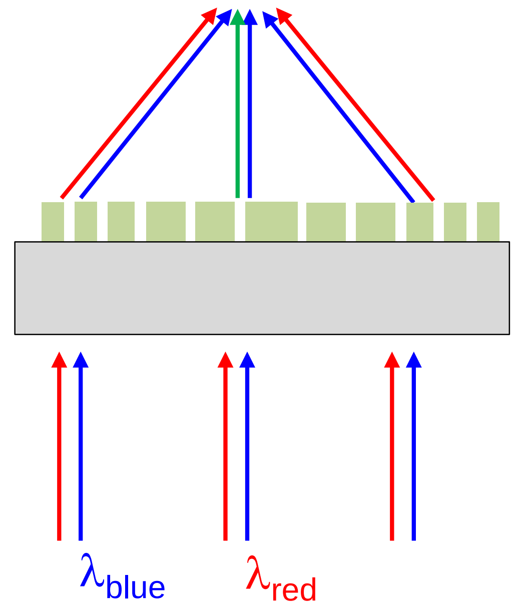
An Ideal Metalens

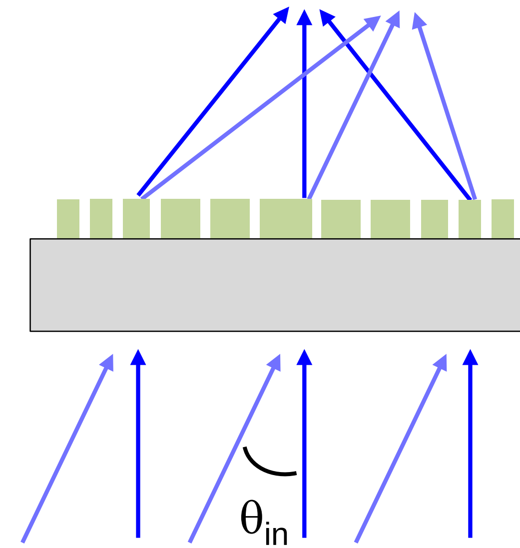
- **No monochromatic aberrations**
  Spherical, coma, astigmatism and field curvature

- **No chromatic aberrations**
  Minimizing focal length shift

- **High efficiency**
  Transmission as high as possible







This requires the metalens to impart an incident **angle-dependent** phase profile:

$$\varphi(r, \theta_{in})$$

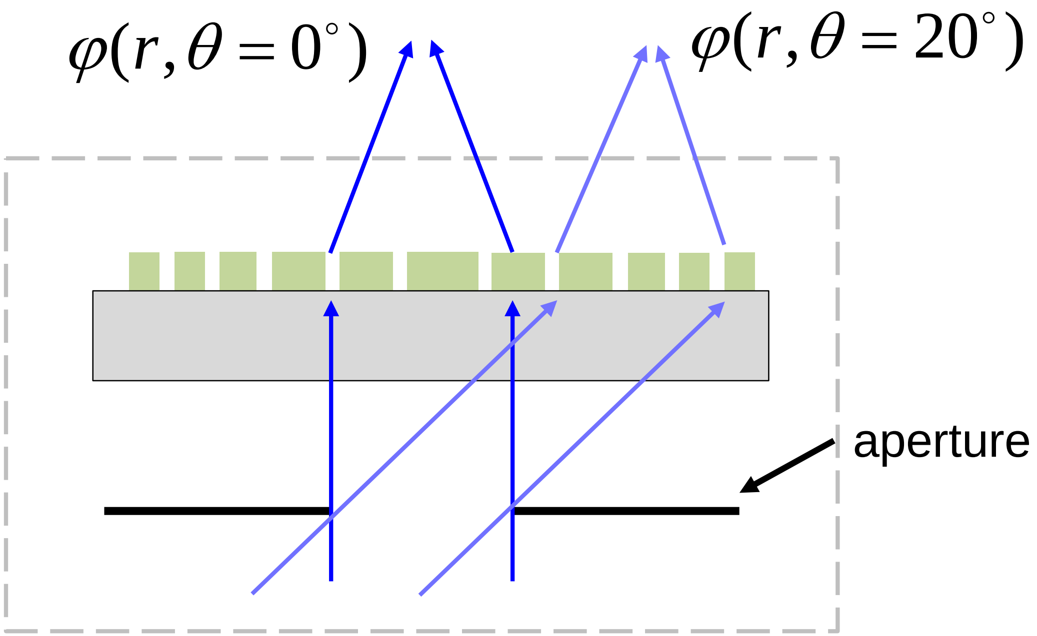
This requires the metalens to impart a **frequency-dependent** phase profile:

$$\varphi(r, \omega)$$

Realizing Angle-dependent Phase Profile by an Aperture

➢ Aperture Stop is the key to realize an angle-depend phase profile

The aperture spatially separates incident light of different angles such that they interact with different regions of a metalens. The phase profile of metalens can then be locally customized resulting in $\varphi(r, \theta_{in})$.

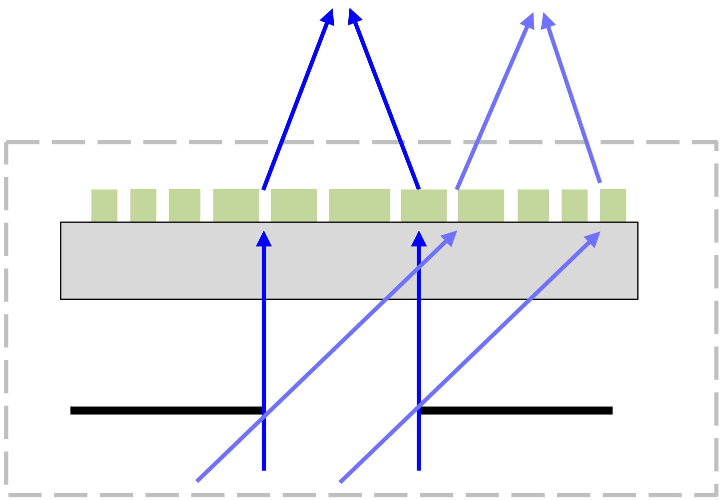


lens system: a metalens + an aperture

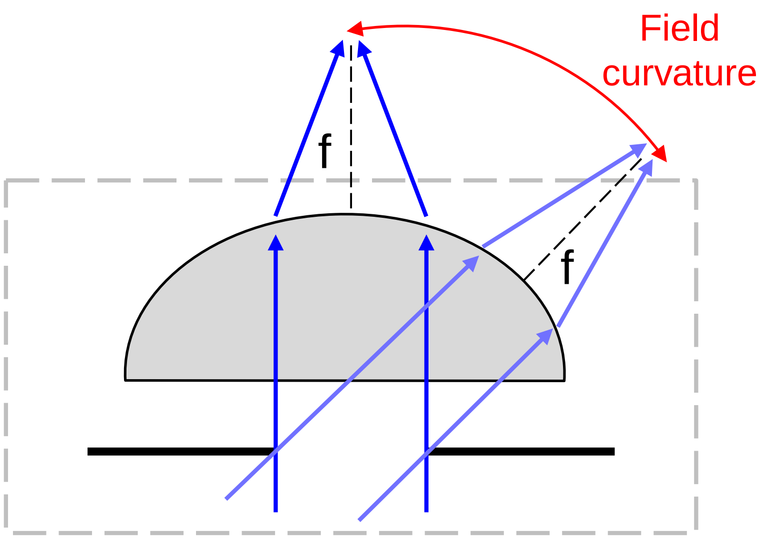
Flat lens leads to flat image plane (no field curvature)

- Such metalens system has no field curvature and therefore is better than a corresponding refractive system of a spherical lens + an aperture

A metalens + an aperture



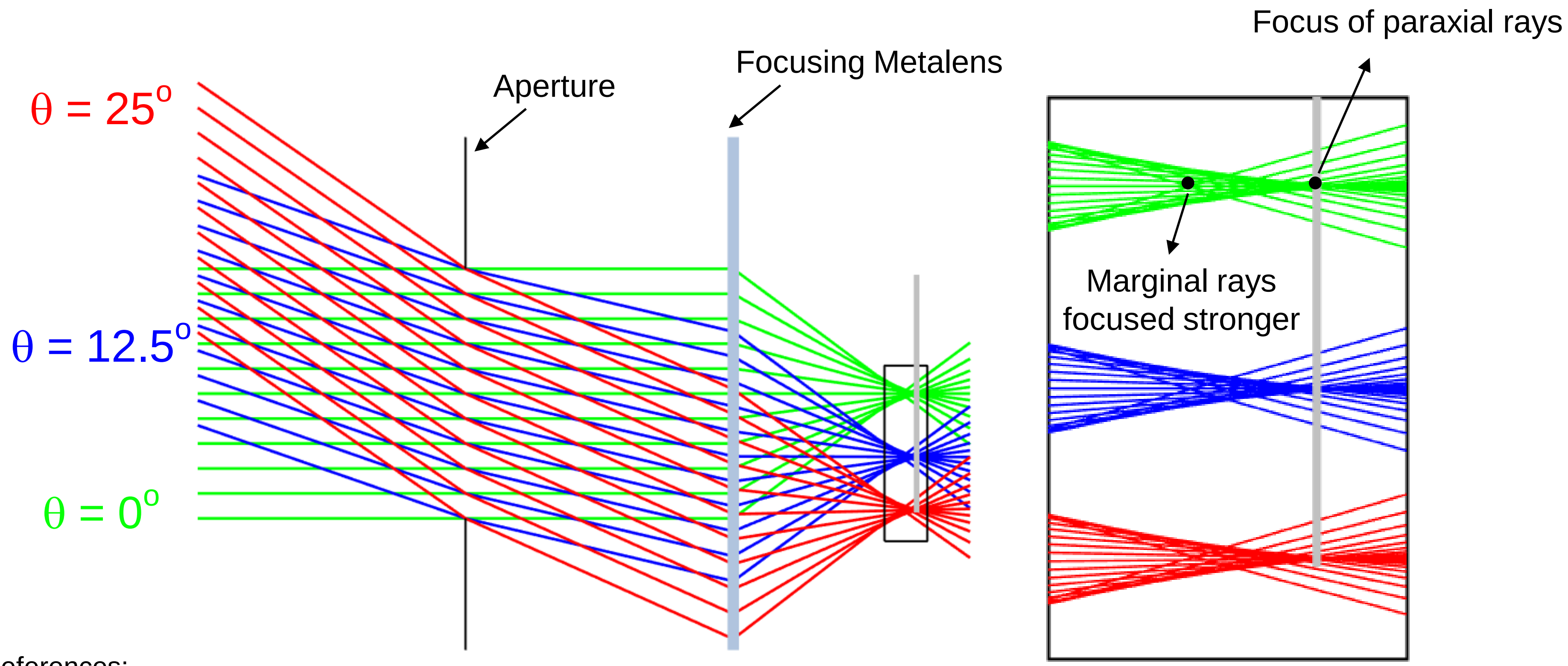
A spherical lens + an aperture



Even replacing with an aspherical lens, such aberration can not be removed

Metalens Doublet

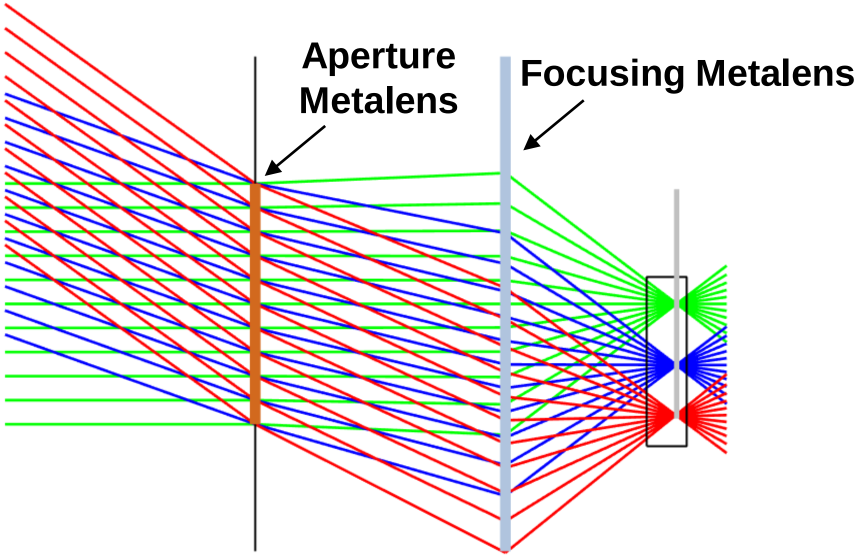
- The major residual aberrations in the aforementioned design (metalens singlet + an aperture) is spherical aberration **for all angles**.

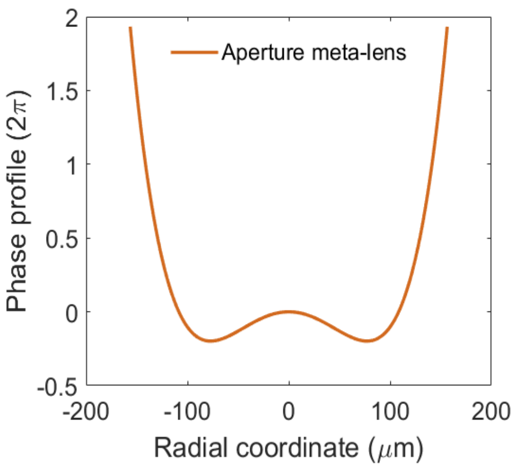


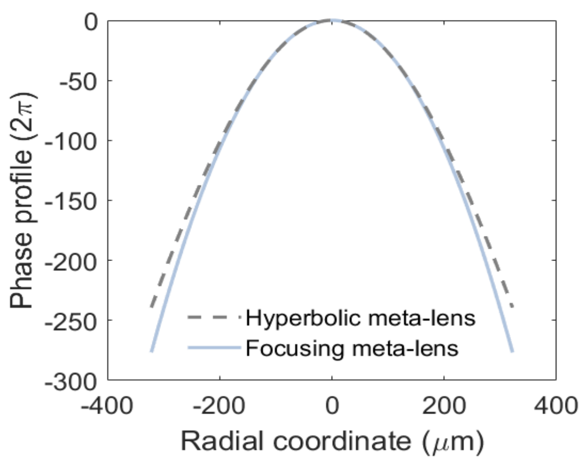
References:
B. Groever, W. T. Chen, and F. Capasso, Nano Lett. **17**, 4902-4907 (2017).
Also see:
A. Arbabi et al., Nat. Commun. **7**, 13682 (2016).
X. Luo's group, Opt. Express **25**, 31471-31477 (2017).

Metalens Doublet

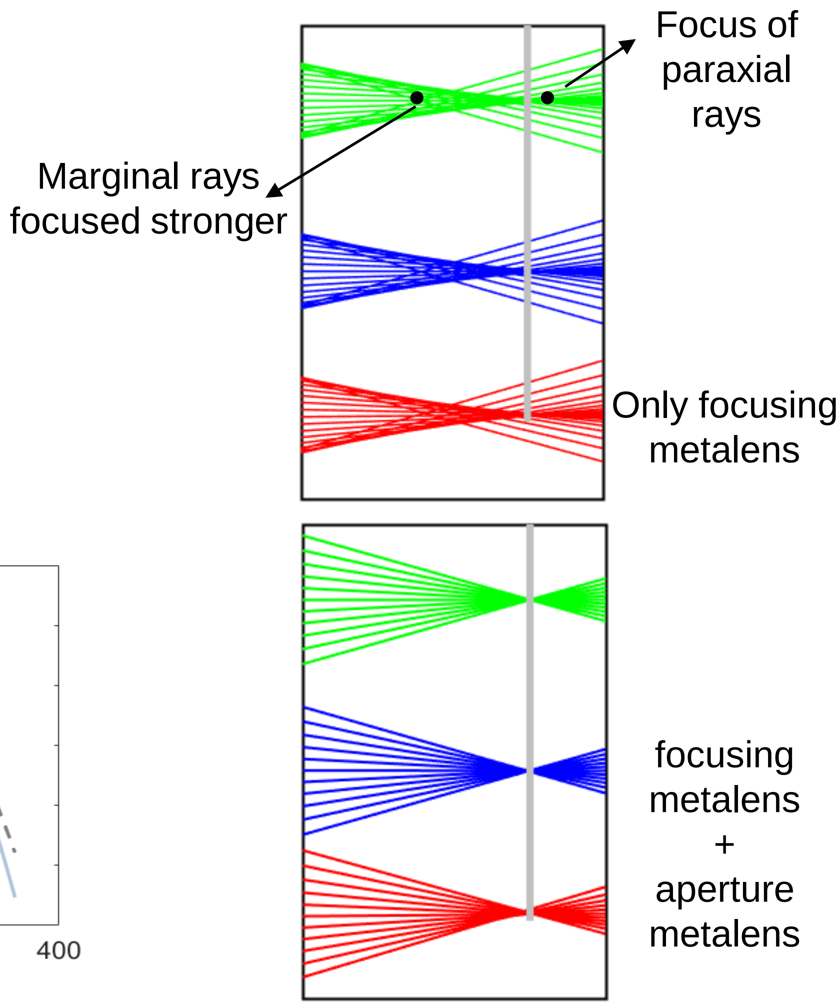
- Aperture + Focusing metalenses





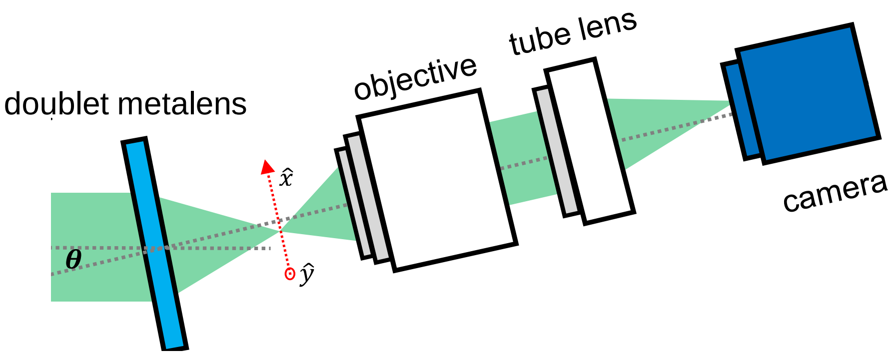


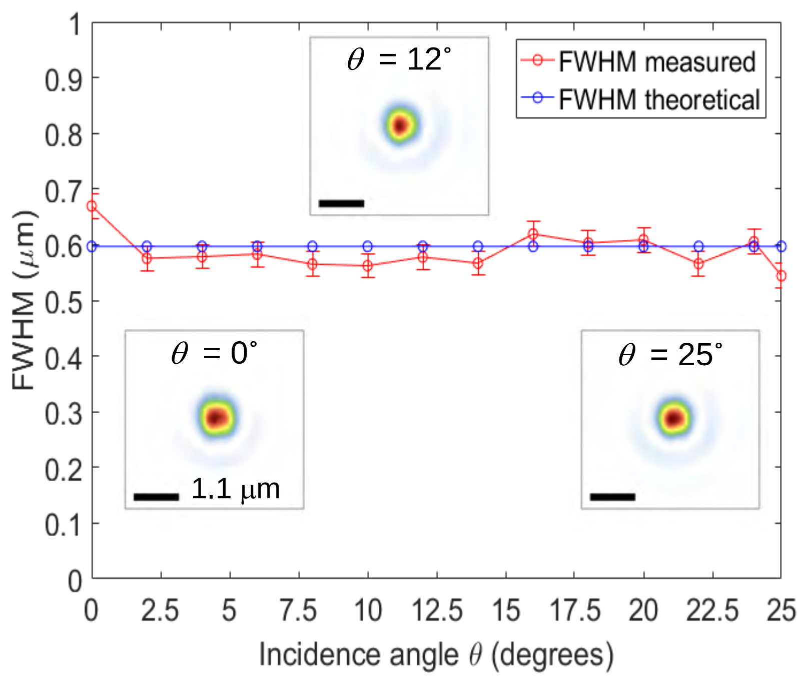
- Correction by the concave and convex phase profiles



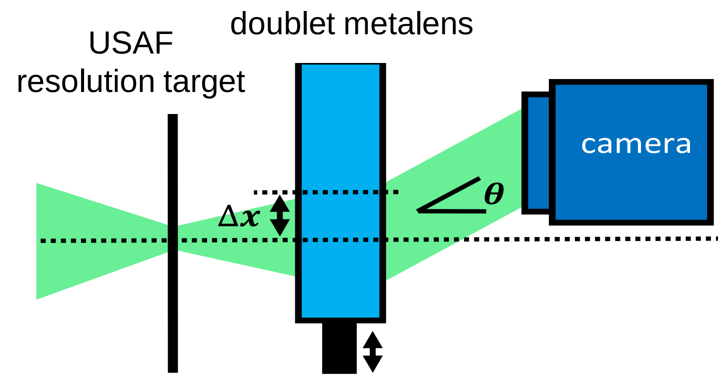
Focal spot and imaging

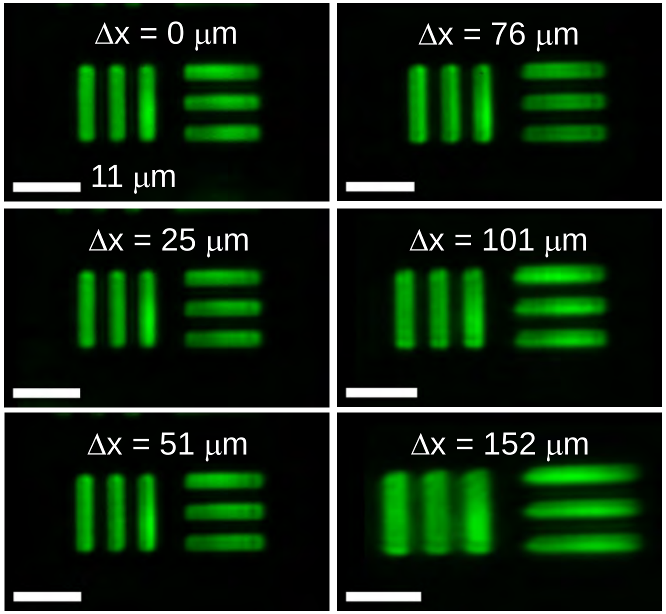
➢ Lens test set-up:





➢ Imaging set-up:

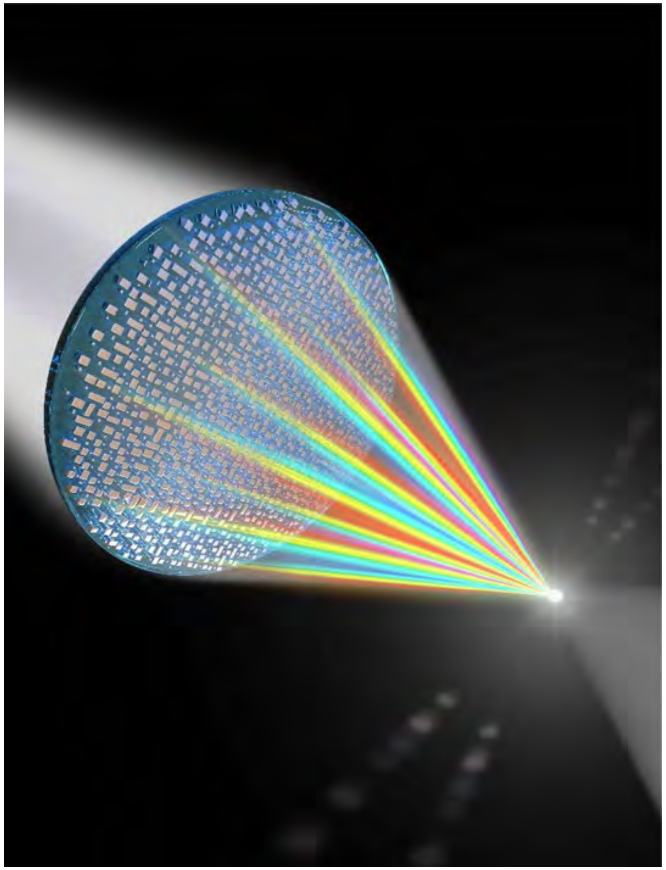


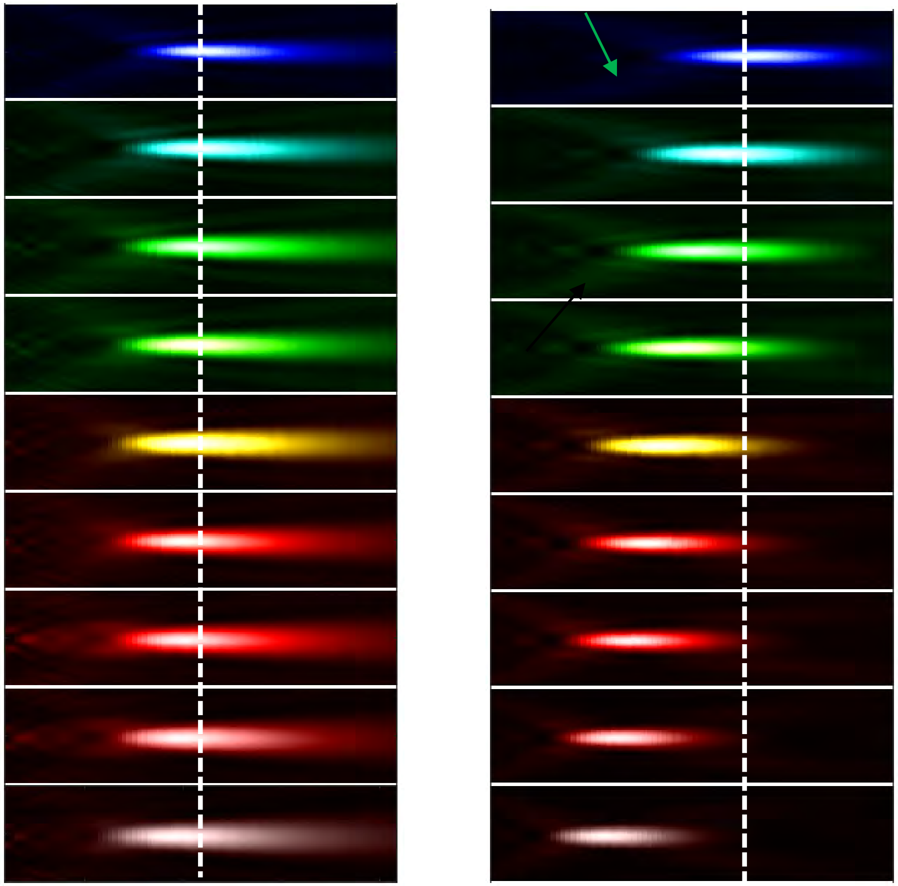


Scale bar: 11 µm

Dispersion Engineering: Achromatic Metalens

- Metalens (NA = 0.2) $F(\omega) = k\omega^n$

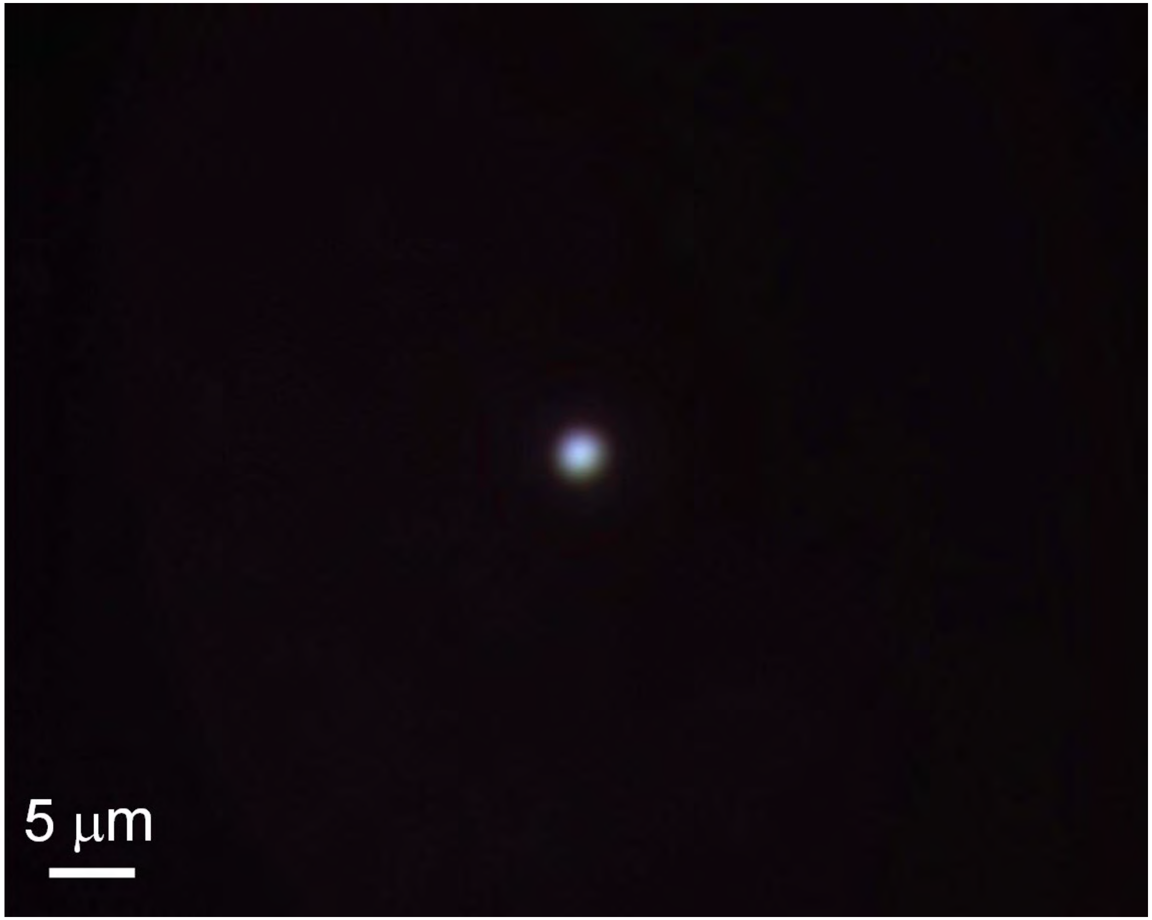




- Size limitation due to limited range of group delay

W. T. Chen, A. Y. Zhu, J. Sisler, Z. Bharwani, F. Capasso, *Nat. Commun.* **10**, 355 (2019)

White light focusing

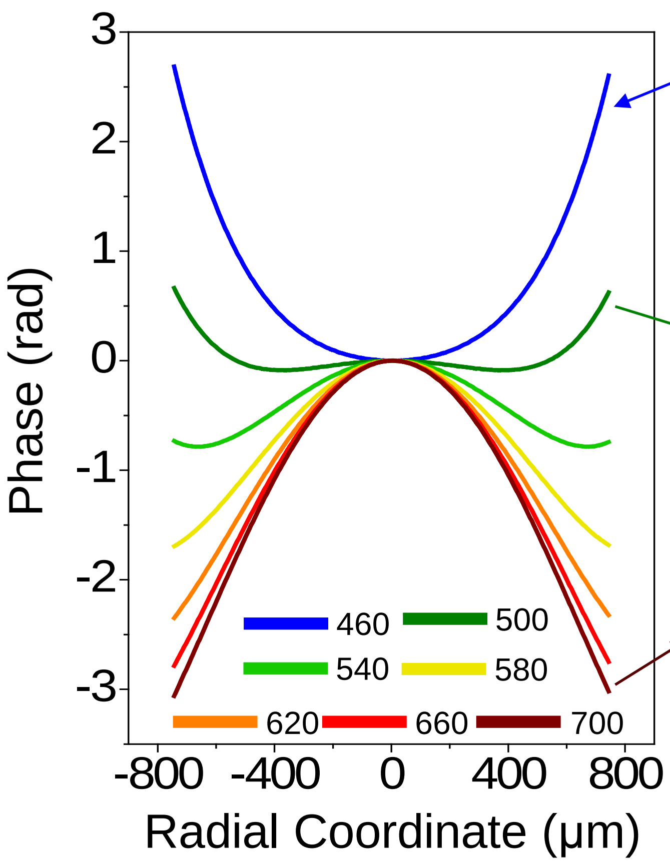


Correction of Achromatic Aberrations

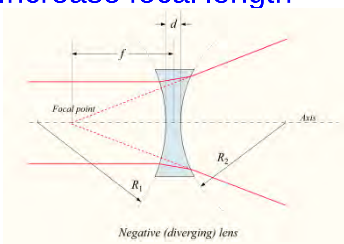
➢ Phase profile of metacorrector

W. T. Chen et al. *Nano Letters* **18**, 7801 (2018)

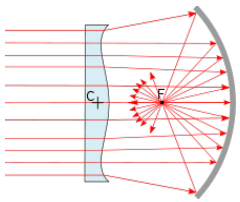
$$\varphi(r,\omega)=\varphi(r,\omega_d)+\frac{\partial\varphi}{\partial\omega}(\omega-\omega_d)+\frac{\partial^2\varphi}{2\partial\omega^2}(\omega-\omega_d)^2$$



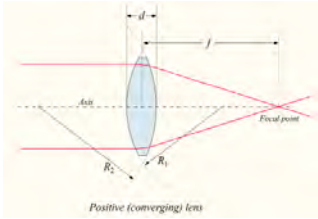
Concave lens
Increase focal length

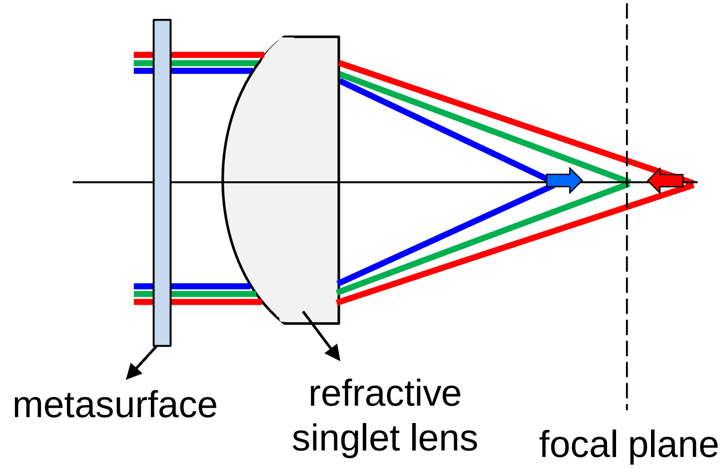


Schmidt plates
reduce spherical aberration

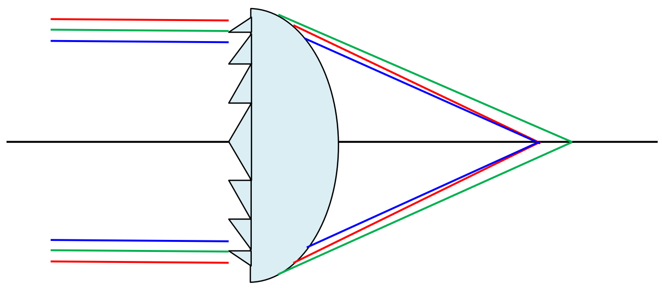


Convex lens
decrease focal length





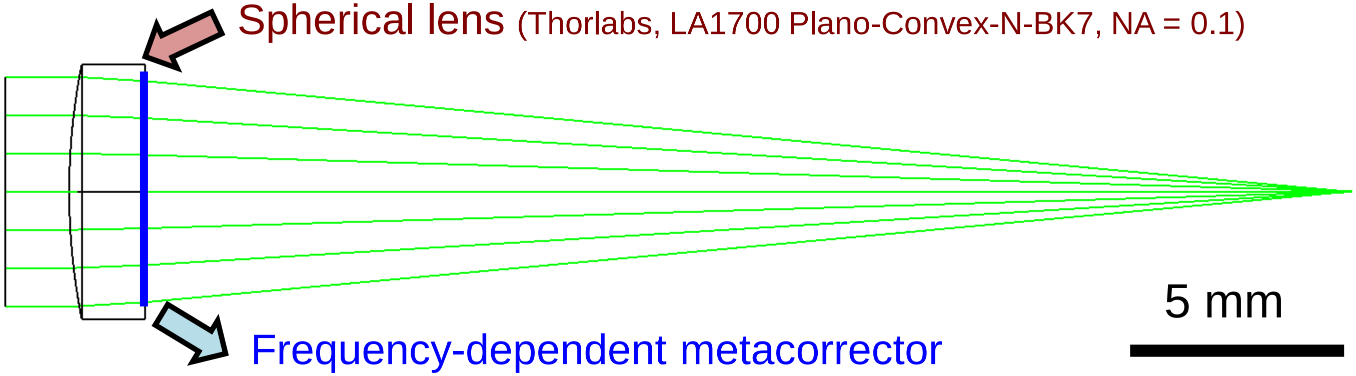
- Fresnel-refractive lens: hard to do

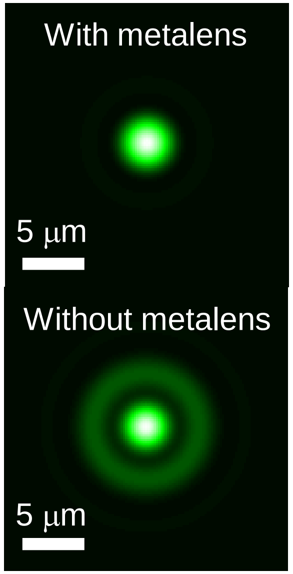


Hybrid Achromatic Metalens

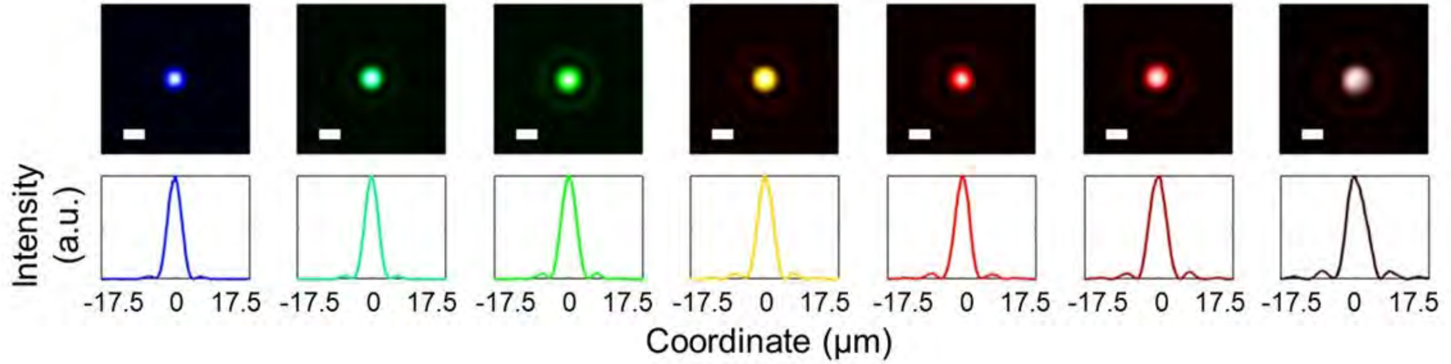
➢ Ray-tracing simulation

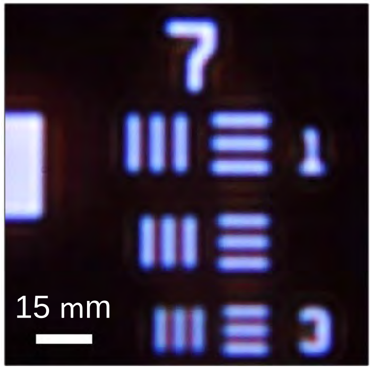
W. T. Chen et al. *Nano Letters* **18**, 7801 (2018)





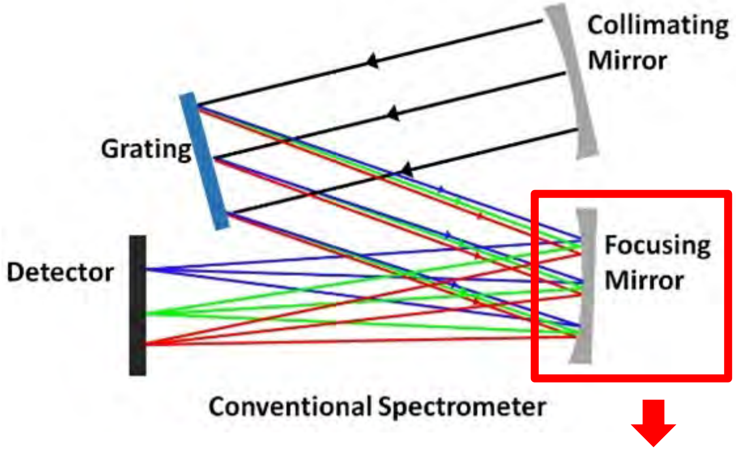
- Spherical lens + metacorrector (Dia = 1.5 mm, NA = 0.075)





Meta-spectrometers: Making good use of Chromatic Effect

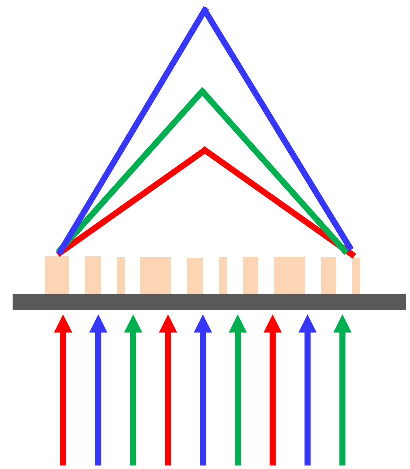
➢ Conventional grating-based spectrometers



Achromatic reflective focusing lens

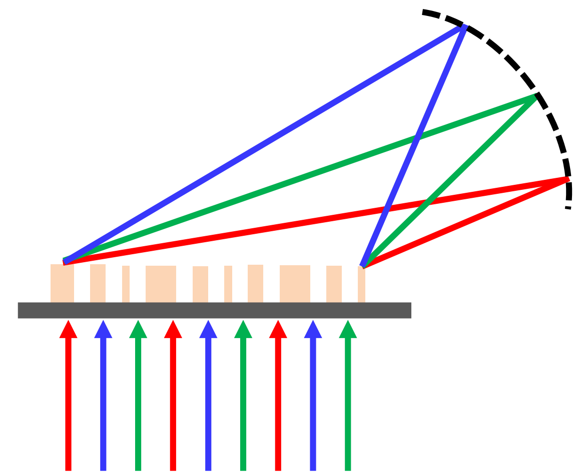
- angular dispersion

➢ On-axis focusing metalens



- longitudinal dispersion

➢ Off-axis focusing metalens



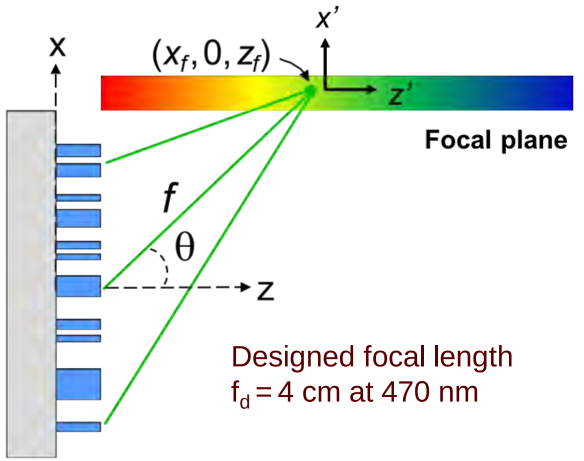
- angular dispersion + longitudinal dispersion

➢ Off-axis metalens has better spectral resolution because of angular and longitudinal dispersions.

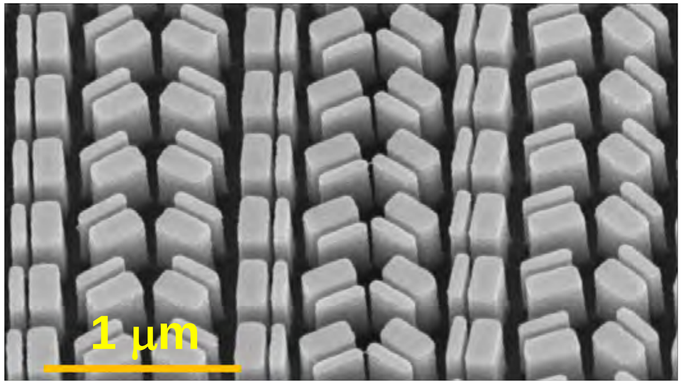
➢ Off-axis metalens suffers two major aberrations (field curvature and astigmatism), which limite its spectral resolution and range in a narrow bandwidth.

Aberration-corrected metalens spectrometer

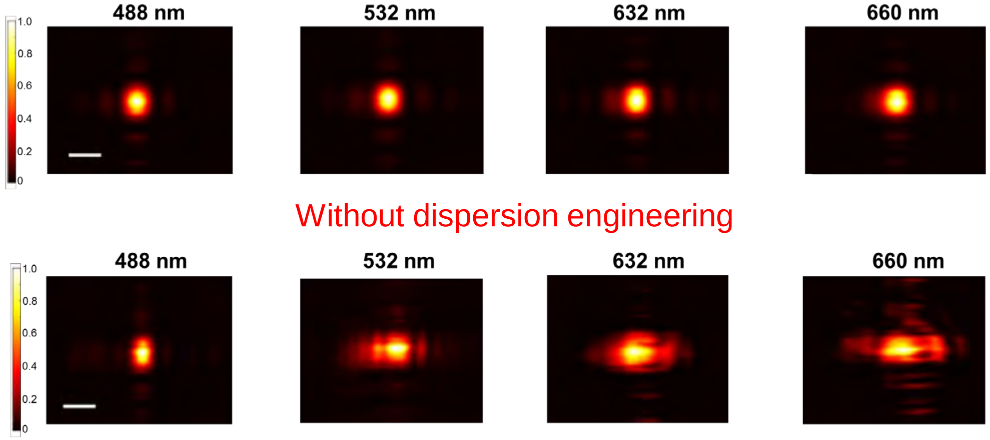
- Flat and perpendicular focal plane realized by dispersion-engineered metalens



- Coupled TiO_2 waveguide for fine tuning dispersion

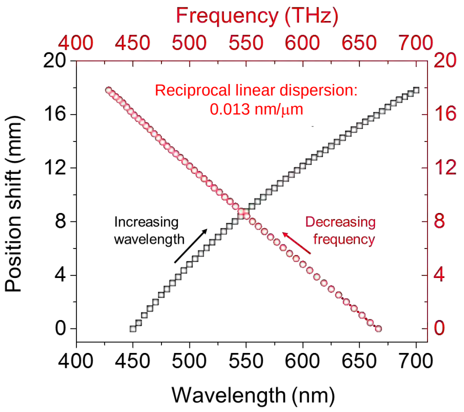


- Measured focal spots (FWHM ~ 56 μm)



- Metalens dispersion and spectral resolution

- Dispersion



- Spectral resolution

(Reciprocal linear dispersion × Focal spot size)

0.013 nm/μm   56 μm

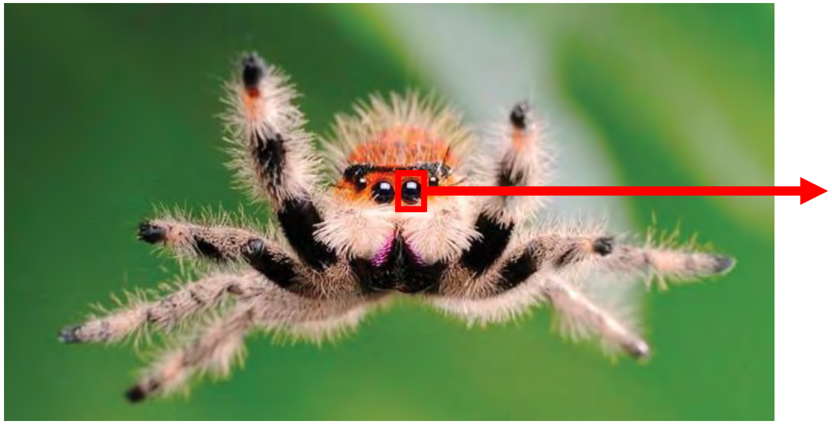
~ 0.73 nm spectral resolution from 470 to 660 nm in the visible

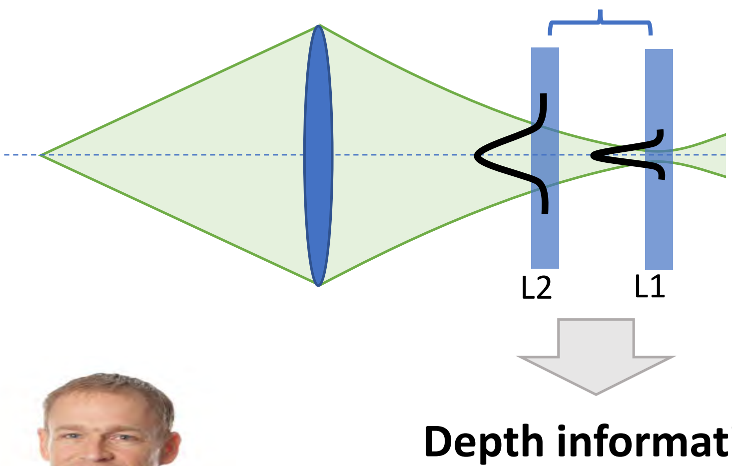
Bio-inspired metalens depth sensor

- Motivation: small, low power depth sensors

  Jumping spiders - an example of micro depth sensing platform

- High computational power means a fancy GPU or cluster, whereas low power computations can be easily implemented on small platforms with limited energy budge such as cellphones, microrobots, drones etc.





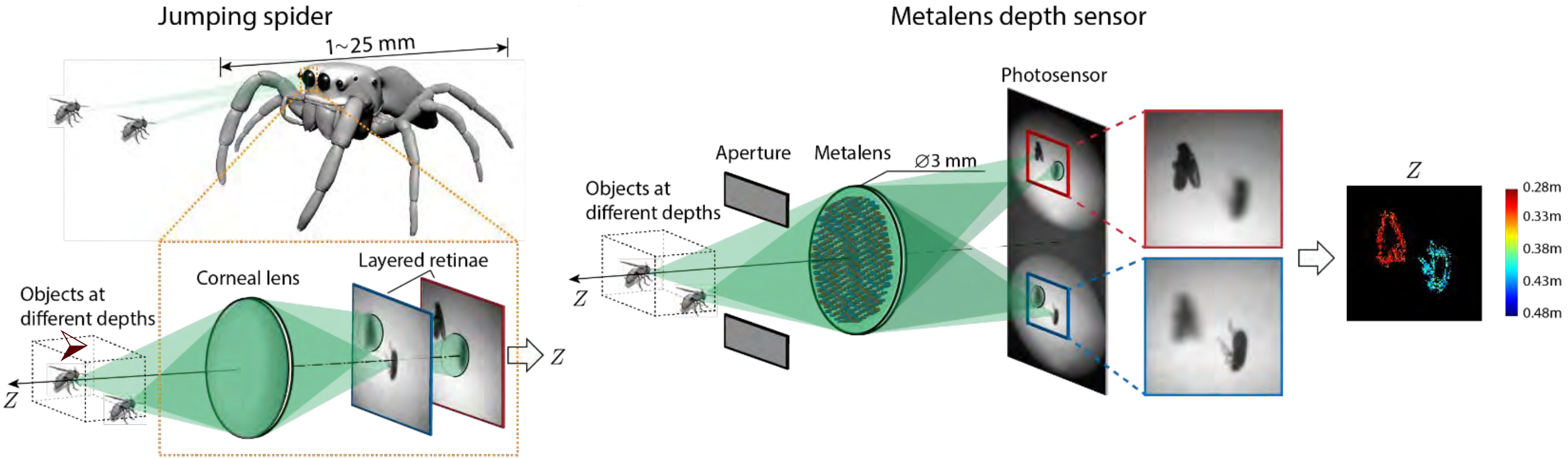
Zhujun Shi

Prof. Todd Zickler

Bio-inspired metalens depth sensor

Q. Guo et al. PNAS **116**, 22959 (2019)

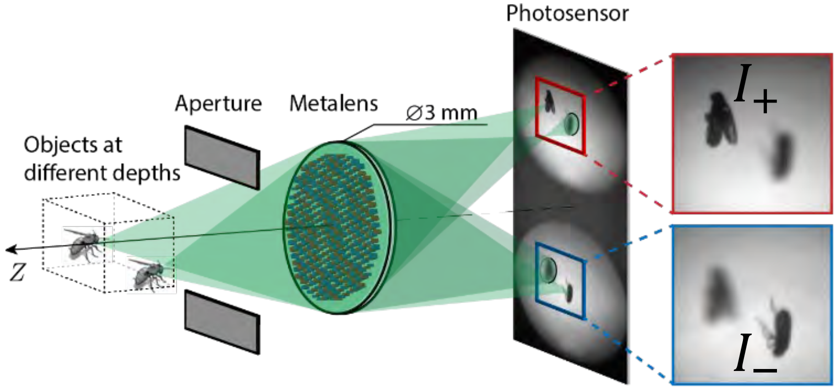
- Metalens depth sensor that mimics the jumping spider.



- Co-design of hardware (optics) and software (algorithm)
- Metalens that simultaneously creates side-by-side two images of the same scene but with different amount of defocus.

Depth from Defocus

Metalens depth sensor



$$\delta I = I_+ - I_-;\ I = \frac{1}{2}(I_+ + I_-)$$

- Depth map reconstruction equation

$$Z(x,y) = \left(\alpha + \beta \frac{\delta I(x,y)}{\nabla^2 I(x,y)}\right)^{-1}$$

- Advantages:
  - Greatly reduced computational burden: **10 times less computation** then typical stereo or light field depth sensors.
  - High speed: ~160 frame per second (fps) (for comparison, standard movies are 24 fps).
  - Snapshot, compact, lightweight.

- **Amount of computation** = **floating point operations per output pixel** (**FLOPS**). Our method uses ~600 FLOPS, whereas traditional stereo depth sensing requires ~ 7000 FLOPS. Make FLOPS as small as possible: small chips at high speed and low power consumption.

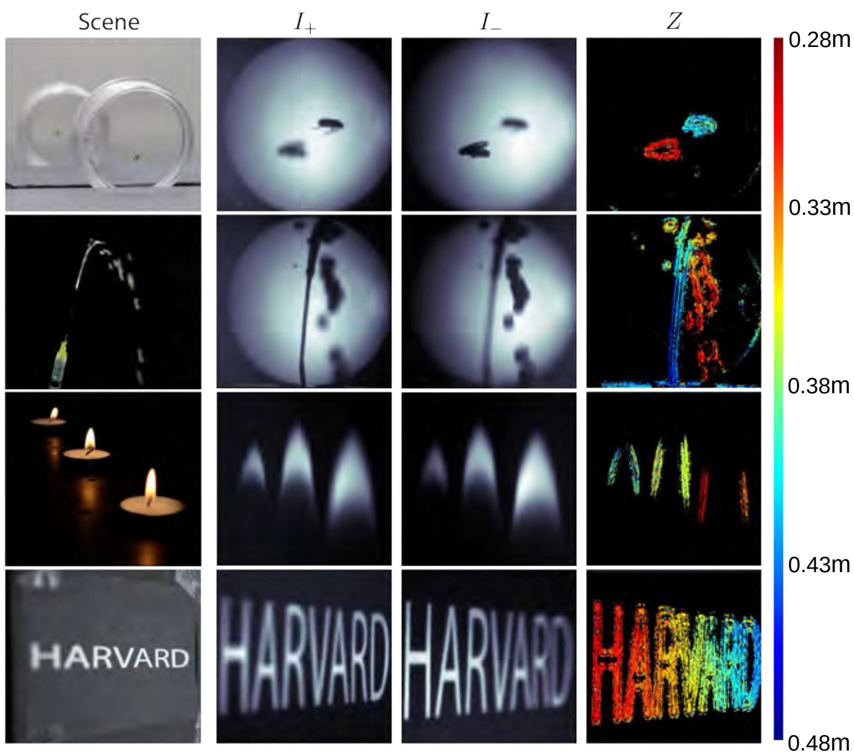
Results

Fruit flies

Water stream

Candle flames

Slanted plane with texts

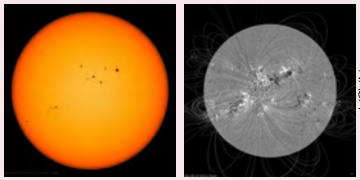


- Working range: 30-40 cm
- Depth resolution: ~3% of the true depth
- Working range and resolution can be adjusted by modifying the metalens design.

Why care about seeing polarization?

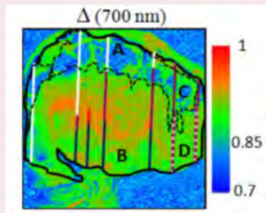
Science

Astrophysics



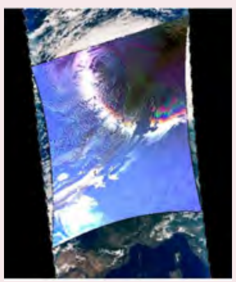
NASA

Medicine



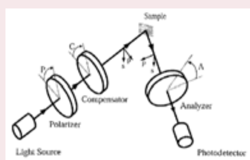
Opt. Express (2013)

Atmospheric science



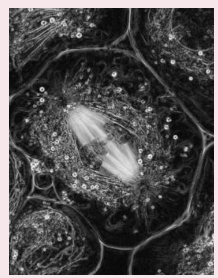
POLDER

Materials science



Appl. Opt.

Biology



OpenPolScope

Technology

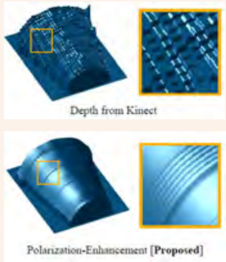
Remote sensing

Proc. SPIE

Autonomous vehicles

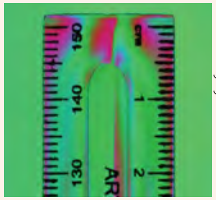
Aust. Natl. Univ.

3D reconstruction



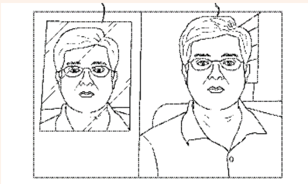
MIT Media Lab

Machine vision



Teledyne DALSA

Security



Apple, Inc.

Noah Rubin

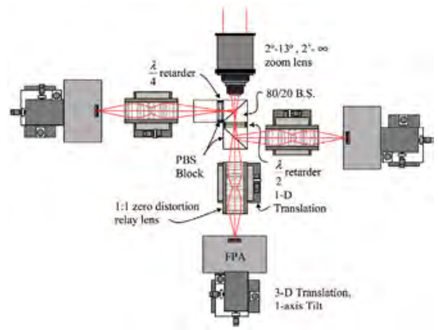
Paul Chevalier

Polarization imaging: techniques and hardware

Division of time:

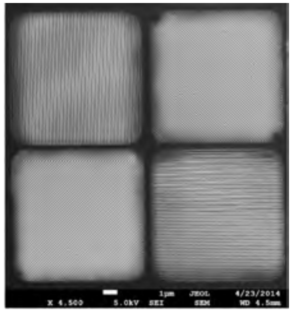
- -Minimum of componentry ✓
- -Limited time resolution ×
- -Moving parts ×

Division of amplitude:



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

Division of focal plane:



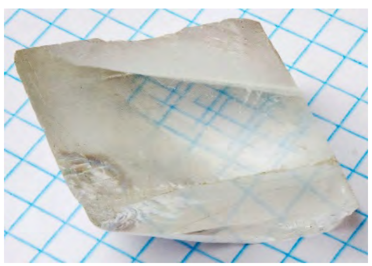
- -No real limit to time-resolution ✓
- -No moving parts ✓
- -Difficult fabrication, sensitive alignment ×
- -Expensive ×
- -Usually only sensitive to linear polarization ×

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 optics

~1650:



"Iceland spar"
(calcite)

Today:

Polarizing prisms

Waveplates

Rhombs

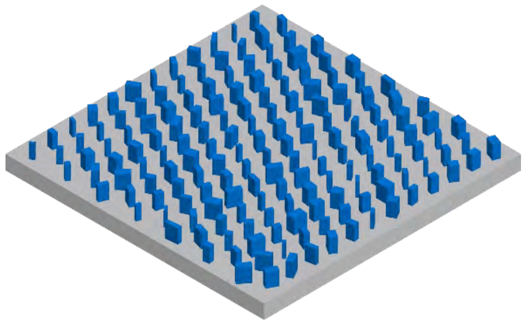
Polarizing sheet
Polaroid, Inc.

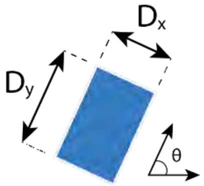
In free space, we still rely on the same tools whose discovery prompted the first investigations into polarization optics 350 years ago.

What new polarization optics and physics can we explore?

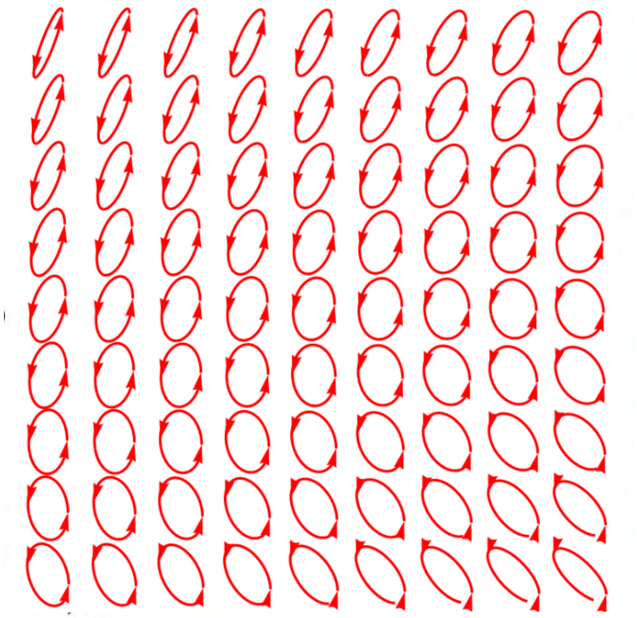
Metasurfaces and polarization optics

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





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



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

NA Rubin et al., *Phys. Rev. Lett.* **118**, 113901 (2017)

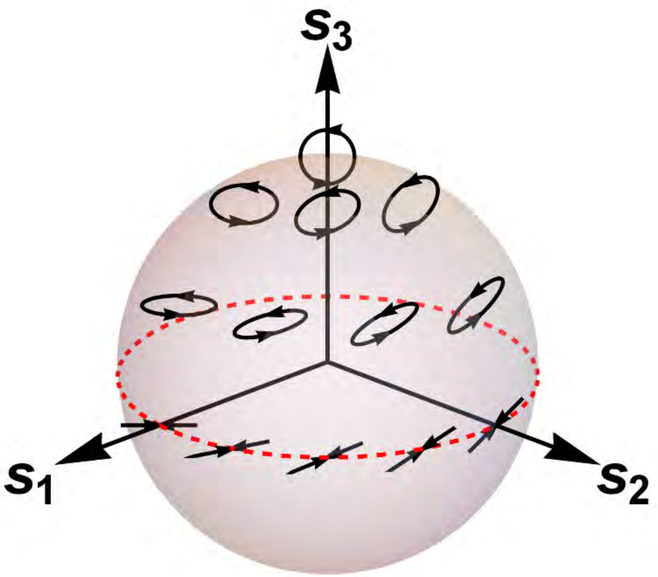
The Stokes formalism

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}$$

"Stokes vector"

In its most general form, light's polarization is described by **4 parameters**.

Un/partially polarized light.

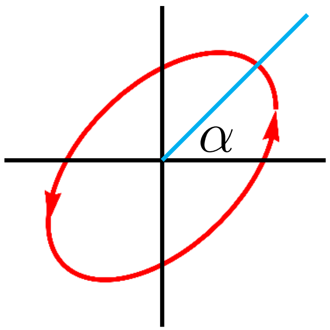


The Poincaré sphere

Four intensity measurements with four different filters uniquely characterize polarization

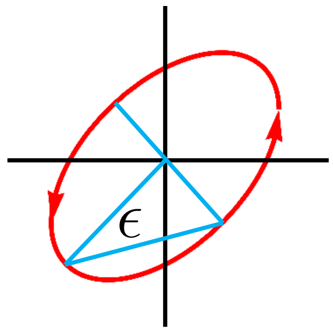
Quantities derived from the Stokes vector

These correspond to physical properties of the polarization ellipse.



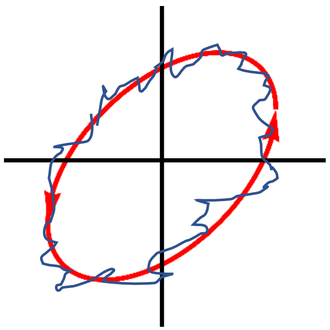
Azimuth

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



Ellipticity

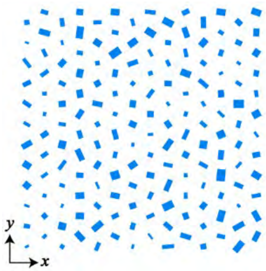
$$\epsilon(\vec{S}) = \arctan \frac{S_3}{\sqrt{S_1^2 + S_2^2}}$$



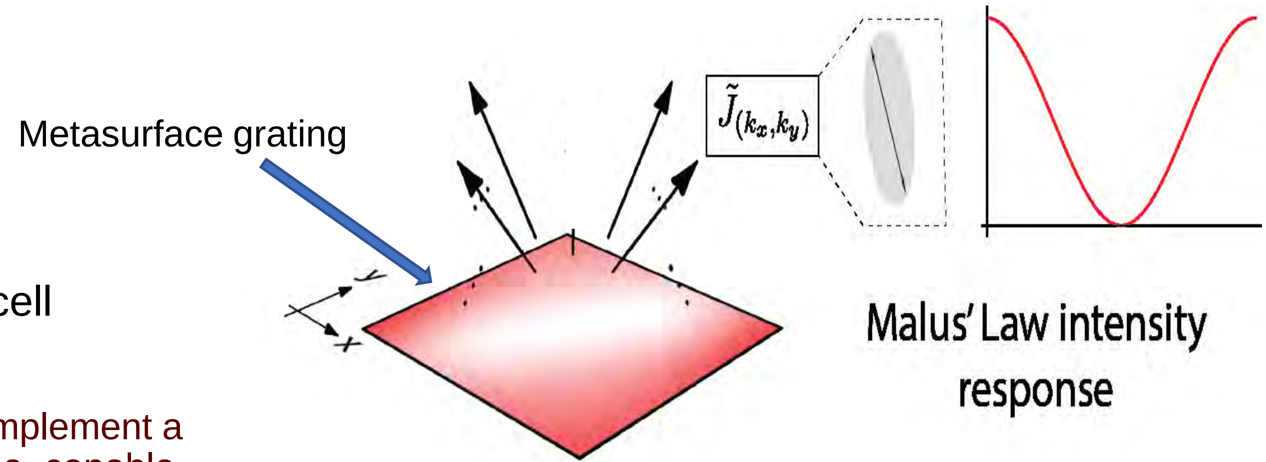
Degree of polarization

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

Polarization imaging with metasurfaces



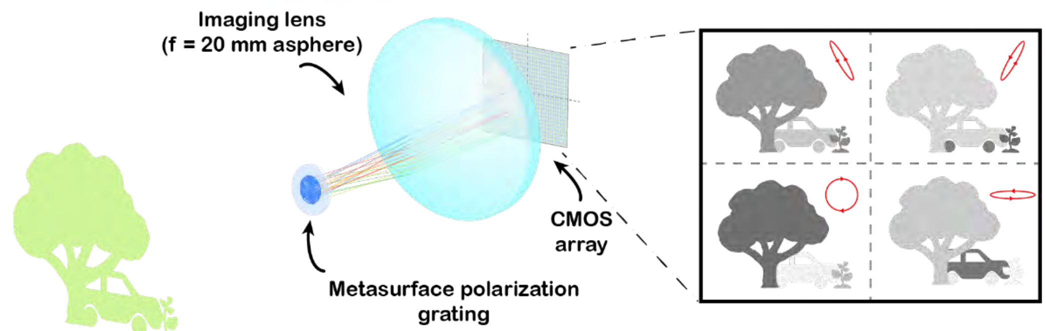
Metasurface unit cell



- 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

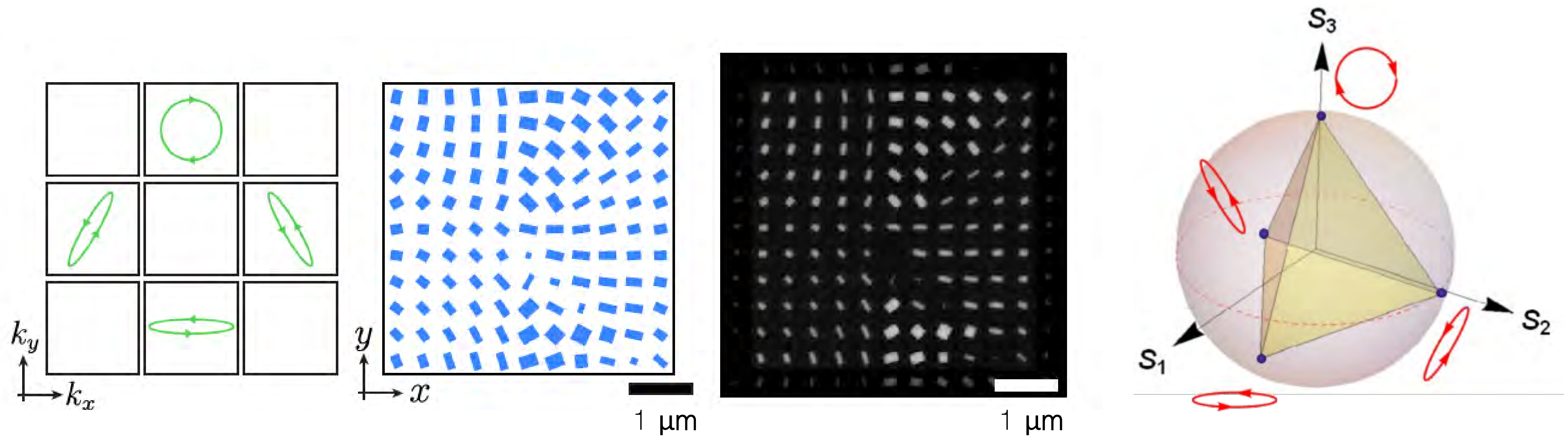
- This grating can be used to construct a polarization camera with a minimum of componentry



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)

Gratings for parallel polarization analysis



A grating formed from many of the above unit cells **diffracts light into four inner diffraction orders that act as polarizers**.
The grating functions at 532 nm.

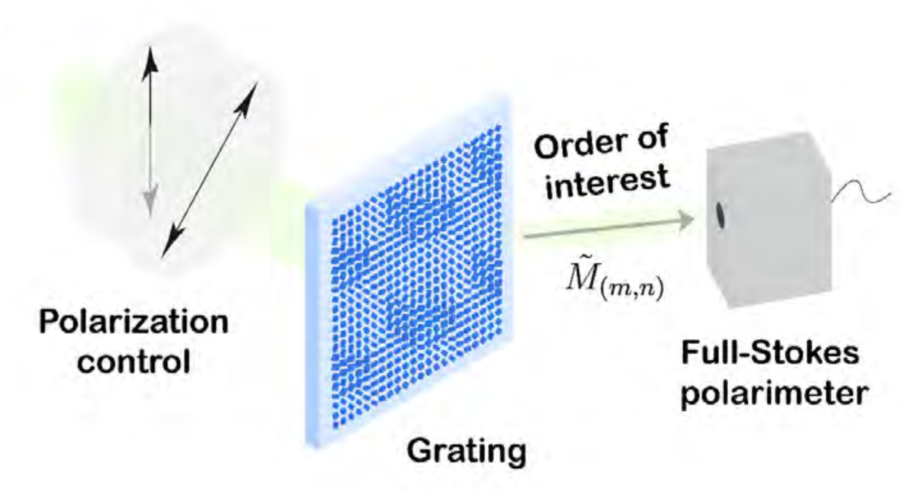
N.A. Rubin et al. *Science,* **365**, 6448 (2019)

Polarimetry of grating orders

How do we characterize the grating?

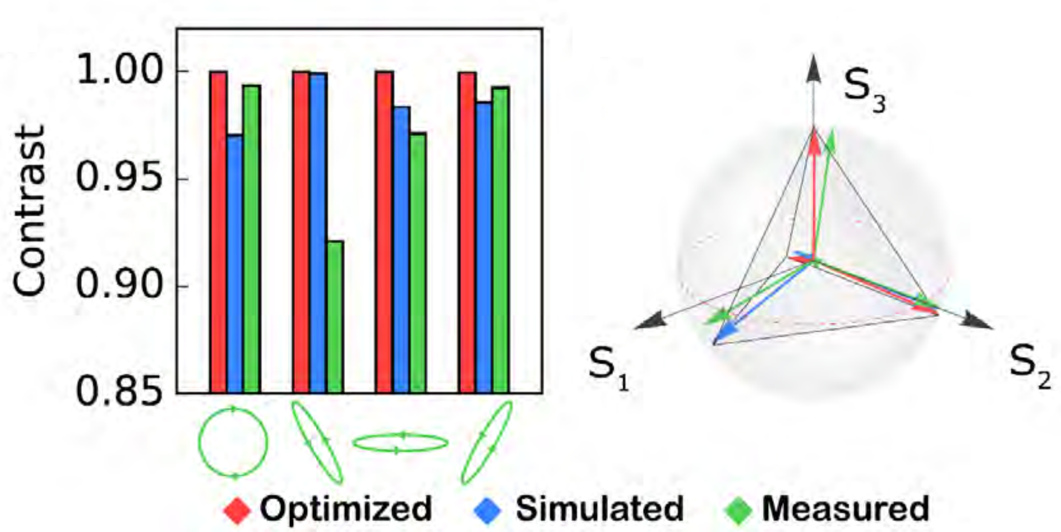
Key Idea: *Probe grating with many test polarization states and see what polarization states come out.*

Mueller matrix polarimetry.

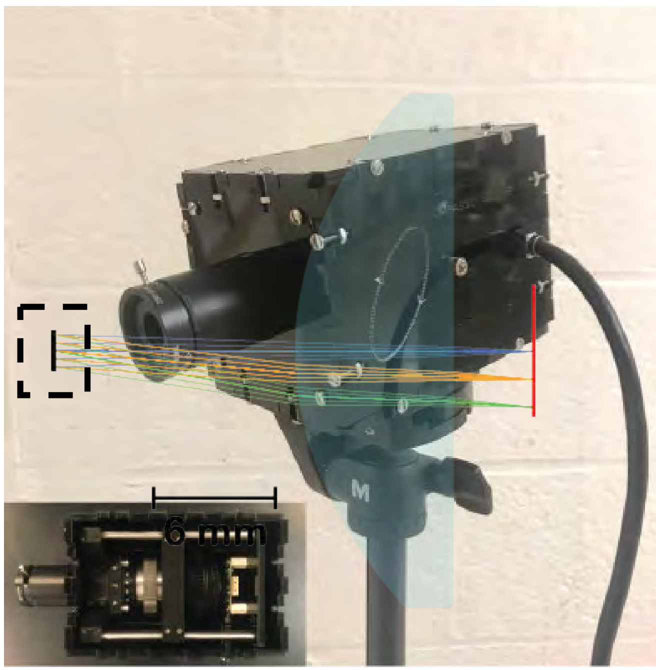


Experimental characterization of gratings

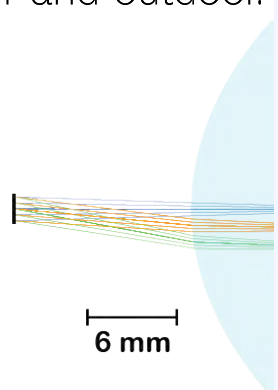
- We find:
  - The orders behave as polarizers for the desired polarization states.
  - They show contrasts exceeding 90%, with *no absorptive polarizers*.
  - On average, over 50% of incident intensity ends up in these four orders.
- The grating can be employed in a practical polarization imaging system!

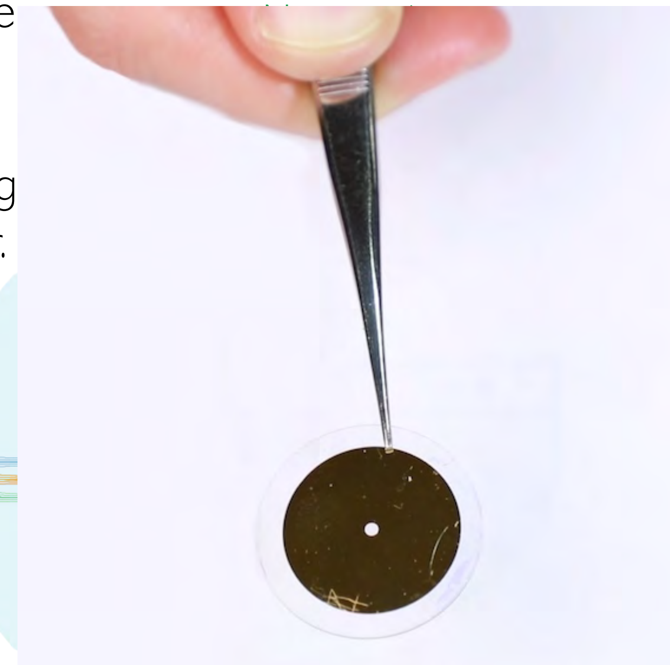


Metasurface polarization camera

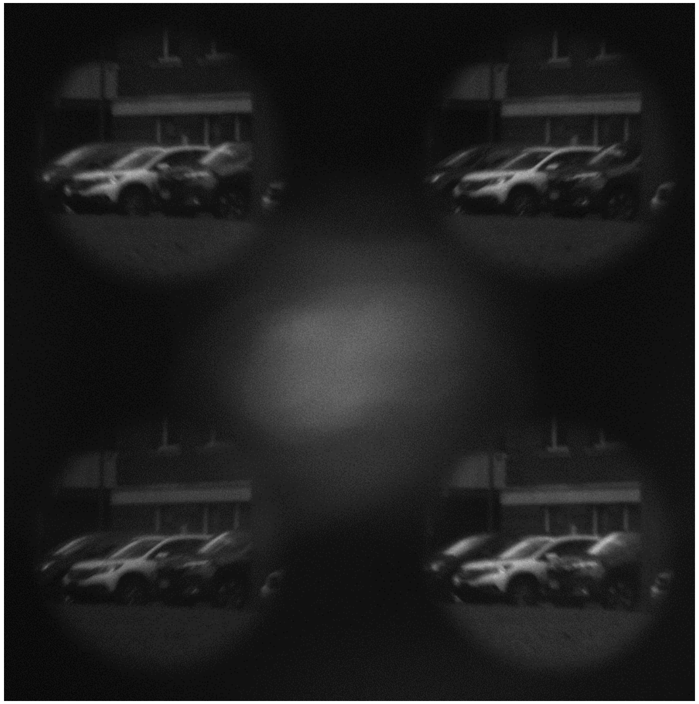


Packaged prototype with user interface for real-time polarization imaging indoor and outdoor.





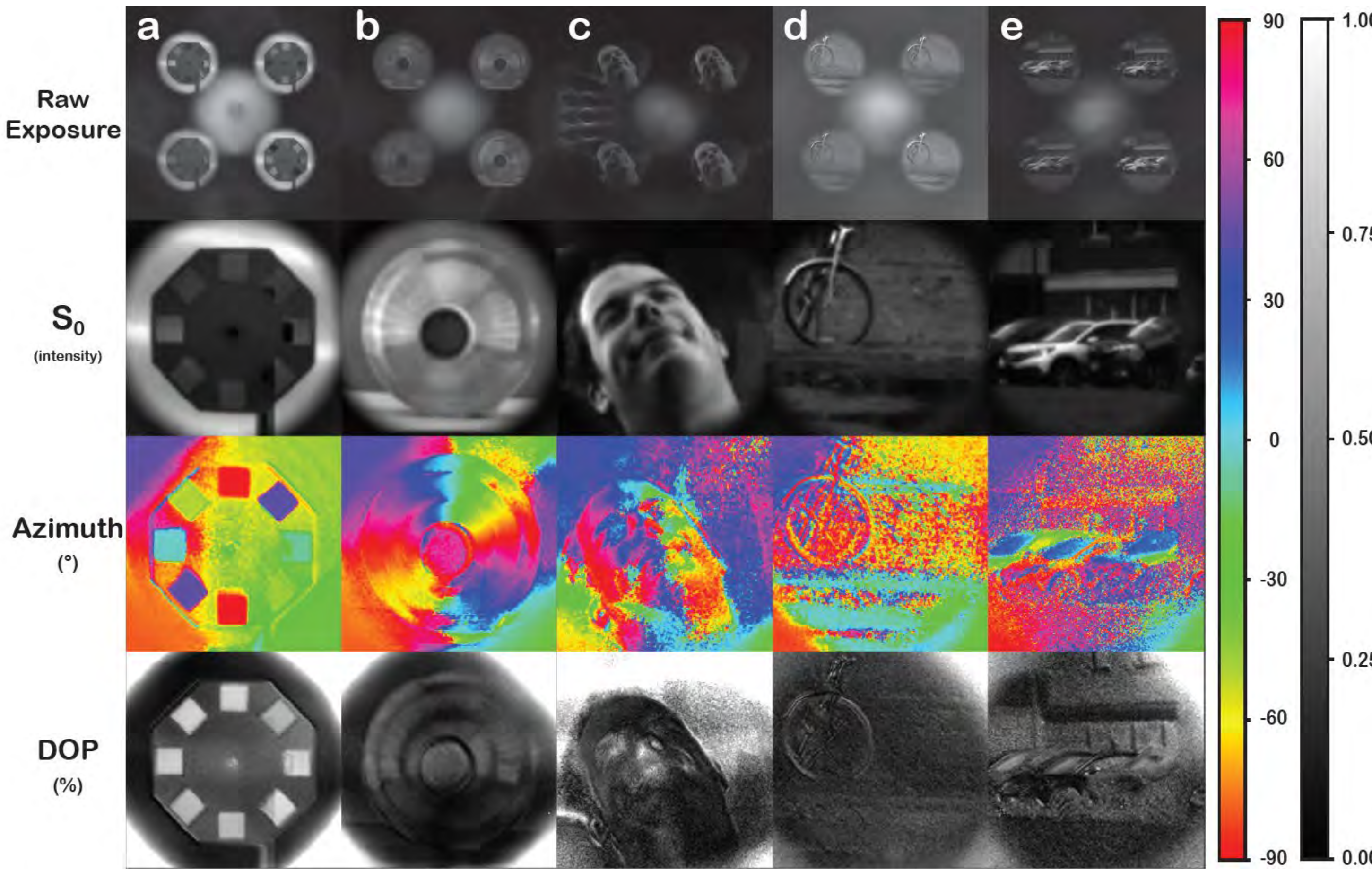
What does the camera see?



Four images with differing polarization response.

The four images must be co-registered and processed to determine the full Stokes vector at each pixel.

Indoor and outdoor polarization imaging



N.A. Rubin et al. *Science,* **365**, 6448 (2019)

Our Vision for Planar ("Flat") Optics

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

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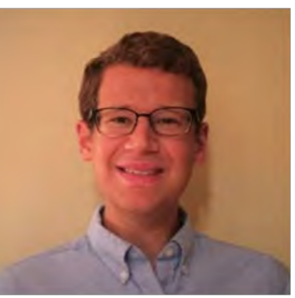

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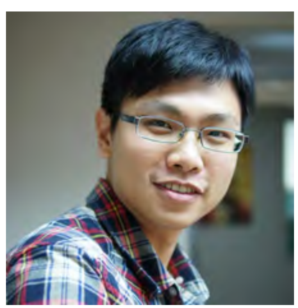

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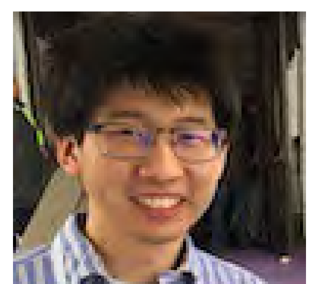
Joon-Suh Park



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