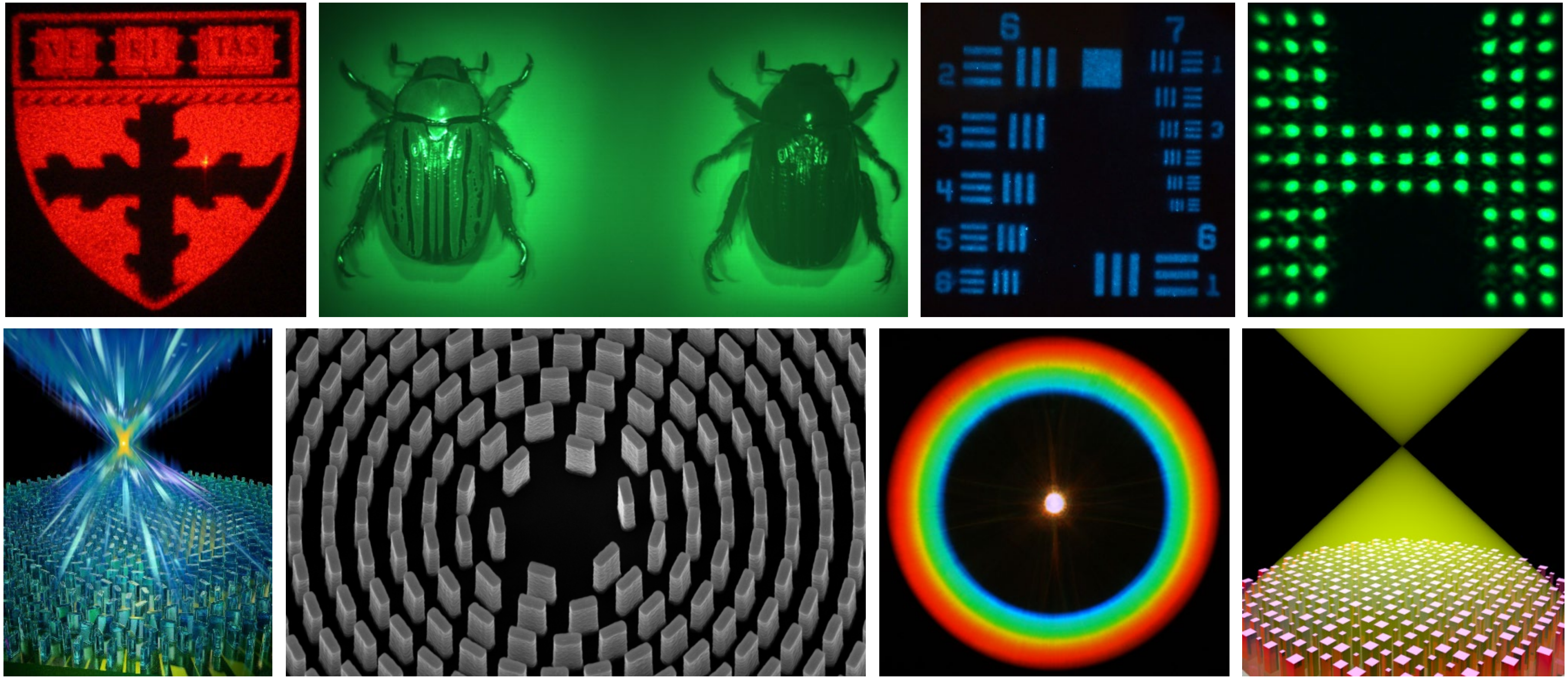
Metasurface Flat Optics



January 12, 2024
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Capasso Group
Harvard School of Engineering and Applied Sciences

Vision for Flat Optics

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

- Planar technology is central to IC technology: Technology platform
- **Same foundries will manufacture camera sensor and lenses using same technology (deep-UV stepper)**
- **Single phase mask (lithographic level) generates the metaoptical component**
- **Metasurfaces that give arbitrary control of the phase, amplitude and polarizations of light**

- **Our goals:**

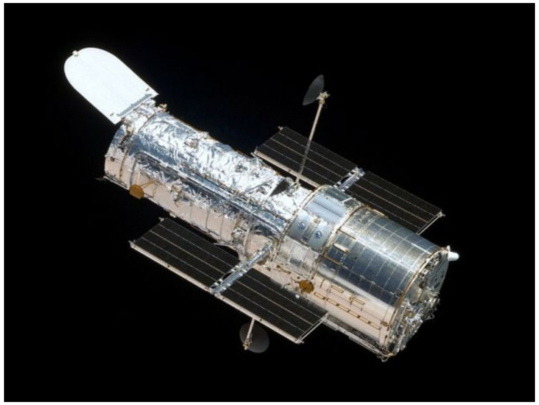
CMOS compatible flat optics platform for high volume markets:
cameras (cell phone camera modules, laptops, automotive, biometrics), displays,
wearable optics (augmented reality).
$TiO2$: high quality material platform for visible
Amorphous Si: same for near IR
Fused Silica (SiO_2)

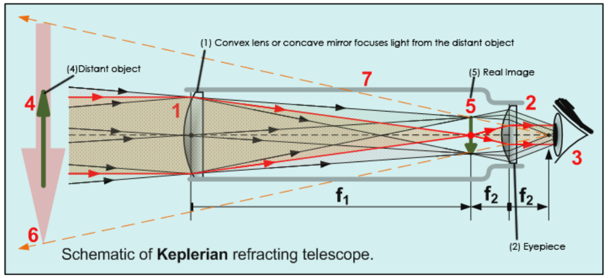
Example: lenses in cell phone camera modules will be replaced by metalenses fabricated by deep UV steppers (same foundry that makes the sensor chip): thinner, easier fabrication and alignment

- **Flat Optics for a wide range of optical components** (lenses, holograms, polarizers, phase plates, etc.) machine vision, biomed imaging, scientific applications (OCT), drones, polarimetry laser lithography, OEM markets

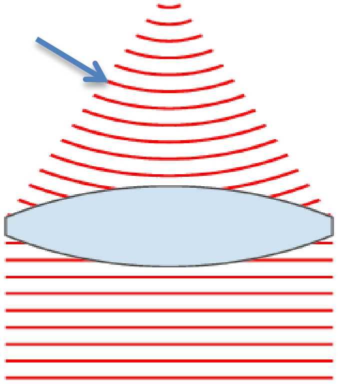
- **Multifunctionality: single flat optical components replaces multiple standard components with attendant reduction of system complexity and footprint**

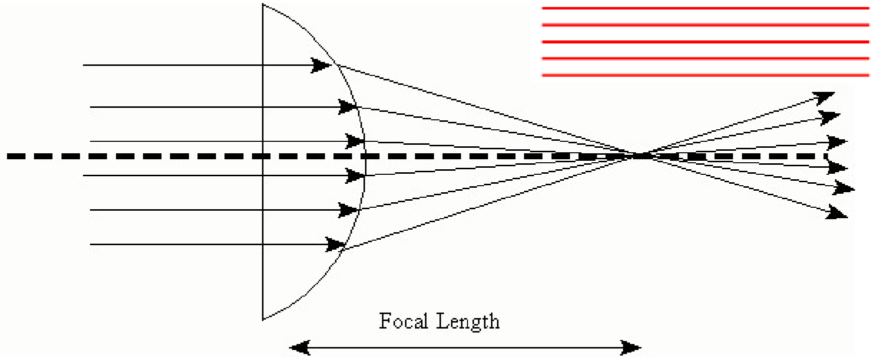
Why Lenses are thick ? Can we make a flat lens?





Propagating Wavefront





- 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

Lens becomes more demanding

- Conventional lens manufacturing: grinding, polishing and plastic molding

Newsroom

Perfecting Smartphone Photos

The back of your mobile phone may soon be covered with tiny lenses that take simultaneous images that are computationally stitched together for new effects and capabilities.

Pixel uses hand movement to calculate object distance and artificially add pixels for better quality zoom

Single lens
GOOGLE PIXEL 3
Released October 2018
+ 12.2-megapixel, dual-pixel lens

Google

iPhone's 'Neural Engine' performs five trillion operations per second

Getty Images

Dual lens
iPHONE XS
Released September 2018
+ 12-megapixel wide-angle lens
+ 12-megapixel telephoto lens with 2x optical zoom

Triple lens
HUAWEI P20 PRO
Released March 2018
+ 40-megapixel main RGB lens
+ 20-megapixel monochrome lens (to help with depth and lowlight situations)
+ 8-megapixel telephoto lens with 3x zoom

3 lenses

Getty Images

The Leica zoom lens system can achieve 5x hybrid zoom

Penta lens
NOKIA 9 PUREVIEW
Available February 2019
A promotional video purportedly showing the Pureview, leaked at year-end 2018, featured a device with five Zeiss lenses, a depth sensor and a dual-LED dual-tone flash

5 lenses

Nokia

It's believed that the Pureview will have the ability to stitch together five images and will offer the option to refocus an image post shot

4 lenses

Samsung

Quad lens
SAMSUNG GALAXY A9
Released October 2018
+ 24-megapixel main lens
+ 8-megapixel, 120° ultrawide lens
+ 5-megapixel depth lens
+ 2x optical zoom telephoto lens

The Galaxy A9 uses a pixel re-mosaic algorithm to produce clear images in low light

9 lenses

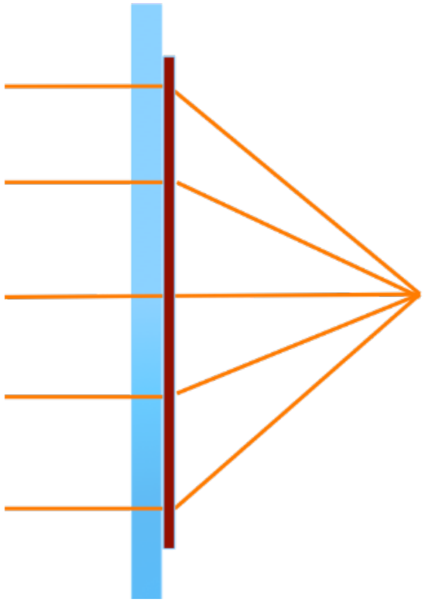
light.co

Nine lenses?
Available date unkown
In mid-2018, the *Washington Post* reported that the startup company Light was developing a smartphone with up to nine lenses, capable of capturing 64-megapixel shots with superior low-light performance and depth effects

Ref: Optics and photonics, February 2019

- Largan Precision company (major cell phone lens supplier) produces ~ 17 billions plastic lens modules
- These lenses are for various applications: cellphone/NB lenses, webcam lenses, car and camera lenses etc.

Can we make a flat lens with no aberrations?



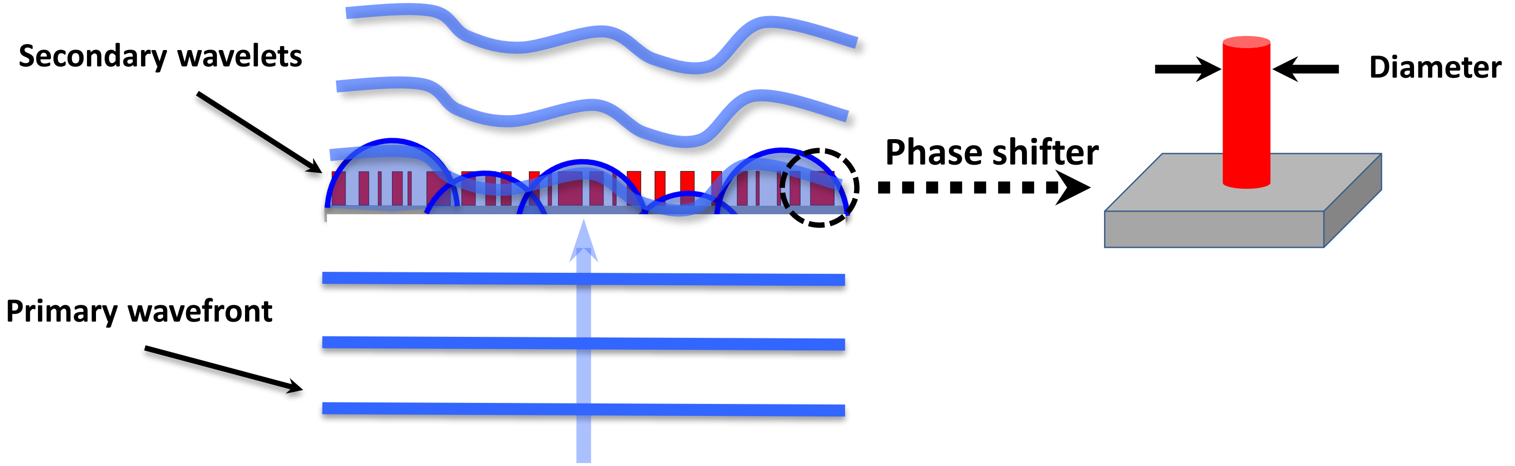
- All rays focused to the same point? i.e. diffraction limited.
- Two challenges: doing it first for “single” wavelength and then for a broad spectrum?

- By structuring with nanotechnology a planar surface so that all rays converge to the same focus

The surface is nanostructured: METASURFACE

Metasurfaces: complete wavefront control

- Huygens-Fresnel Principle



Benefits

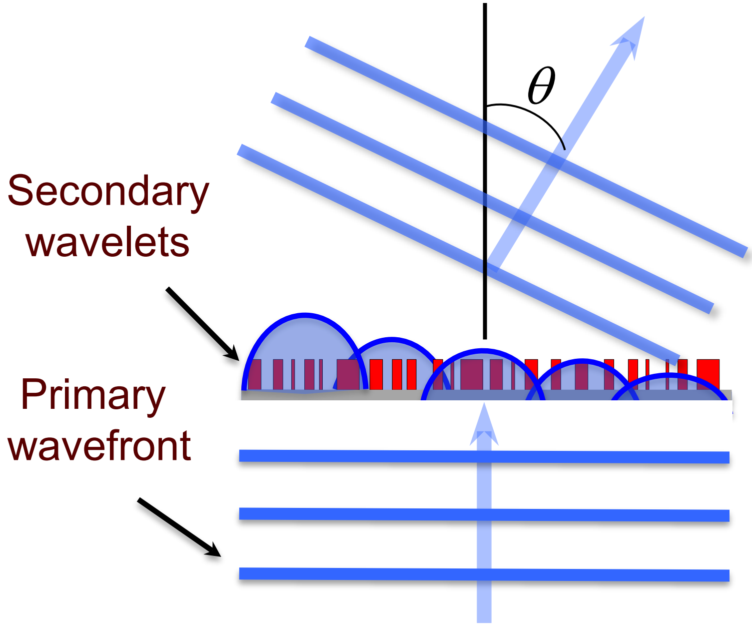
- **Straight-Forward Fabrication**
  - One mask level, cost effective
- **Compact**
  - Light weight, capability to be vertically integrated
- **Unprecedented Control of Dispersion**
- **Overcome Limitations of Conventional Optics**
  - Aberrations, multifunctionality

Metasurface: Manipulating phase using nanostructures

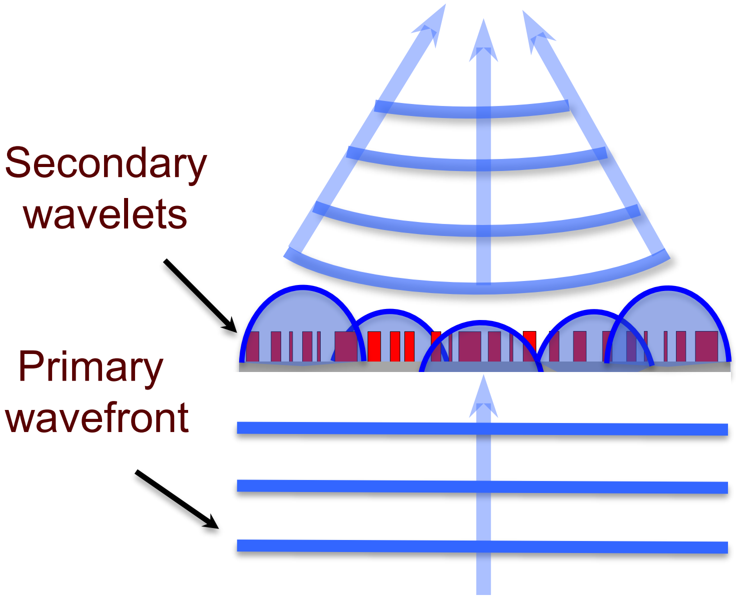
- Control Amplitude, phase, polarization and wavenumber of light

$$\vec{E} = A \cdot \exp^{i(k_z \cdot z+\varphi)} \hat{y}$$

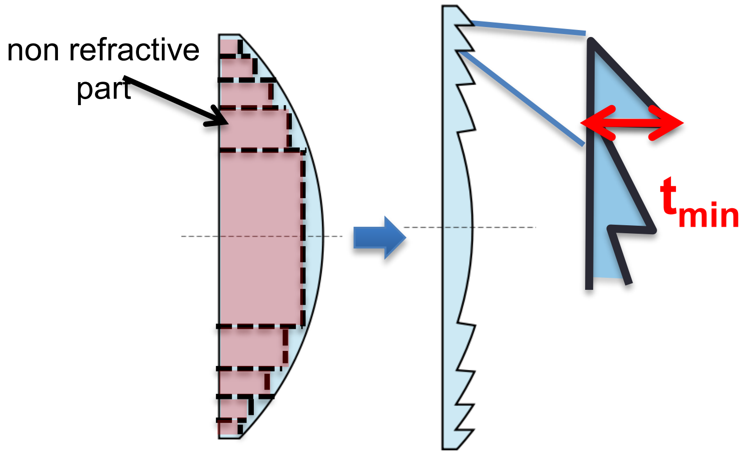
- Example: Beam deflector

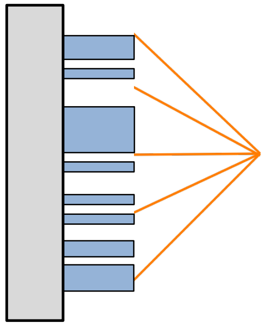


- Example: Lens



Fresnel Optics vs Metasurface Based Optics



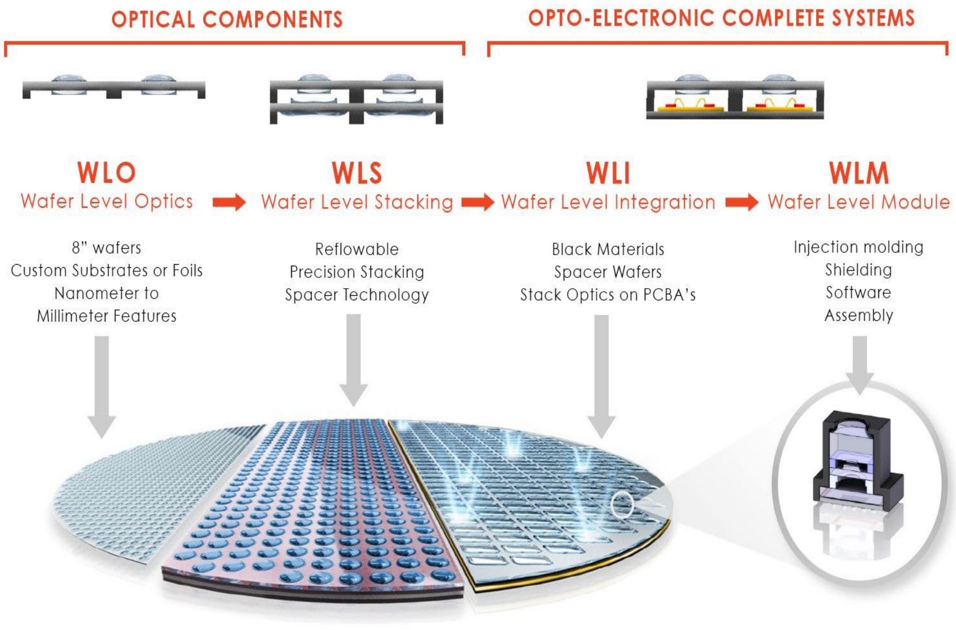


Fresnel Optics	Metasurface
finite lateral phase control	sub wavelength phase control
polarization insensitive	polarization control
multi wavelength operation hard	controlled dispersion: achromatic
multiple steps of lithography: N phase level→$\log_2$ N steps Limited functionality	single lithographic step multifunctional

A single digital pattern (one mask level) can create an arbitrary analog phase profile

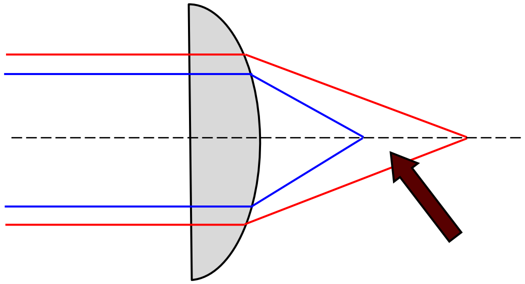
Unique properties of metalens

- Lithography-based Fabrication:
  nano-meter precision with high throughput
- Flat and Compact:
  compatible with wafer packing



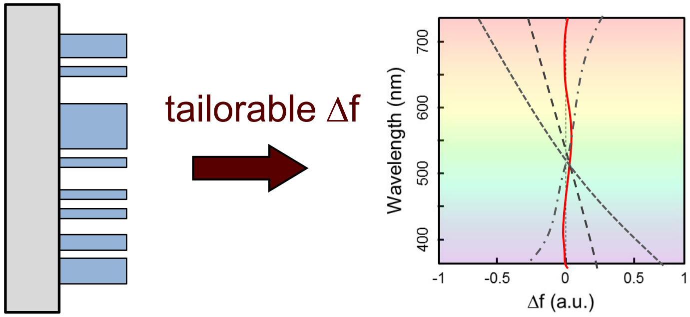
Ref: Heptagon Inc. (Wafer level optics packaging)

- Tunable dispersion:
  - Refractive lens:
    dispersion is given by glass material



Lens maker equation: $F(\lambda) = \dfrac{R}{n(\lambda) - 1}$

  - Metalens:
    Tailorable through nanostructures



General design process

- Flow of convention metasurface design

1. Target phase profiles from analytical solution or raytracing

- Most cases are related to geometric optics
- Hologram is an exception, which requires diffraction calculation to obtain target phase profile.

2. Build a nanostructure library by parameter sweep

- Solving Maxwell's equations by a simulation software

3. Matching target phase with nanostructure phase for each spatial coordinate

- Choosing elements from the library based on a figure of merit

General principle

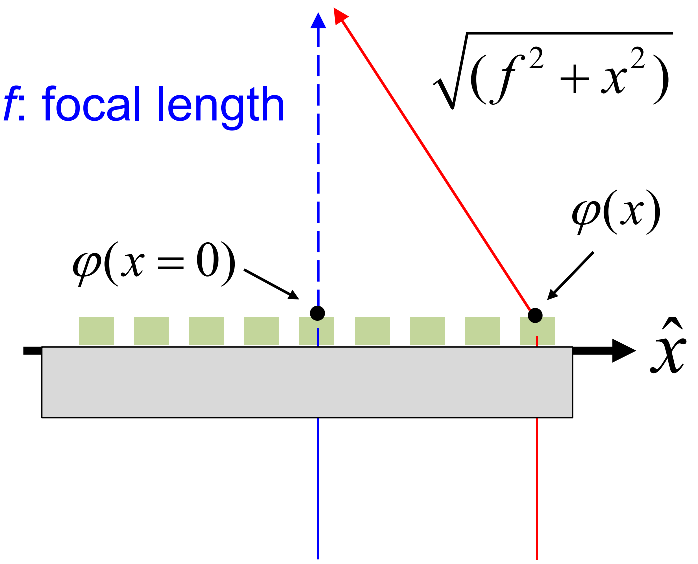
- Light rays propagate to the direction where there are in-phase.
- Phase $\varphi = \frac{2\pi}{\lambda} \cdot n \cdot L$

Propagation length

Wavelength

Refractive index

- Example: Lens



f: focal length

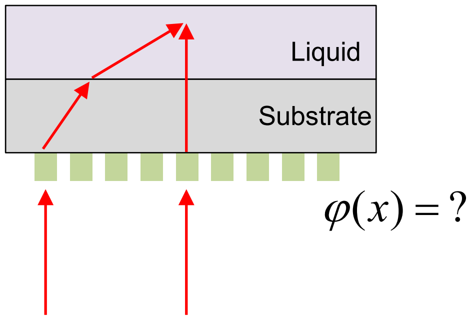
$$\varphi(x=0) + \frac{2\pi}{\lambda_d} f = \varphi(x) + \frac{2\pi}{\lambda_d}\sqrt{(f^2 + x^2)}$$

Set $\varphi(0) = 0$, because only relative phase matters

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

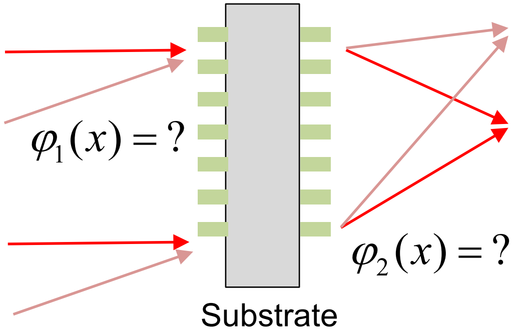
More complicated cases

- **Immersion metalens**



ReF: Chen, W. T. et al. Immersion Meta-Lenses at Visible Wavelengths for Nanoscale Imaging. Nano Lett. 17, 3188-3194 (2017)

- **Doublet metalens**



Ref: Groever, B., Chen, W. T. & Capasso, F. Meta-Lens Doublet in the Visible Region. Nano Lett. 17, 4902-4907 (2017).

Ref: Arbabi, A. et al. Miniature optical planar camera based on a wide-angle metasurface doublet corrected for monochromatic aberrations. Nat. Commun. 7, 13682 (2016).

- **Raytracing software (Zemax: OpticsStudio, Synopsys: CodeV etc):**

- Binary 2 surface in OpticsStudio

Taylor expansion of φ(x) :

Only considers even terms, because lens phase profile is symmetric

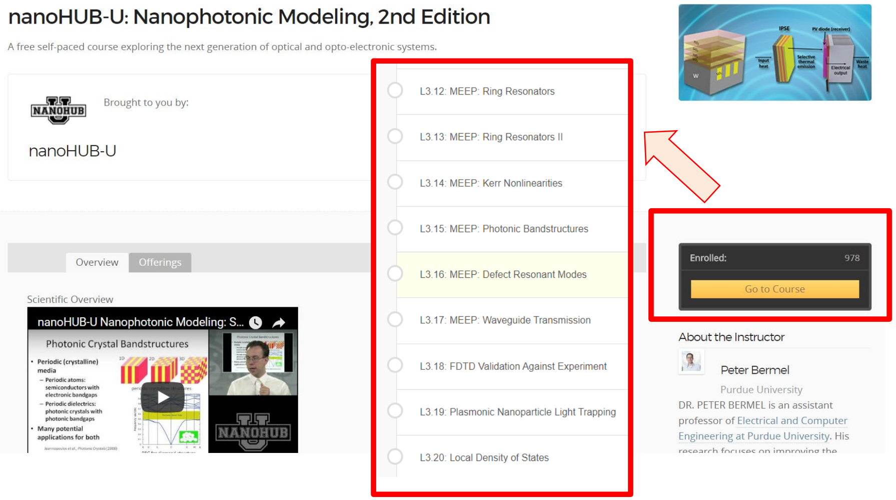
$$\varphi(x) = \sum_n a_n \left(\frac{x}{R}\right)^{2n}$$

The software tunes a_n to minimize figure of merit

Normalization constant

Available simulation packages

- ➢ Simulation packages (solving full Maxwell's Equations)
  CST : https://www.cst.com/
  COMSOL: https://www.comsol.com/
  Lumerical: https://www.lumerical.com/
- ➢ Our codes are developed based on Lumerical. However, the simulation principle is valid using other simulation packages.
- ➢ Other useful information:
  Nano-hub: https://nanohub.org/courses/NPM EM lab: On Youtube, search CEM lectures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Scientific Overview

- ○ L3.12: MEEP: Ring Resonators
- ○ L3.13: MEEP: Ring Resonators II
- ○ L3.14: MEEP: Kerr Nonlinearities
- ○ L3.15: MEEP: Photonic Bandstructures
- ○ L3.16: MEEP: Defect Resonant Modes
- ○ L3.17: MEEP: Waveguide Transmission
- ○ L3.18: FDTD Validation Against Experiment
- ○ L3.19: Plasmonic Nanoparticle Light Trapping
- ○ L3.20: Local Density of States

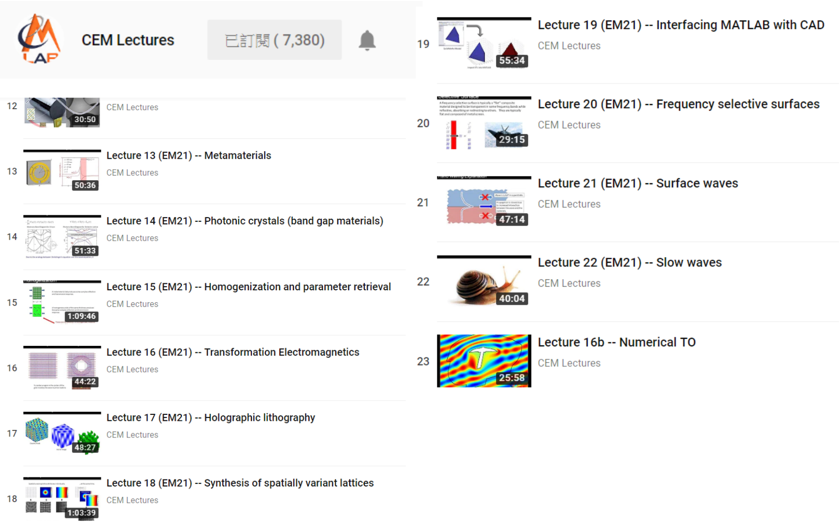
Enrolled: 978

About the Instructor

Peter Bermel

Purdue University

DR. PETER BERMEL is an assistant professor of Electrical and Computer Engineering at Purdue University. His research focuses on improving the


CEM Lectures 已訂閱 (7,380)

12 CEM Lectures 30:50

13 Lecture 13 (EM21) -- Metamaterials, CEM Lectures 50:36

14 Lecture 14 (EM21) -- Photonic crystals (band gap materials), CEM Lectures 51:33

15 Lecture 15 (EM21) -- Homogenization and parameter retrieval, CEM Lectures 1:09:46

16 Lecture 16 (EM21) -- Transformation Electromagnetics, CEM Lectures 44:22

17 Lecture 17 (EM21) -- Holographic lithography, CEM Lectures 48:27

18 Lecture 18 (EM21) -- Synthesis of spatially variant lattices, CEM Lectures 1:03:39

19 Lecture 19 (EM21) -- Interfacing MATLAB with CAD, CEM Lectures 55:34

20 Lecture 20 (EM21) -- Frequency selective surfaces, CEM Lectures 29:15

21 Lecture 21 (EM21) -- Surface waves, CEM Lectures 47:14

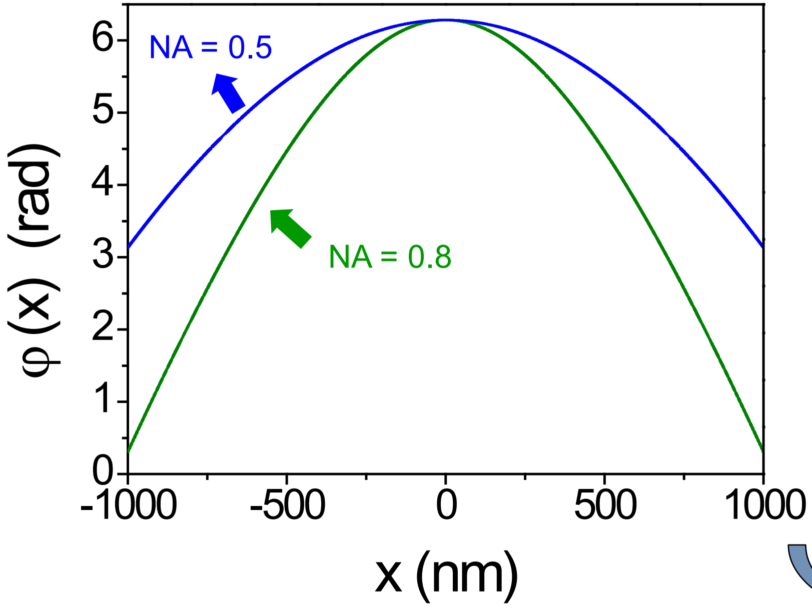
22 Lecture 22 (EM21) -- Slow waves, CEM Lectures 40:04

23 Lecture 16b -- Numerical TO, CEM Lectures 25:58

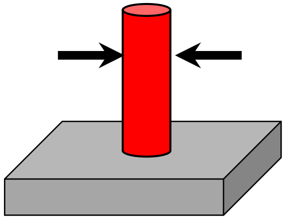
Choose element based on merit functions

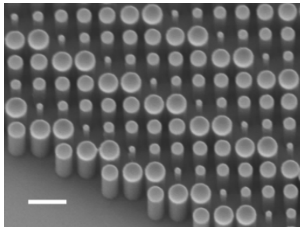
- Target phase

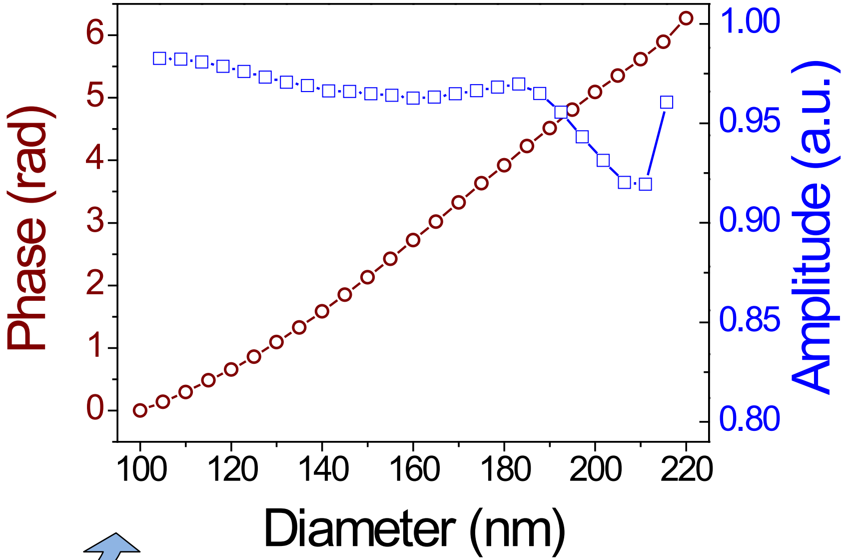
$$\varphi(x) = -\frac{2\pi}{\lambda_d}\left(\sqrt{(f^2 + x^2)} - f\right)$$



- Structure phase





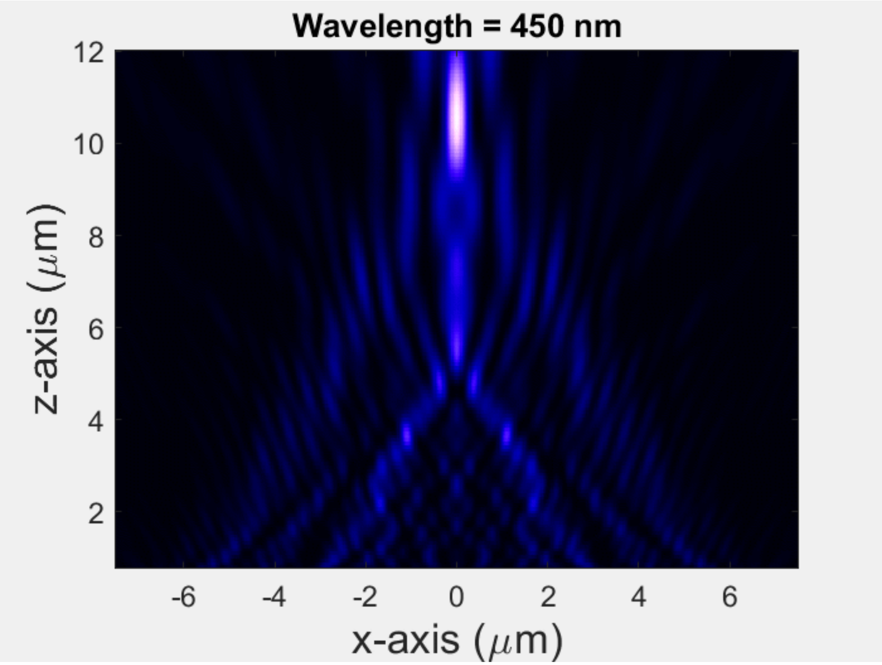


$$FOM = \min\left(\left|\varphi_{structures} - \varphi_{target}(x_0)\right|\right)$$

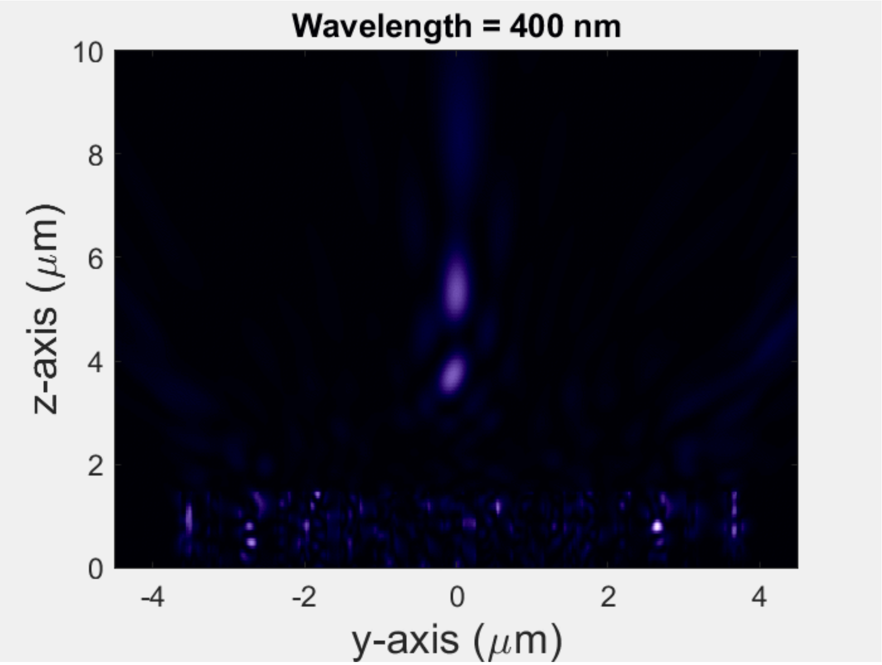
- Repeat this for all coordinates to choose proper structure

Chromatic response of metalenses

- Polarization-insensitive chromatic metalens



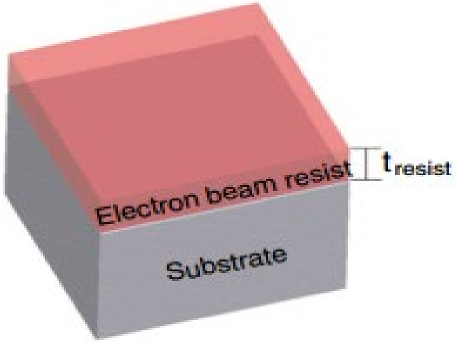
- Polarization-sensitive achromatic metalens



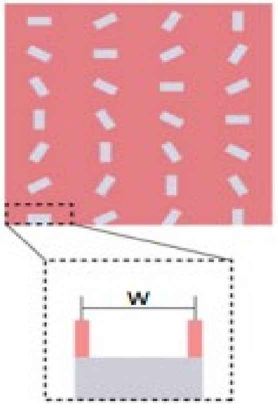
Metalens Fabrication Process: ALD & Ebeam Lith.

- **Current fabrication approach**

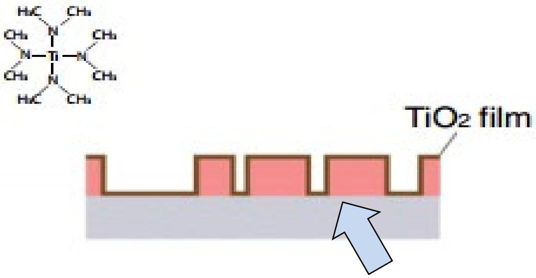
1. Substrate with resist



2. Pattern Exposure



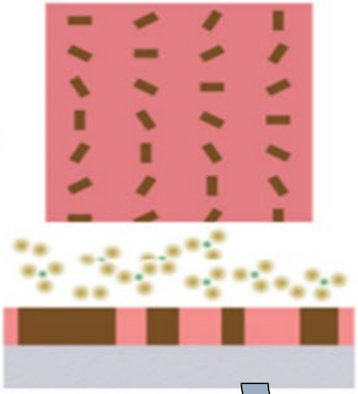
3. Initial ALD



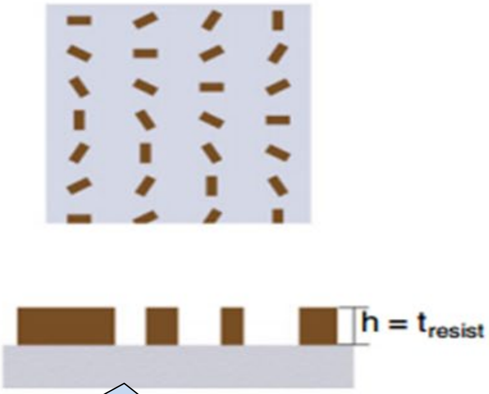
The thicker the resist, the taller the structure.

4. Completed ALD

5. Top layer etch



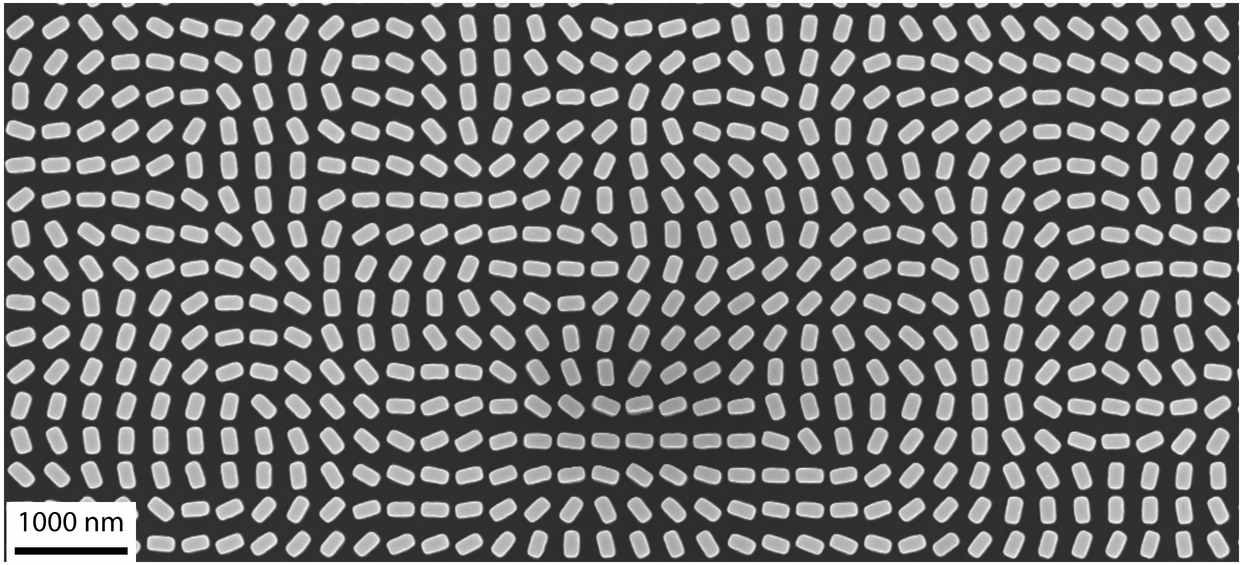
6. Final metasurface



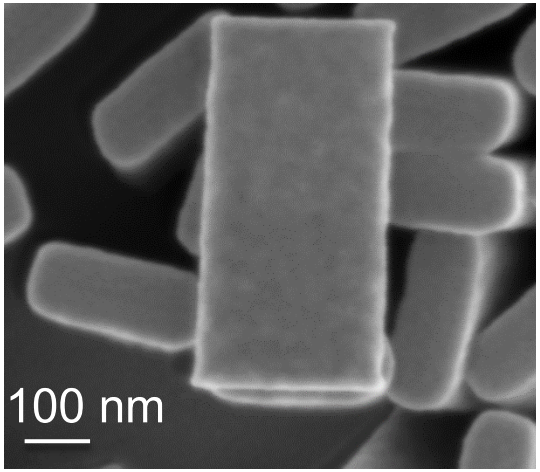
ALD process is compatible with deep UV lithography

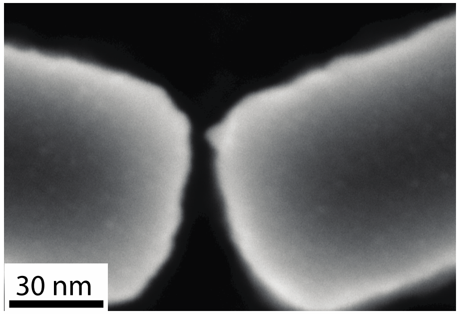
TiO2 Metasurfaces by Atomic Layer Deposition:

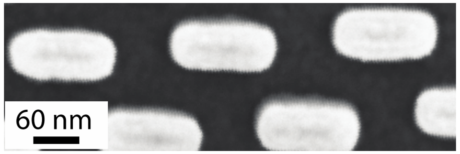
Completely transparent in the visible;
Negligible roughness, Vertical walls

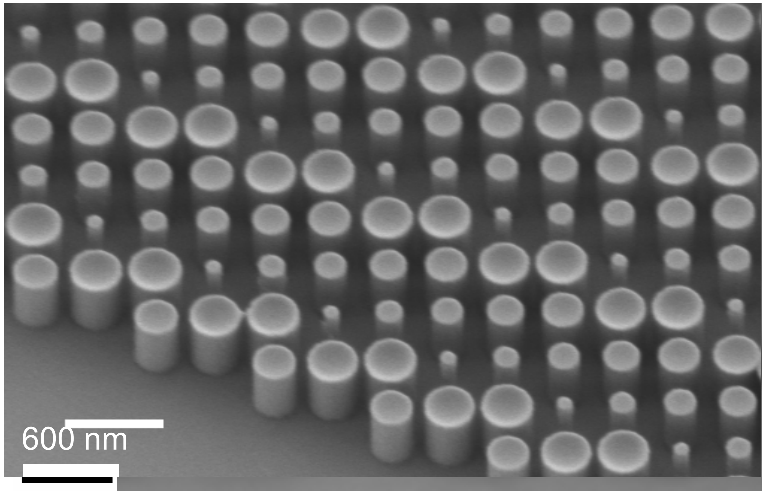


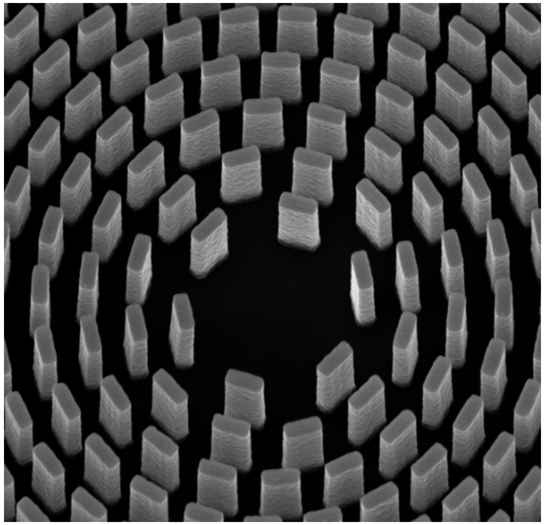
Side view







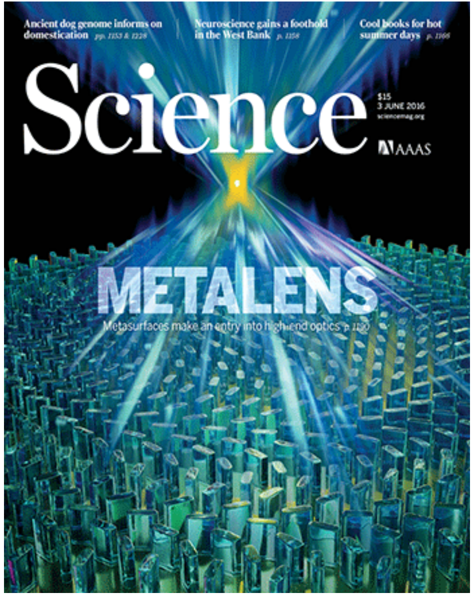


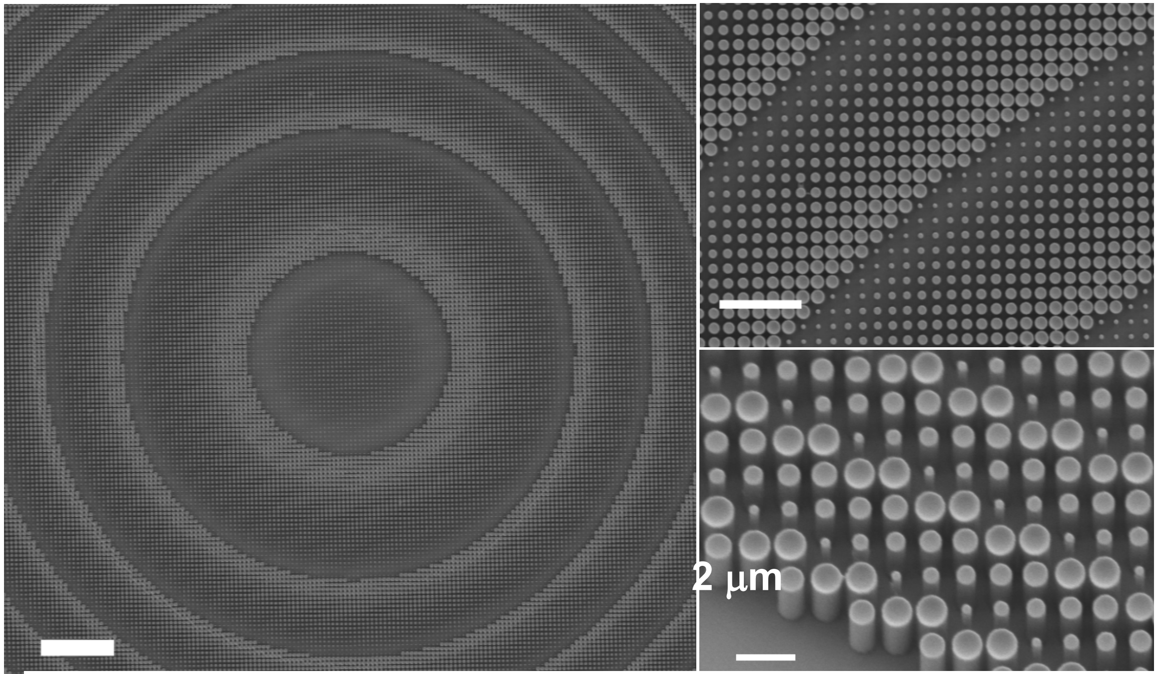


R.C. Devlin, *et al. Proc. Nat. Acad. Sci .***113**, 10473 (2016)
E. Shkondin, et al. *J. Vac. Sci. Technol* **34**, 031605 (2016).

Diffraction Limited High NA Metalenses

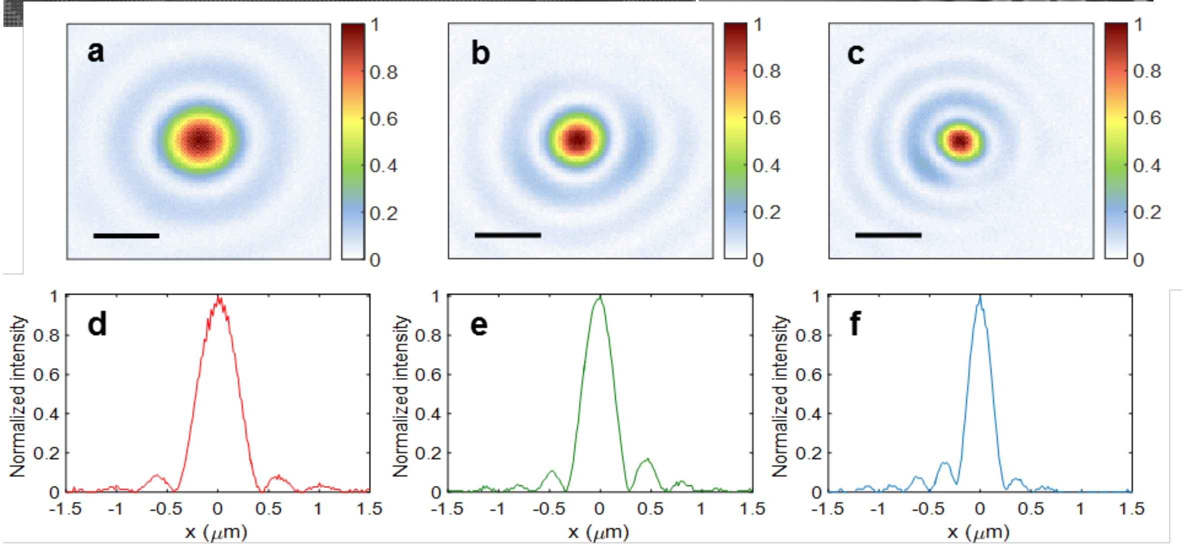
M. Khorasaninejad et al. *Nano Lett.*, **16**, 7229 (2016).



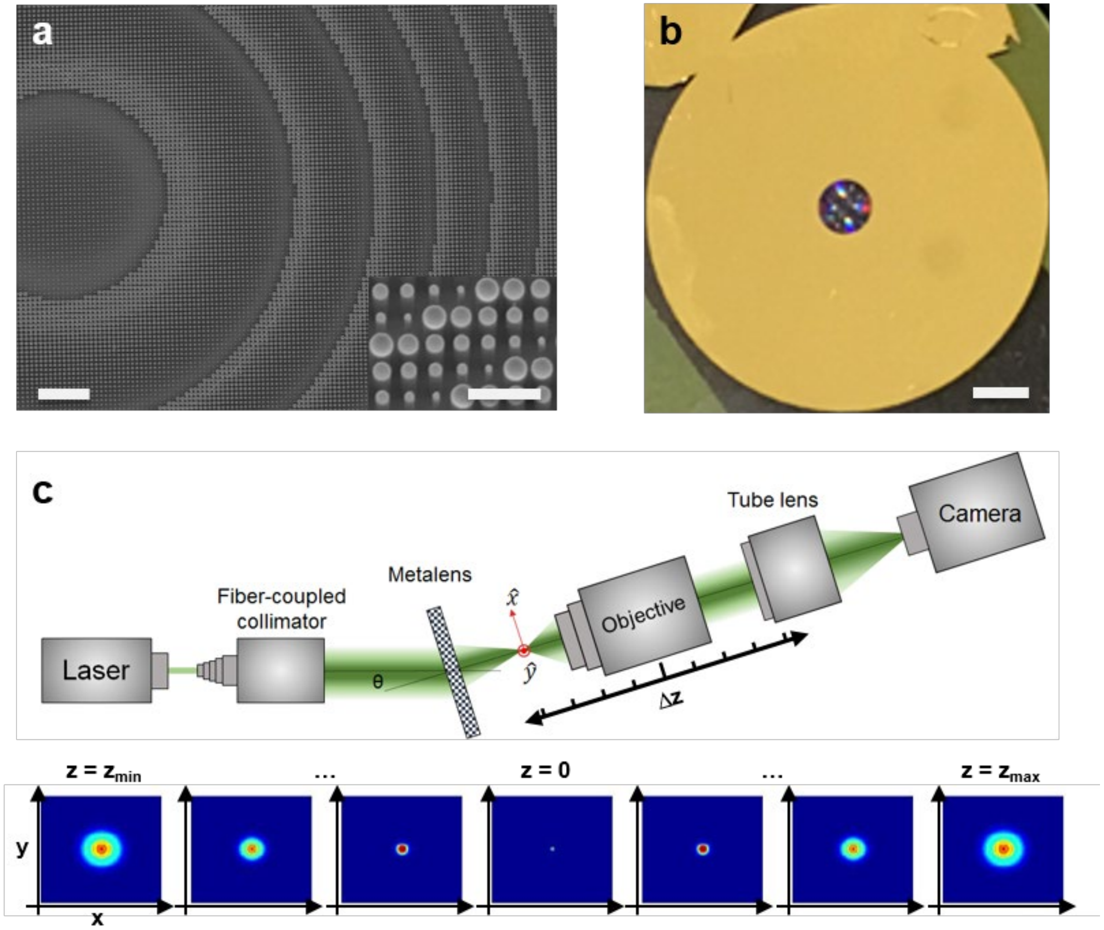


Ø = 2 mm; f= 800µm
NA= 0.8

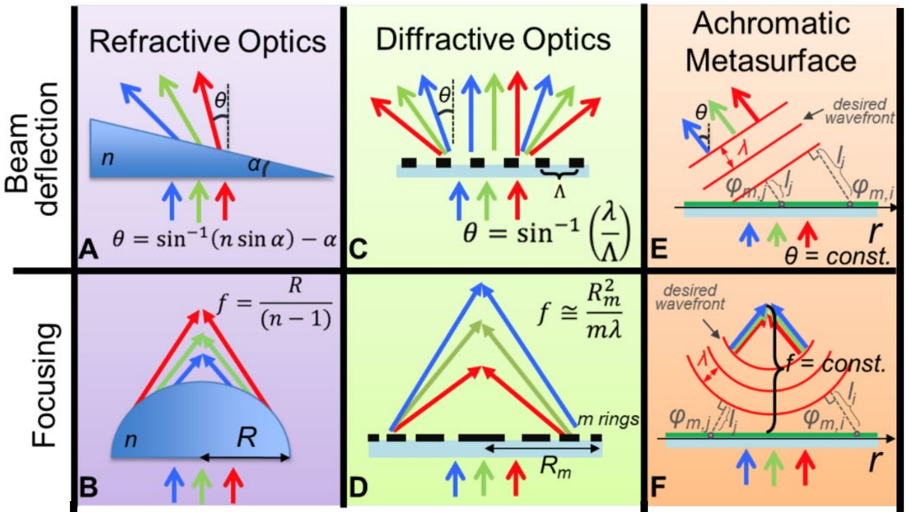
Focusing efficiency:
60% to 80 % depending
For NA in 0.8 to 0.6 range



Experimental Setup for Point Spread Function Measurement



Chromatic dispersion control with Metasurafces



Chromatic dispersion (CD) is predetermined by material property and grating effect

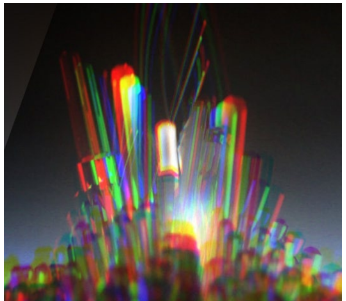
CD can be tuned by engineering the phase shifters

F. Aieta, et al. Science, (2015).

Controlling chromatic dispersion is critical in

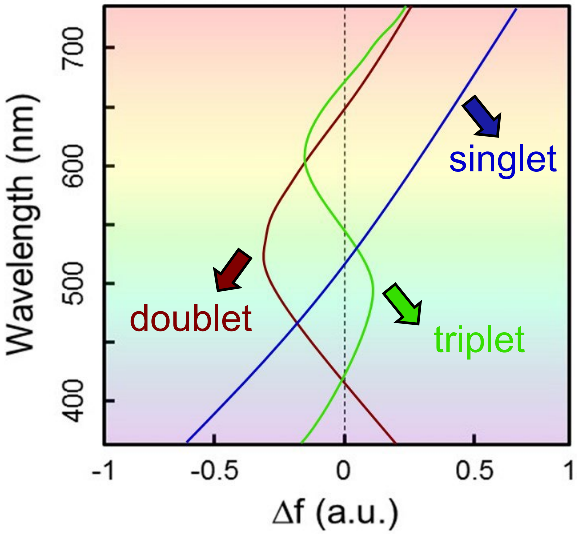
- Maintaining the same functionality over a bandwidth (important for imaging applications)
- Implementing different functionalities at different wavelengths (spectral multifunctionalities)

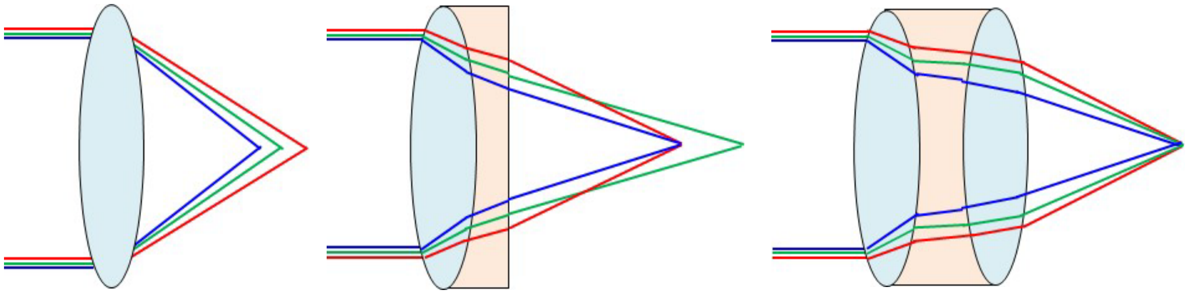
Effect of chromatic aberration



Complexity of Achromatic Lens Design

- Conventional approaches for reducing chromatic aberration



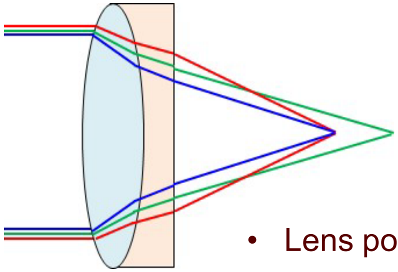


- Singlet
- Doublet
- Triplet

🟦 Crown glass 🟧 Flint glass

- 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 $V = \frac{n_{598nm} - 1}{n_{486nm} - n_{656nm}}$

- Limited choices of glass

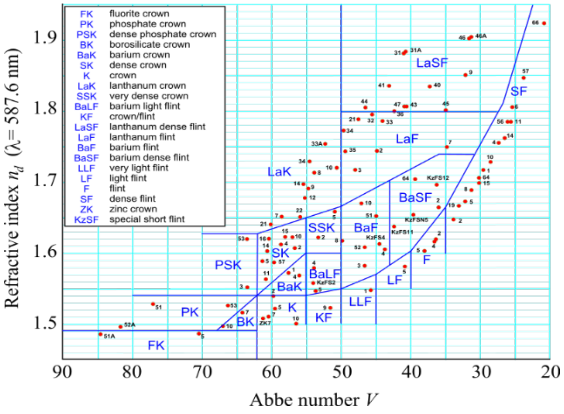
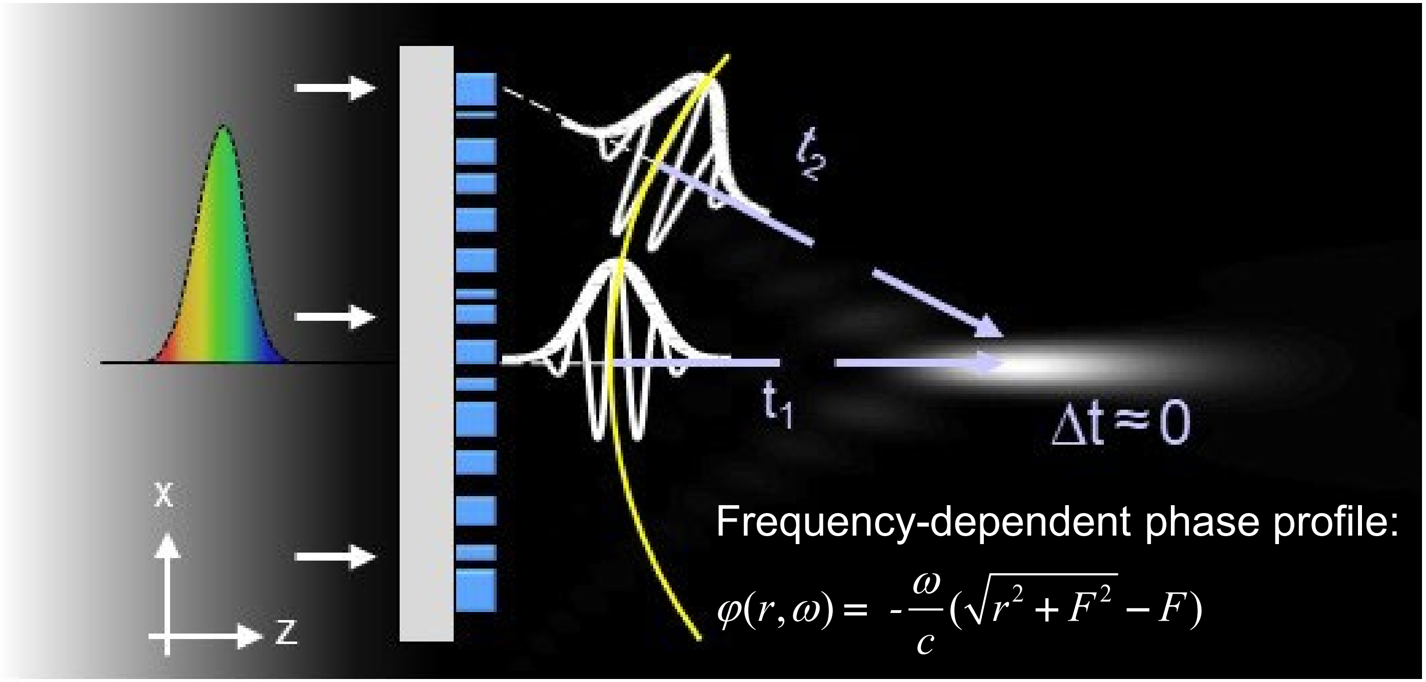


Image resource: Wikipedia

Achromatic metalens

- To realize achromatic focusing, one needs to manipulate wavepackets in both spatial and time domains.



Frequency-dependent phase profile:

$$\varphi(r,\omega) = -\frac{\omega}{c}\left(\sqrt{r^2+F^2}-F\right)$$

$$\varphi(r,\omega) = \varphi(r,\omega_d) + \left.\frac{\partial\varphi(r,\omega)}{\partial\omega}\right|_{\omega=\omega_d}(\omega-\omega_d) + \frac{1}{2}\left.\frac{\partial^2\varphi(r,\omega)}{\partial\omega^2}\right|_{\omega=\omega_d}(\omega-\omega_d)^2 + \ldots$$

gives lens function

Group delay (GD): time delay

Group delay dispersion (GDD): temporal width

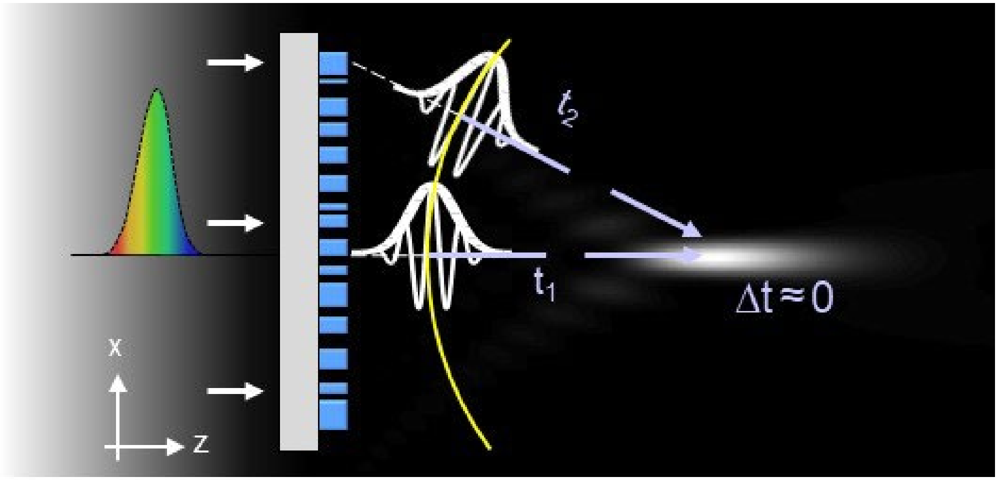
Ref: W. T. Chen ...and F. Capasso et. al. *Nature Nanotechnology*, **13**, 220–226 (2018)

Broadband Achromatic Metalenses

W-T Chen et al. *Nature Nanotechnology* Jan 1 (2018) doi:10.1038/s41565-017-0034-6

- **Frequency-dependent phase profile:** $\varphi(r,\omega) = -\frac{\omega}{c}\left(\sqrt{r^2+F^2}-F\right)$

gives lens function



$$\varphi(r,\omega) = \boxed{\varphi(r,\omega_d) +} \; \boxed{\left.\frac{\partial\varphi(r,\omega)}{\partial\omega}\right|_{\omega=\omega_d}(\omega-\omega_d) + \frac{1}{2}\left.\frac{\partial^2\varphi(r,\omega)}{\partial\omega^2}\right|_{\omega=\omega_d}(\omega-\omega_d)^2 + \ldots}$$

Time delay

Wave packet width

determines dispersion

- **Dispersion requirements for achromatic:**

$$Group\ delay: \frac{\partial\varphi(r,\omega)}{\partial\omega} = -\frac{\sqrt{r^2+F^2}-F}{c} \qquad Group\ delay\ dispersion: \frac{\partial^2\varphi(r,\omega)}{\partial\omega^2} = 0$$

$$F \rightarrow F(\omega) = k\omega^n \ \ (k\ is\ a\ constant)$$

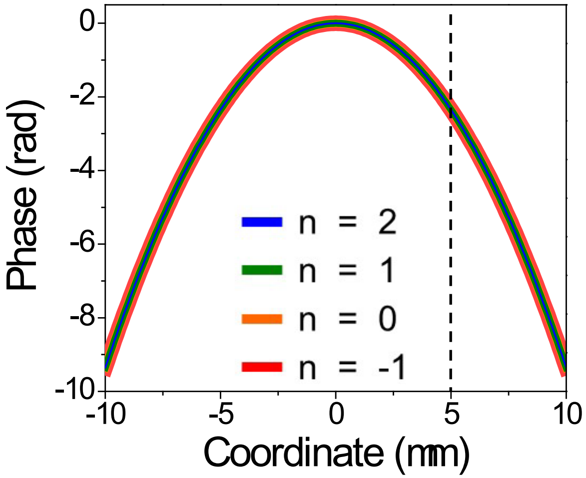
Achromatic n = 0, Conventional diffractive n =1, Anomalous diffractive n =2, Refractive n = -1

Requirement for GD and GDD

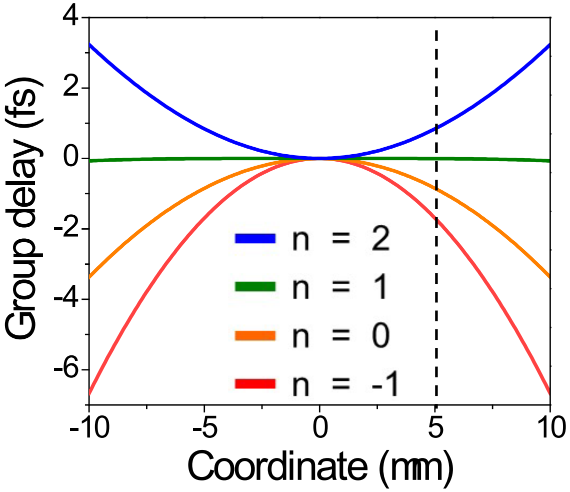
$$\varphi(r,\omega) = -\frac{\omega}{c}\left(\sqrt{r^2+F^2}-F\right),\quad F \to F(\omega) = k\omega^n \ (k \text{ is a constant})$$

Achromatic n = 0, Conventional diffractive n =1, Anomalous diffractive n =2, Refractive n = -1

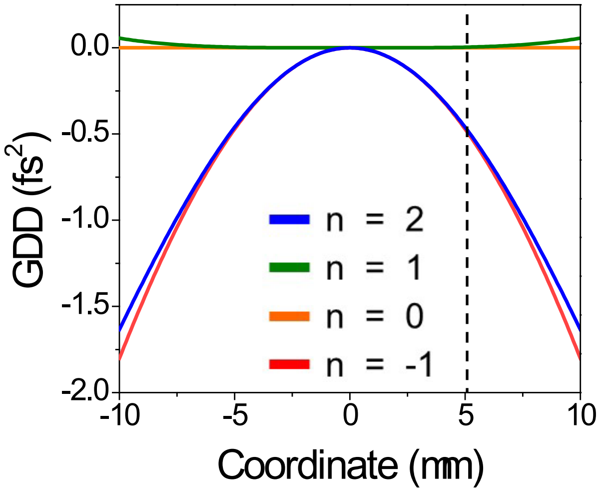
- Required phase at 530 nm



- Group delay (GD)

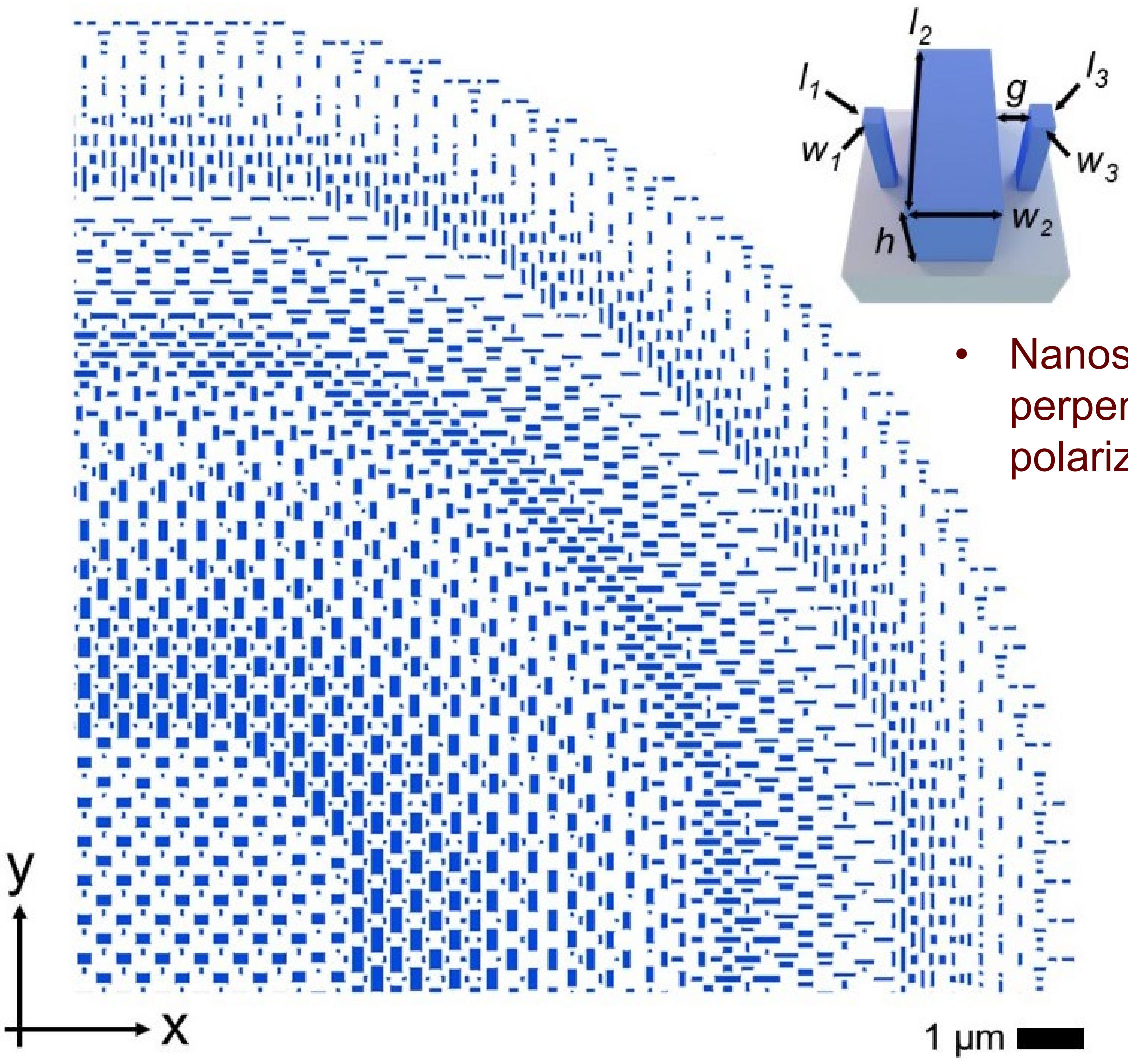


- Group delay dispersion (GDD)

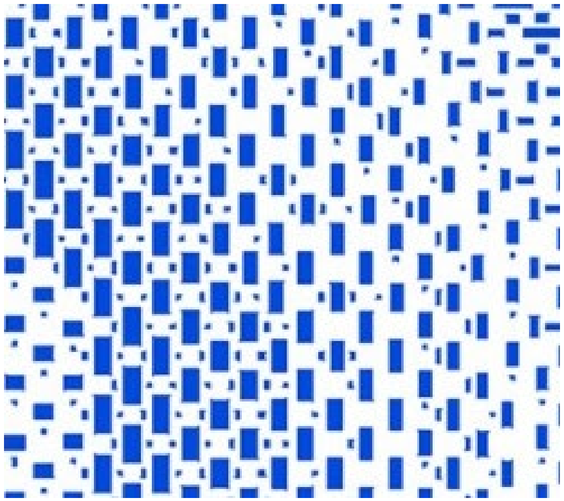


- NA = 0.2, F = 64 μm at 530 nm

Polarization-insensitive lens consisting of anisotropic nanostructures



- Nanostructures are either parallel or perpendicular to their neighbor to ensure polarization insensitivity.

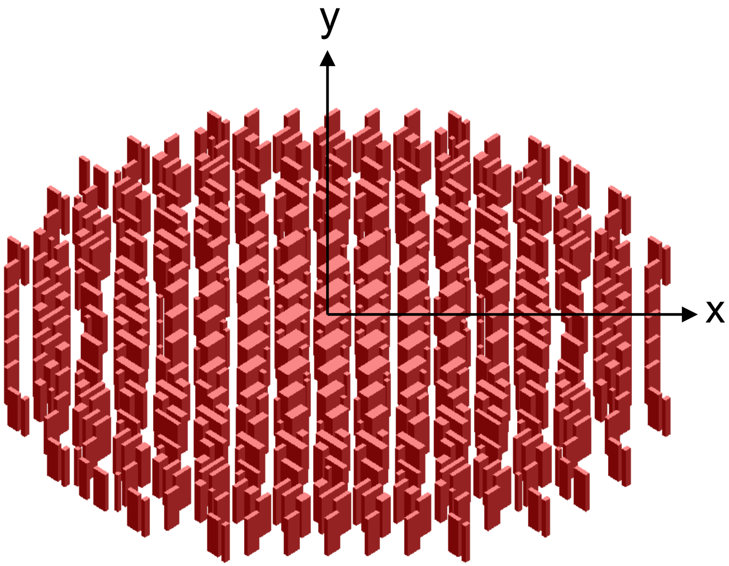


REF: W-T Chen et al Nature Communications In press

Full lens simulation

- NA = 0.55, Dia = 6.5 μm

- Layout: Achromatic and polarization-insensitive metalens

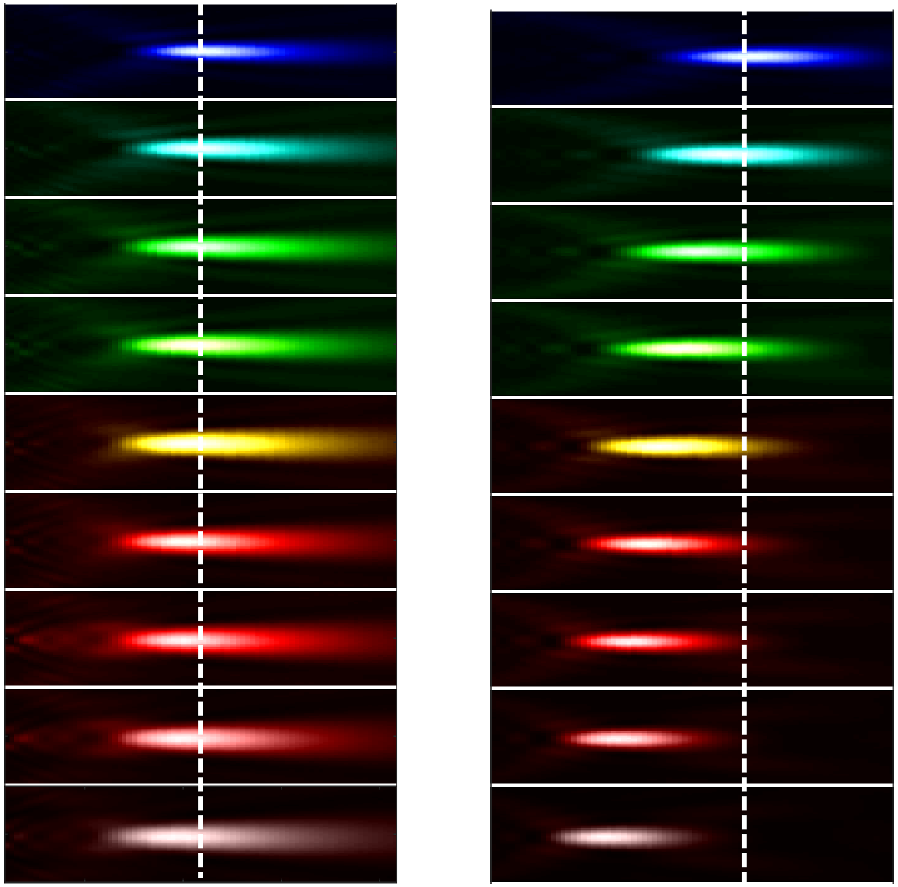


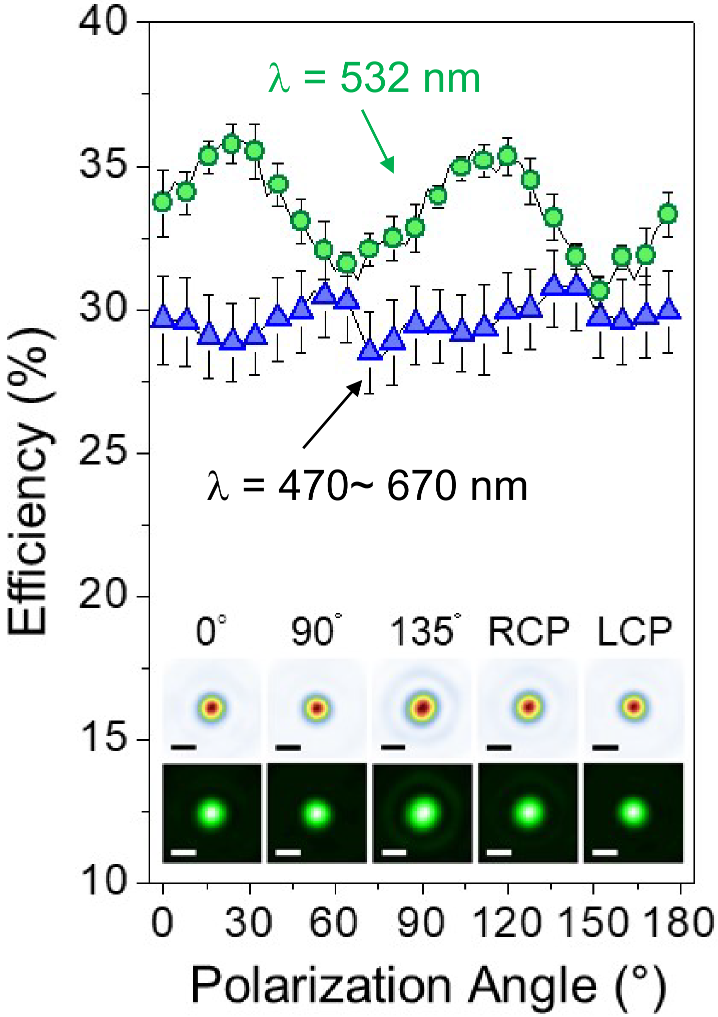
- FDTD simulation

Chromatiic
(Without dispersion
Engineering)

Polarization-insensitive and Achromatic Metalens

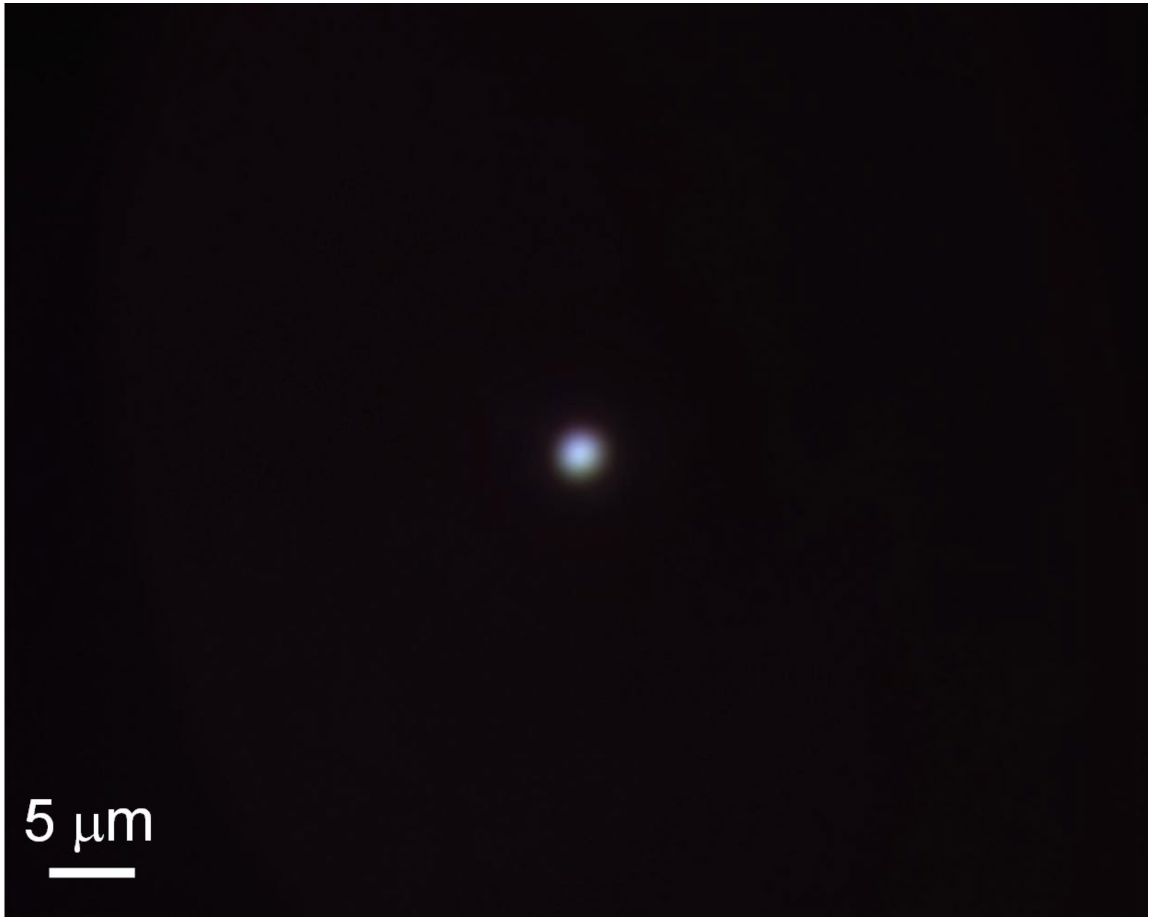
- Metalens (NA = 0.2, Diameter = 26 μm)





- Capable of focusing any incident polarization
- Doubled efficiency compared to our previous results published in Nature Nano.

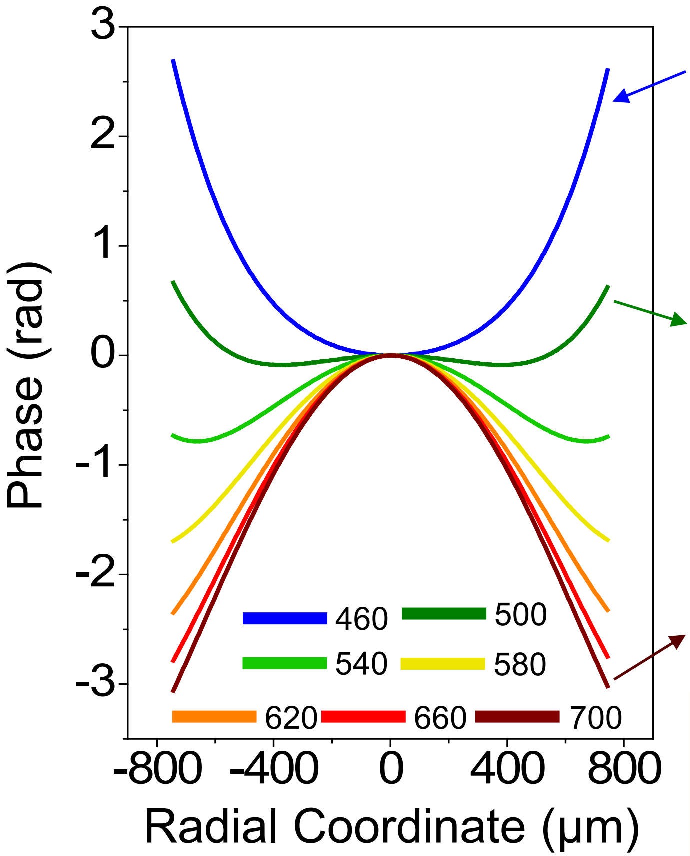
White light focusing



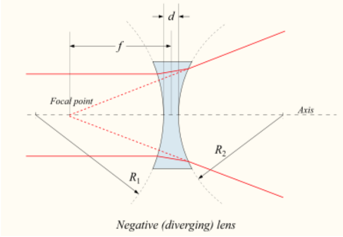
Dispersion Engineered Metasurfaces for Hybrid Design

➢ Phase profile of metacorrector

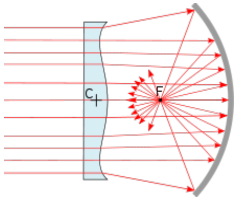
$$\varphi(r,\omega)=\varphi(r,\omega_d)+\frac{\partial\varphi}{\partial\omega}(\omega-\omega_d)+\frac{\partial^2\varphi}{2\partial\omega^2}(\omega-\omega_d)^2$$



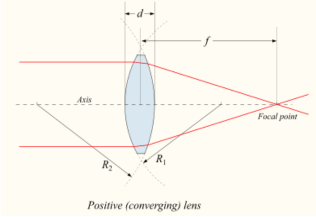
Concave lens
Increase focal length

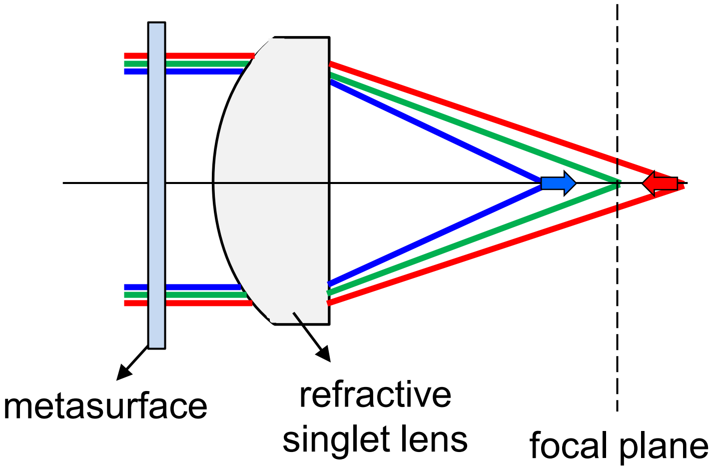


Schmidt plates
reduce spherical aberration



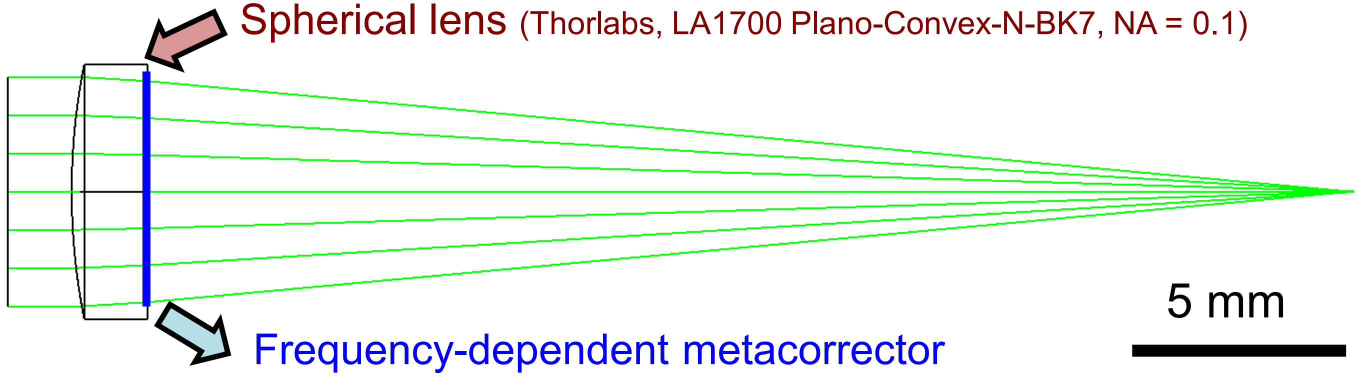
Convex lens
decrease focal length





Hybrid Metalens Design

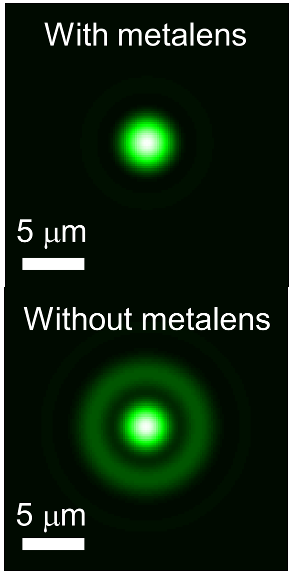
- Ray-tracing simulation



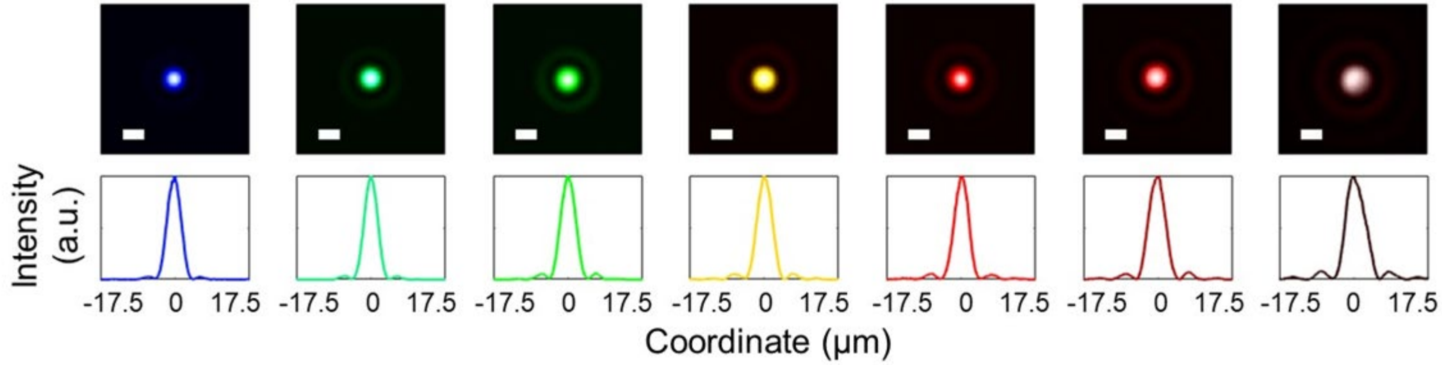
Spherical lens (Thorlabs, LA1700 Plano-Convex-N-BK7, NA = 0.1)

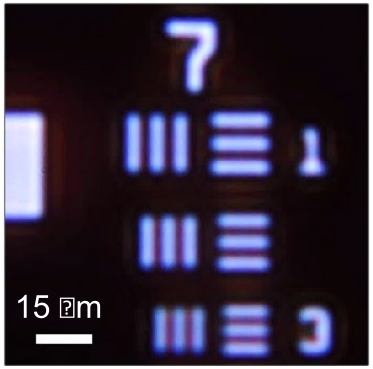
Frequency-dependent metacorrector

5 mm



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





Inverse design of large-area multi-wavelength (RGB) metalenses

☐ Design flow:

1. Determine objective function

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

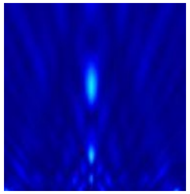
Target position

Design parameters

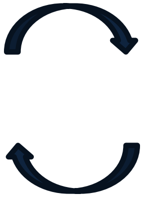
2. Initial random design

Fast approximate solver

3. Objective function evaluation

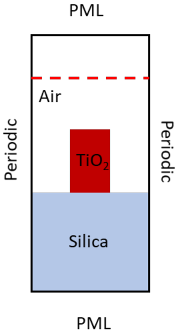


Adjoint method

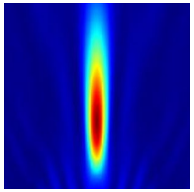


Fast approximate solver

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

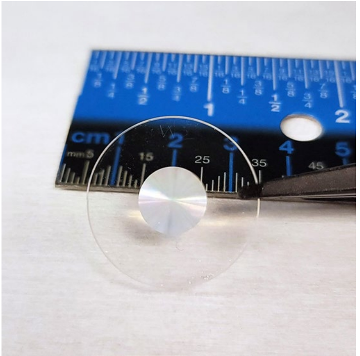


5. Final design: validation/ fabrication

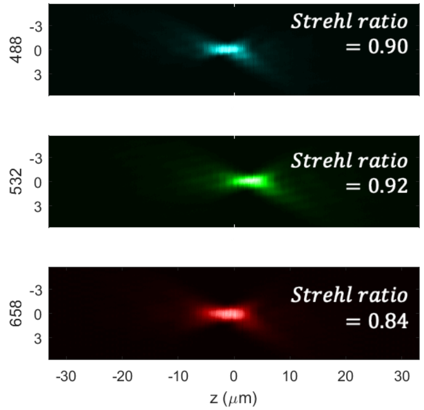


- Diameter: 1 cm
- NA: 0.3
- TiO$_2$ on fused silica
- Polarization insensitive

- Device image



- Measurements: Focal shift

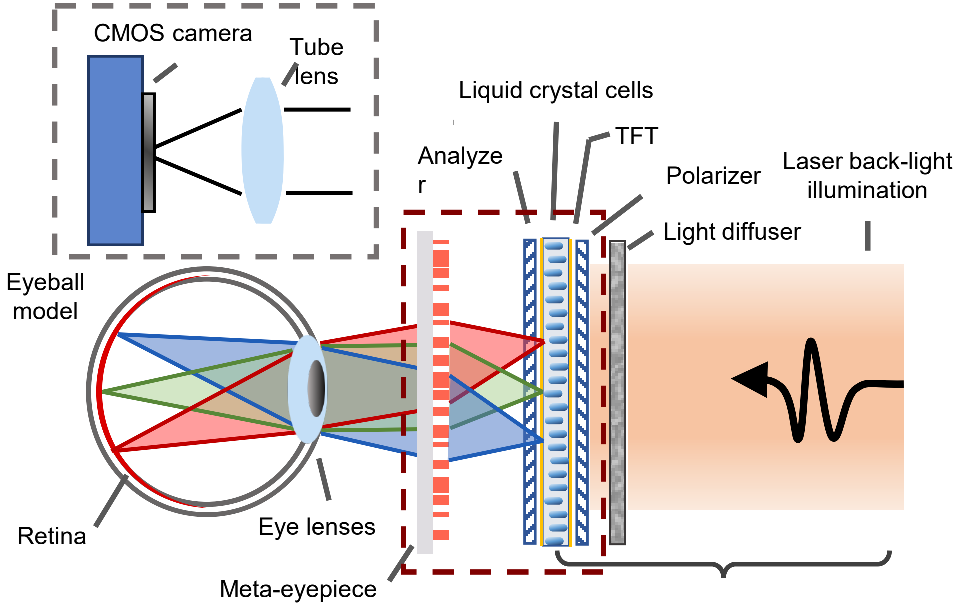


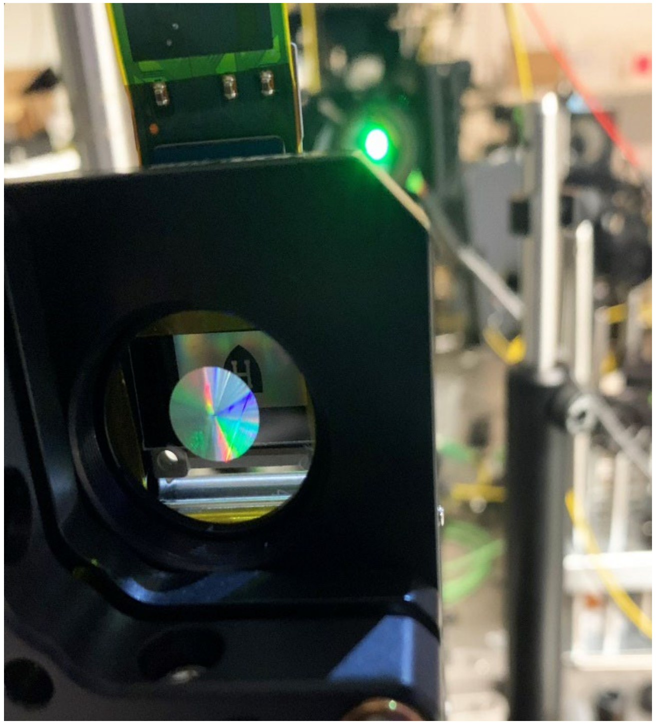
- RGB-achromatic
- Maximum focal shift: 4.5 μm (0.03% of design focal length)
- Diffraction-limited focusing

*Collaboration with Raphael Pestourie, Steven Johnson, MIT

Virtual Reality platform

Meta-eyepiece X laser-illuminated micro-LCD





Eyepiece:

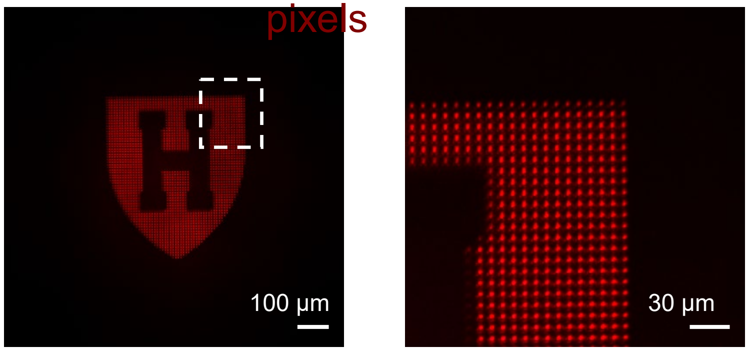
- Compact and lightweight
- High-resolution
- RGB-achromatic

Near-eye display:

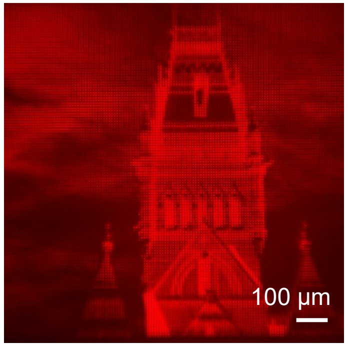
- Pixel size: 8 μm
- High brightness
- Wide Color gamut

VR demos

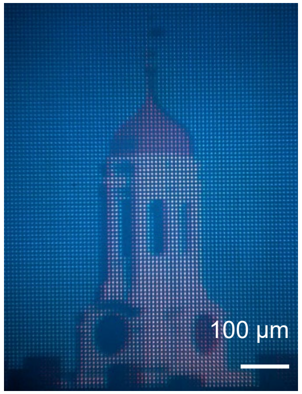
Binary VR images resolving pixels



Greyscale VR image



Color-mixing results

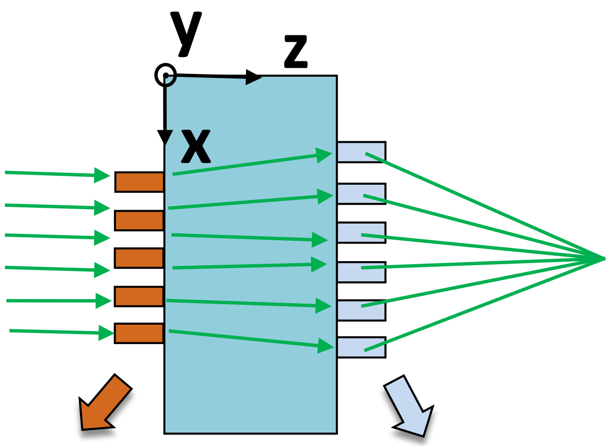


VR movie: a running cat

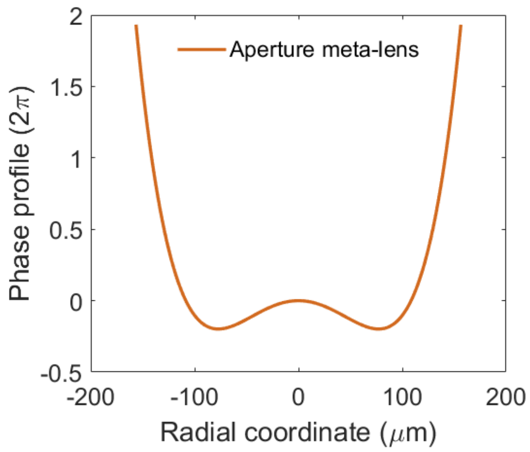
- Frame refresh rate: 60Hz

Metalens Doublet to correct monochromatic aberrations (spherical, coma, astigmatism and field curvature)

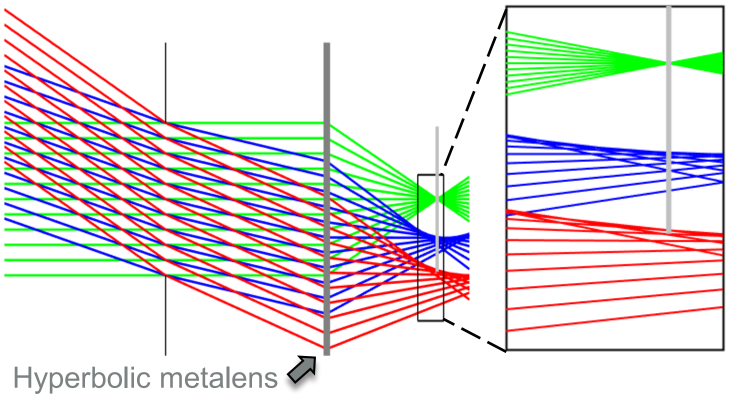
- Doublet metalens: NA = 0.45, FOV = 50˚



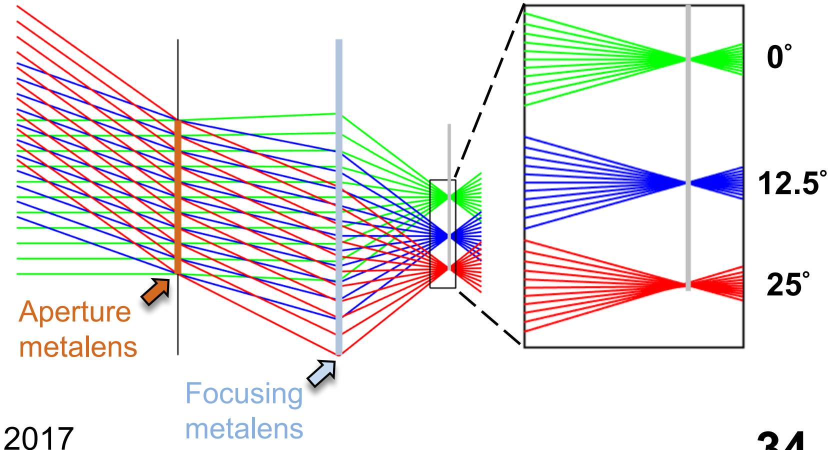
Aperture metalens



- Ray-tracing diagrams:
  - Singlet metalens



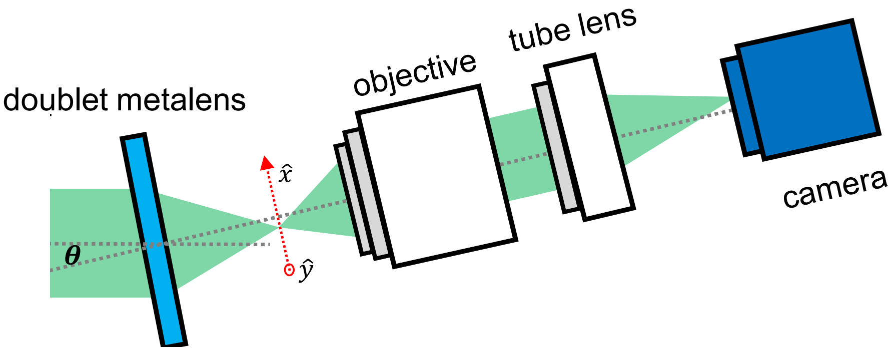
  - Doublet metalens

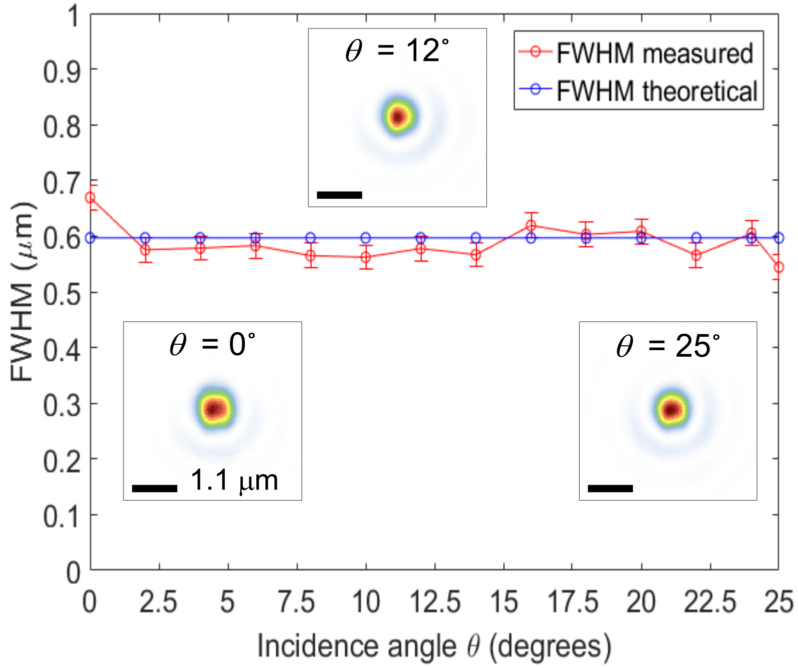


B. Grover et al. Nano Lett., **DOI:** 10.1021/acs.nanolett.7b01888 June 29, 2017

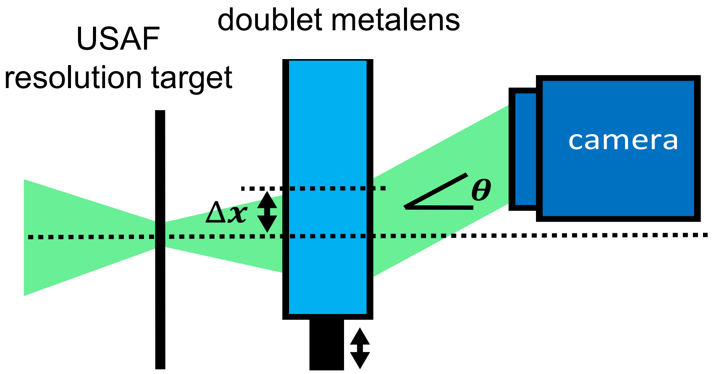
Focal spot and imaging

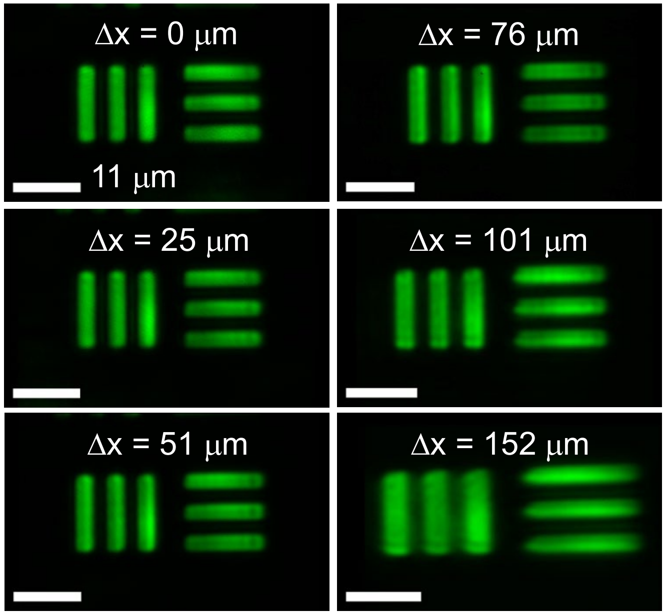
- Lens test set-up:





- Imaging set-up:



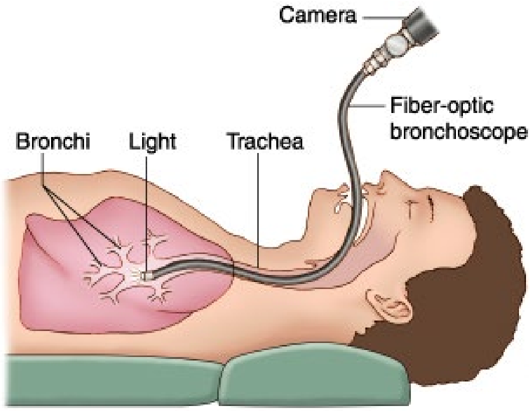


Scale bar: 11 μm

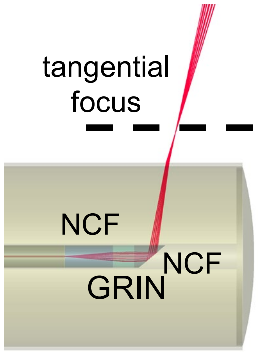
Metalens for High Resolution Bronchoscopes

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

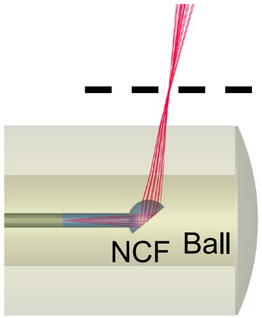
- Collaboration with Mass General Hospital, Prof. Melissa Suter



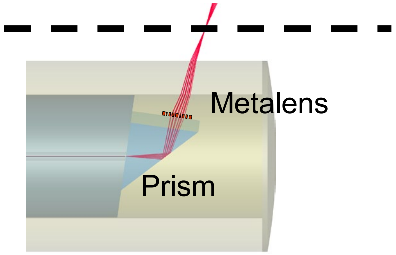
GRIN lens catheter

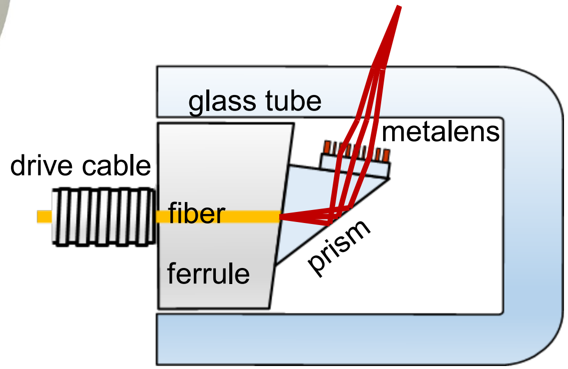


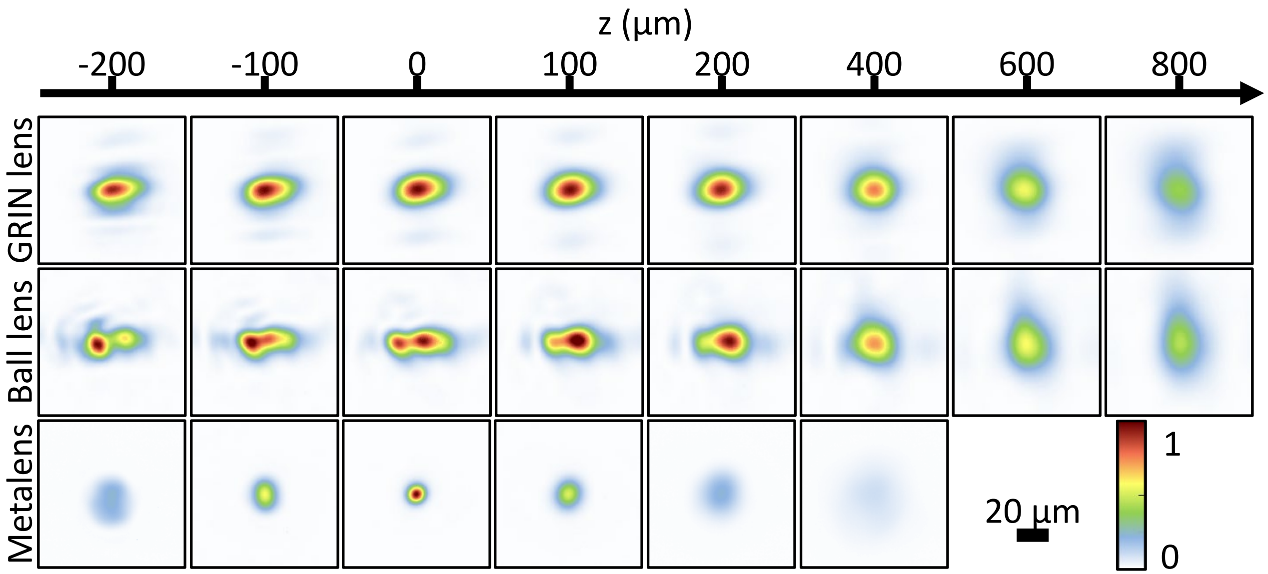
Ball lens catheter

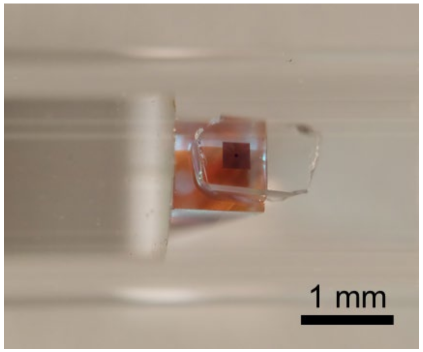


Metalens catheter









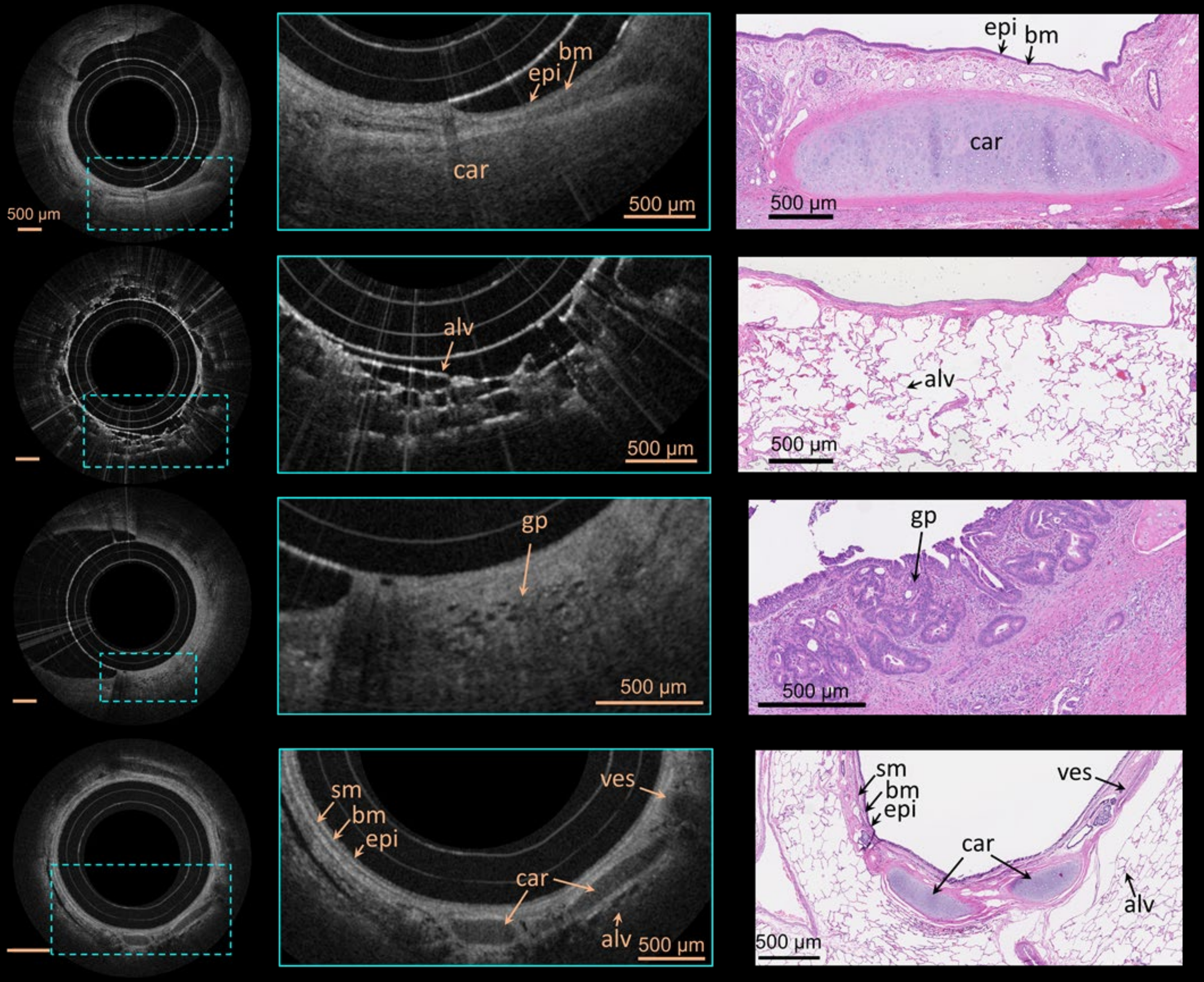
Endoscopic imaging using metalens catheter

OCT images

Histological images

Ex vivo human lungs

in vivo sheep lung

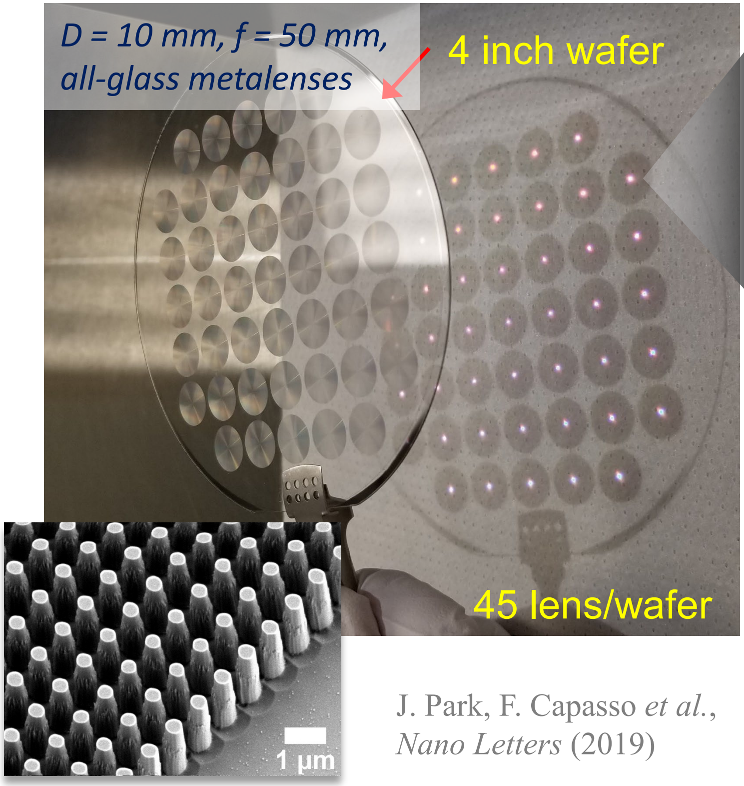


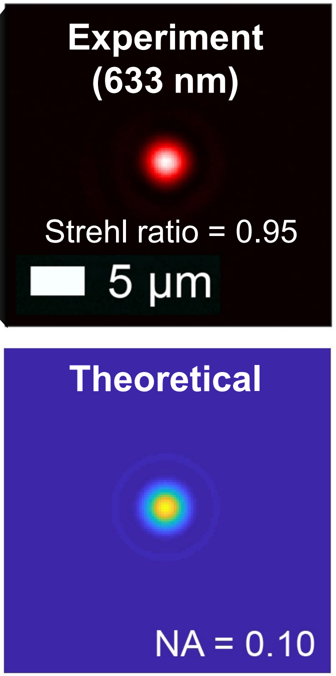
epi: epithelium; bm: basement membrane; car: cartilage
ves: blood vessels; alv: alveolar; gp: glandular patterns

Fabrication of metalenses with semiconductor technology

❑ Fabrication with deep-UV (DUV) projection lithography

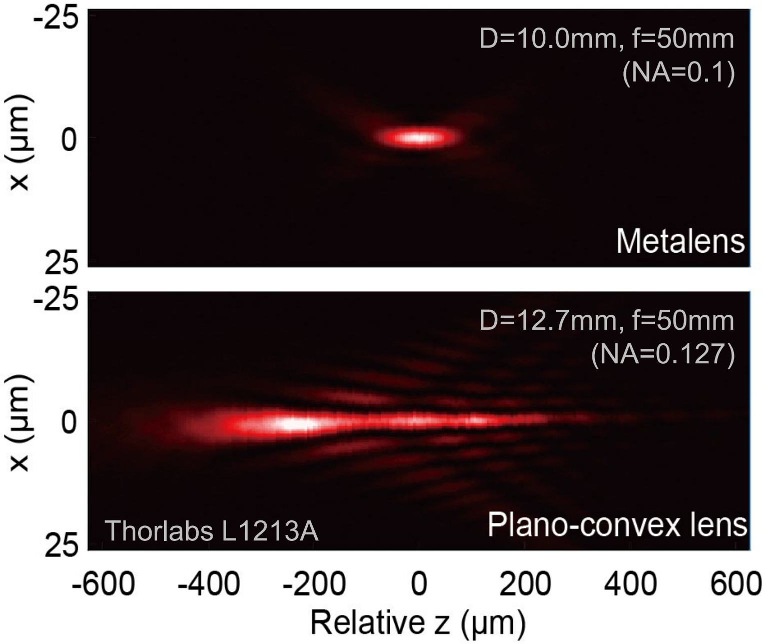
(Fused silica nanostructures etched into a fused silica wafer)





J. Park, F. Capasso *et al.*, *Nano Letters* (2019)

Focusing profile along optic axis



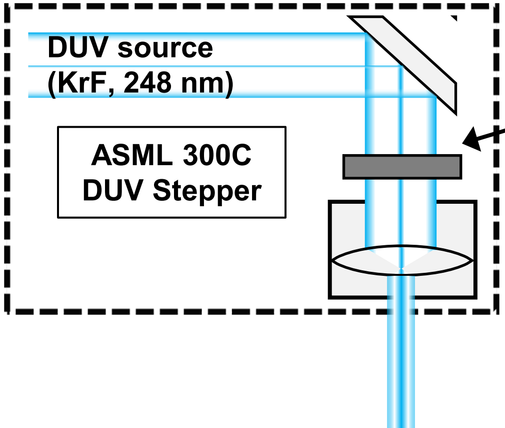
Metalens exhibits low spherical aberration

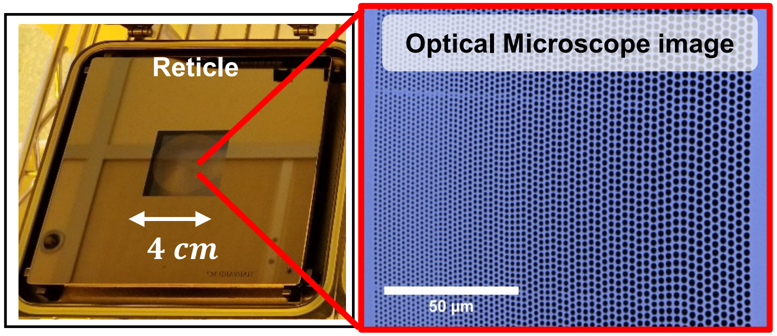
.

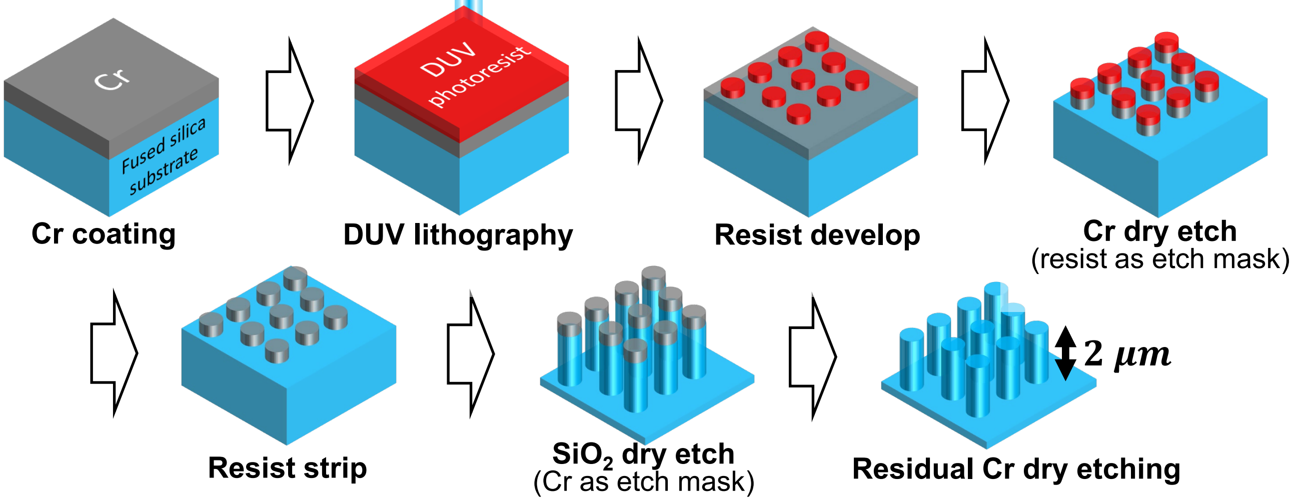
Fabrication process

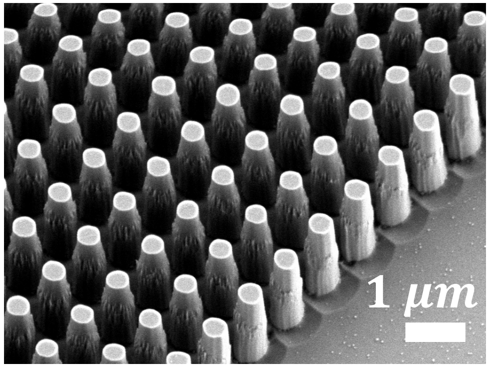
- **Fabrication process** (on 4-inch SiO_2 wafer)

Projection lithography (same technique used in chip manufacturing)

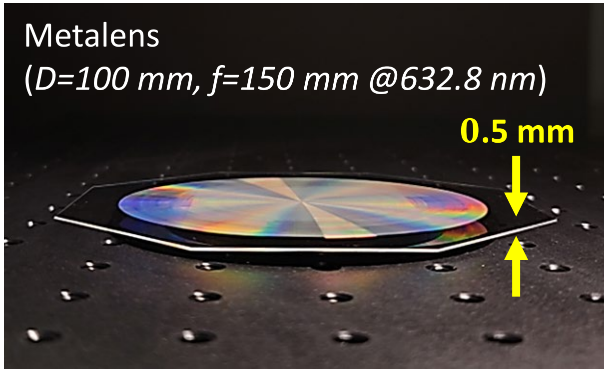


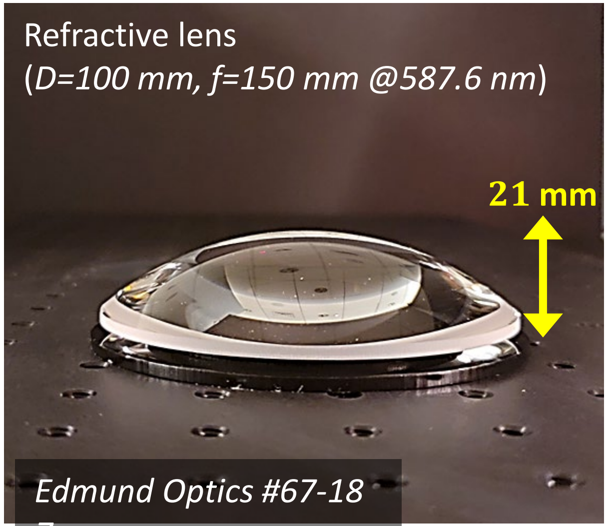




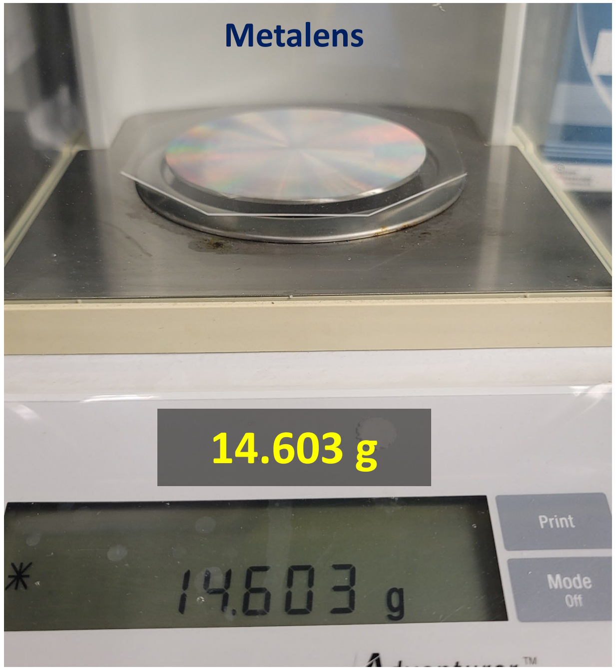


Large diameter (10cm) metalens: Comparison with Similar Optical Power Refractive Lens


Metalens
(*D=100 mm, f=150 mm @632.8 nm*)


Refractive lens
(*D=100 mm, f=150 mm @587.6 nm*)

Edmund Optics #67-18 7


Metalens


Refractive Lens

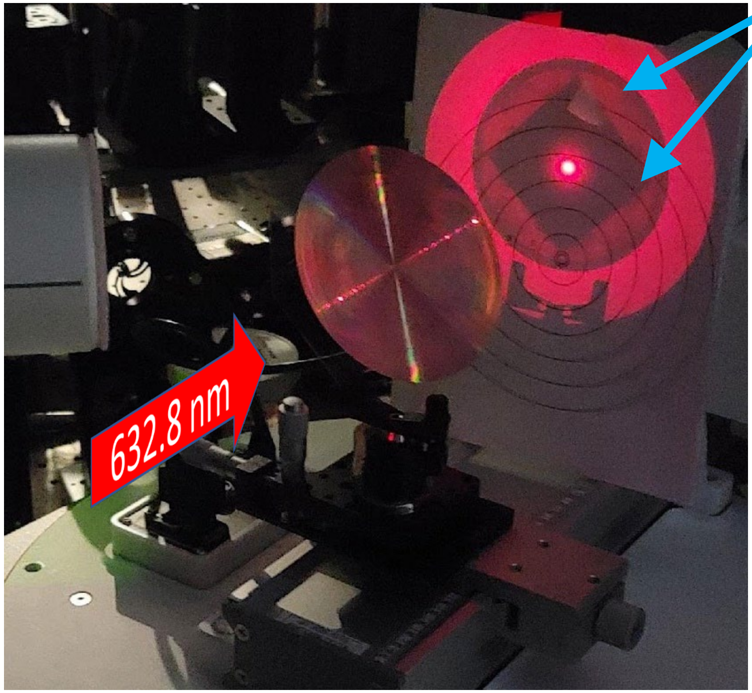
- **42x reduction in thickness, 16.5x reduction in weight**
- **Entire lens is monolithic fused silica.**
  - Low thermal expansion coefficient, high laser damage threshold.
- **Substrate's backside** can be used for anti-reflective coating, color filter stack, polarization filter, etc.

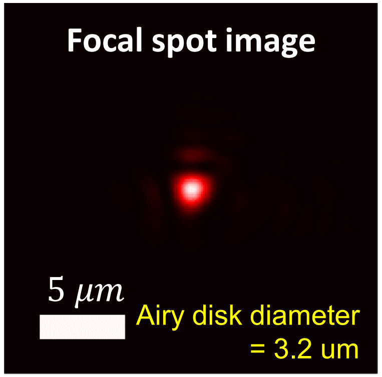
https://pubs.acs.org/doi/abs/10.1021/acsnano.3c09462

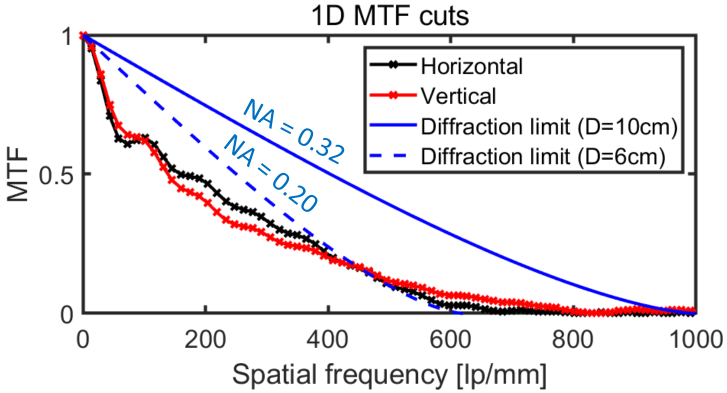
Optical Characterization of 100 mm Diameter Metalens

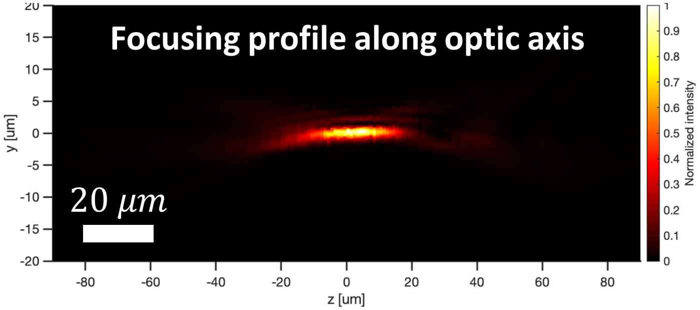
❑ Focusing Quality Measurement

- Apparent reticle quality difference between inner/outer fields.
- Low-quality reticle did not resolve small-diameter nanopillars.
- Results in low diffraction efficiency at outer region.





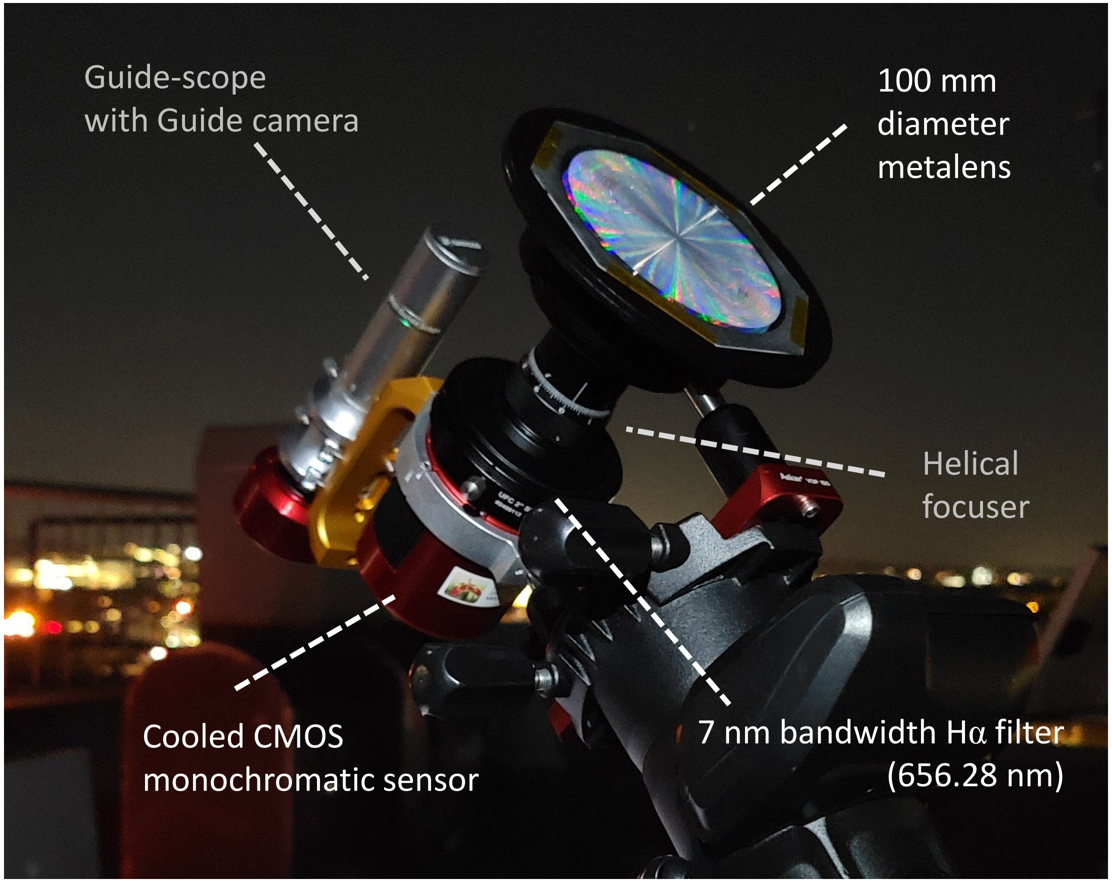




- Total metalens focusing efficiency: 40.4%
- Central area focusing efficiency: 63.1 %

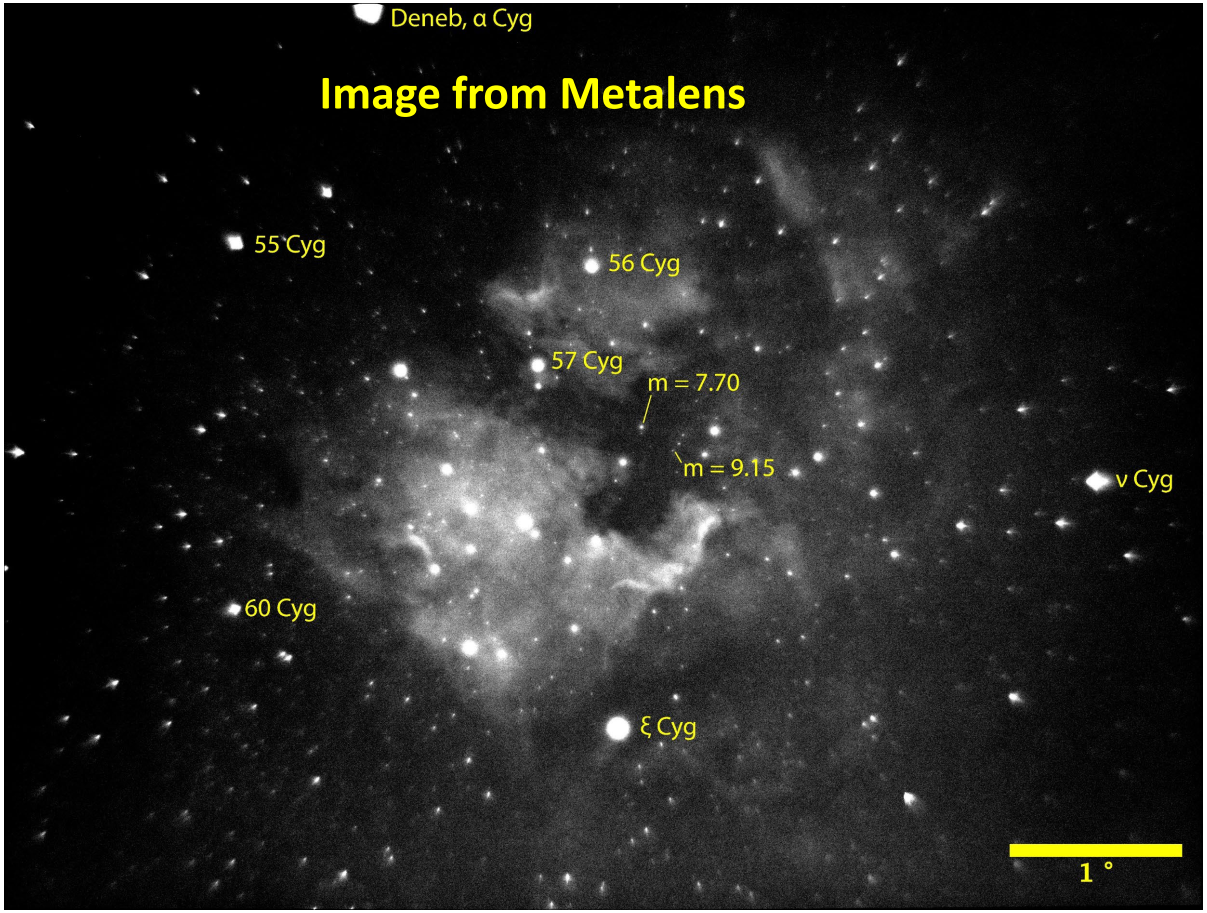
This 100 mm diameter metalens has 19 Billion glass nanopillars

Meta-imaging the Heavens



Astrophotography with 100 mm Metalens

- **North America Nebula (NGC7000),** Cambridge, MA



Metalenz Inc.: spin-off (2016) from the Capasso group

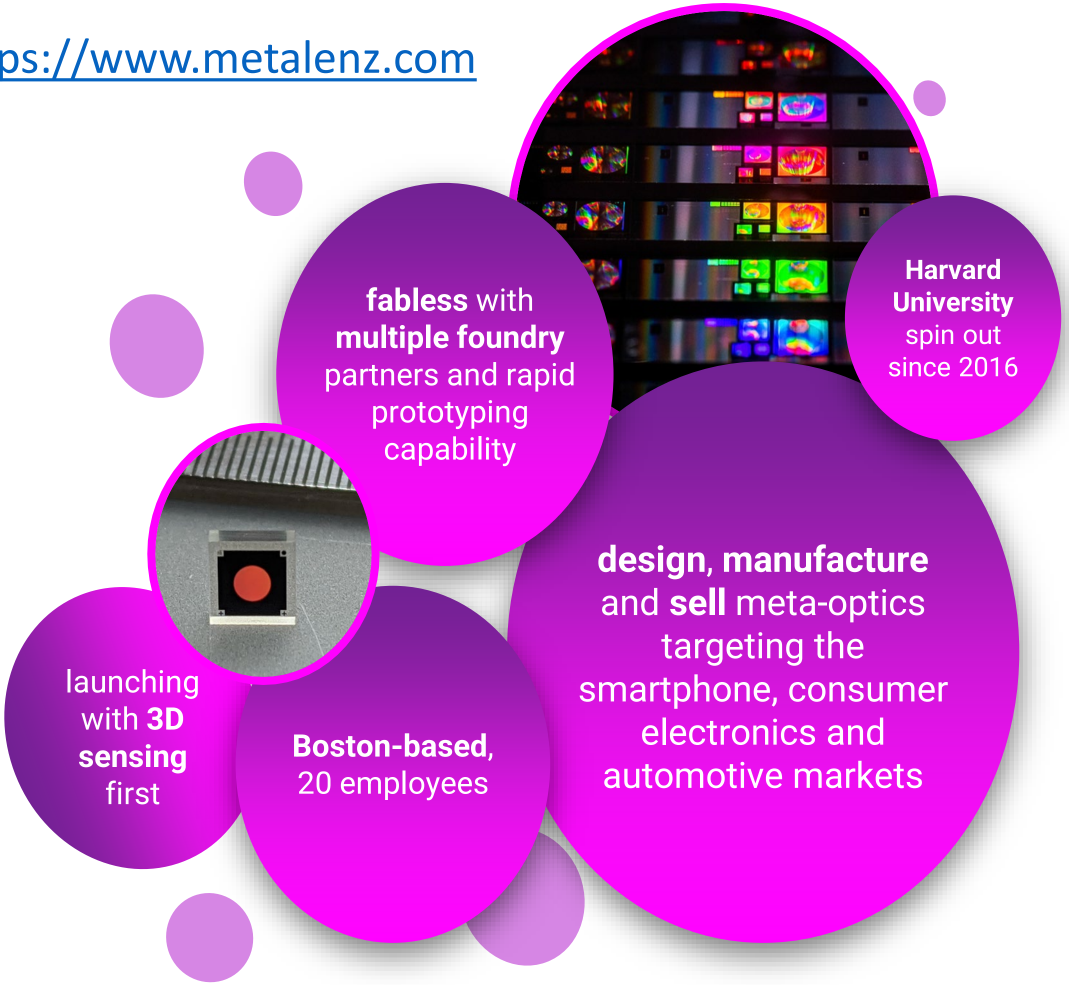
https://www.metalenz.com

CEO Robert Devlin

3M

APPLIED MATERIALS®

BRAEMAR ENERGY VENTURES



fabless with **multiple foundry** partners and rapid prototyping capability

Harvard University spin out since 2016

design, **manufacture** and **sell** meta-optics targeting the smartphone, consumer electronics and automotive markets

launching with **3D sensing** first

Boston-based, 20 employees

intel®

M. VENTURES

TDK

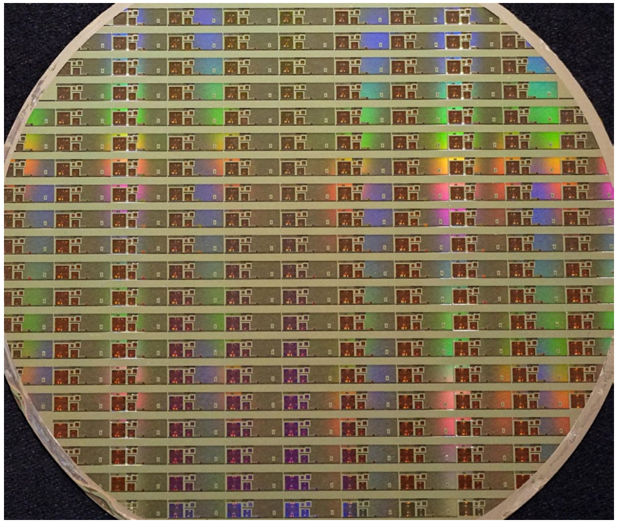
TSINGYUAN VENTURES

Enabling the future of metaoptics in the semiconductor foundry

metalenz

optic design file

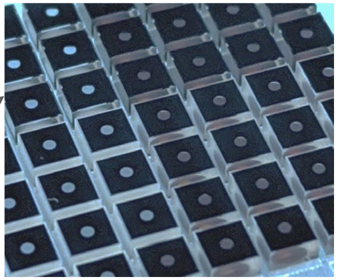
metalenz



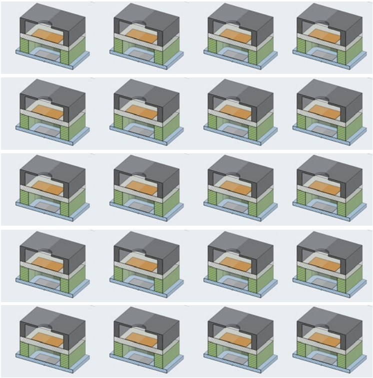
12 inch wafer
~10,000 meta-optics

Singulation

1000s of lens chips



Back-end integration

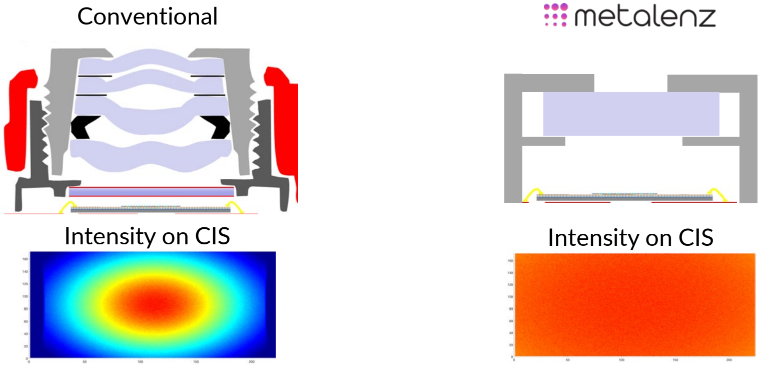


Applications: Depth sensing

- Front facing dot pattern projector for face recognition in cell phones
- World-facing dot pattern projector for motion detection
- LIDAR

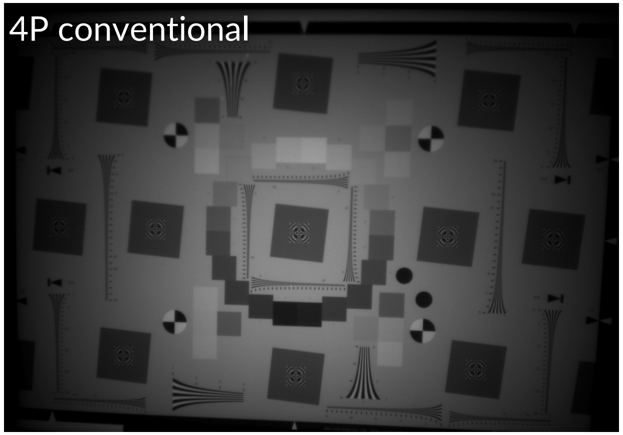
metalenz https://www.metalenz.com/
CEO: Robert Devlin, Ph.D. Harvard

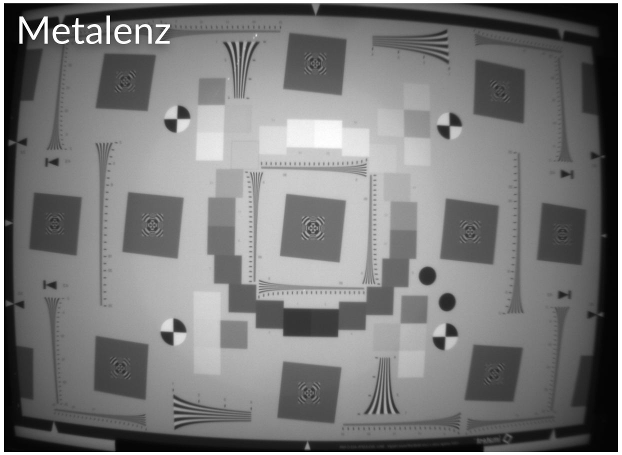
Metalens applications: Imaging



Metrics	4P	WLO	metalenz
Design	4P	2P	1M
Track Length (mm)	3.5	3.1	3.0
Module MTF 0F/0.7F (%) @nyq/2	36/26	15/10	38/32
RI (%)	40	20	70
Total intensity (a.u.)	1	0.75	2
Distortion (%)	2	17	20
Chief ray angle (deg)	30	30	0

Relative Illumination (RI) represents the combined effects of vignetting and roll-off
% of illumination at any point on the sensor, normalized to the with maximum illumination

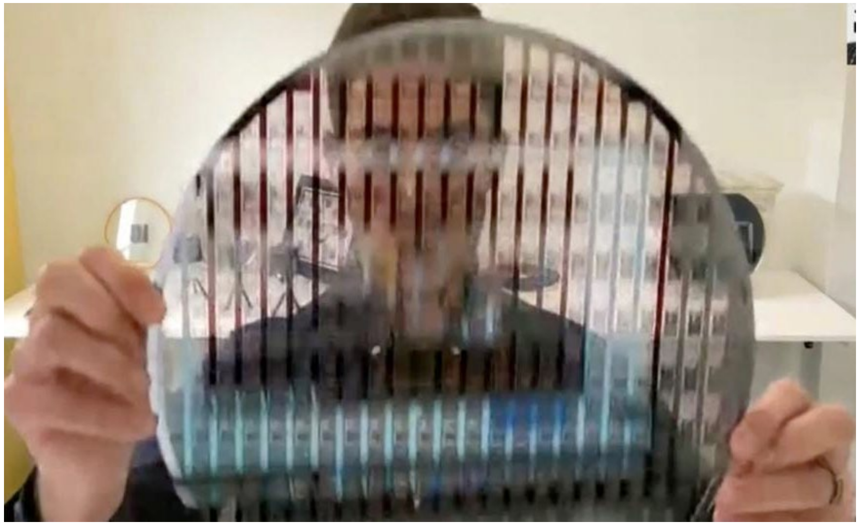




First Metasurface Product for High Volume Markets

life.augmented

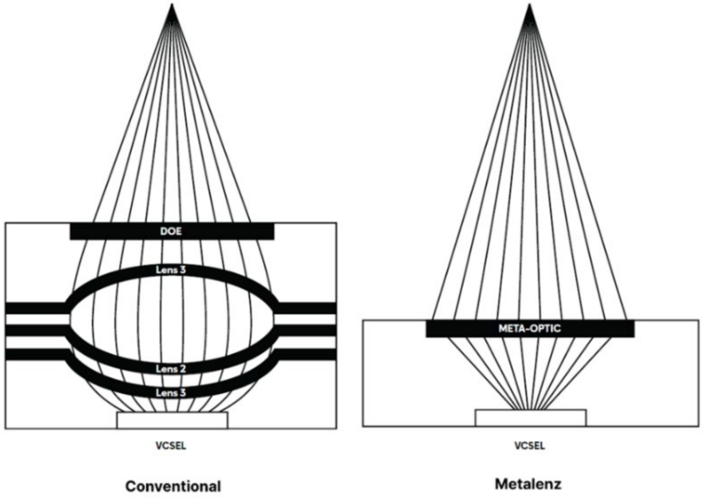
- Metalenz and STMicroelectronics deliver world's first optical metasurface technology for consumer electronics devices
  June 09, 2022 STMicroelectronics N.V.



Metalenz co-founder Rob Devlin holds up a 12-inch wafer of printed metalenses

Forbes Jun 8, 2022
World's First Printable Optical Metasurface For Vision, 3D Sensing, LIDAR Now Shipping In Consumer Products
John Koetsier, Senior Contributor

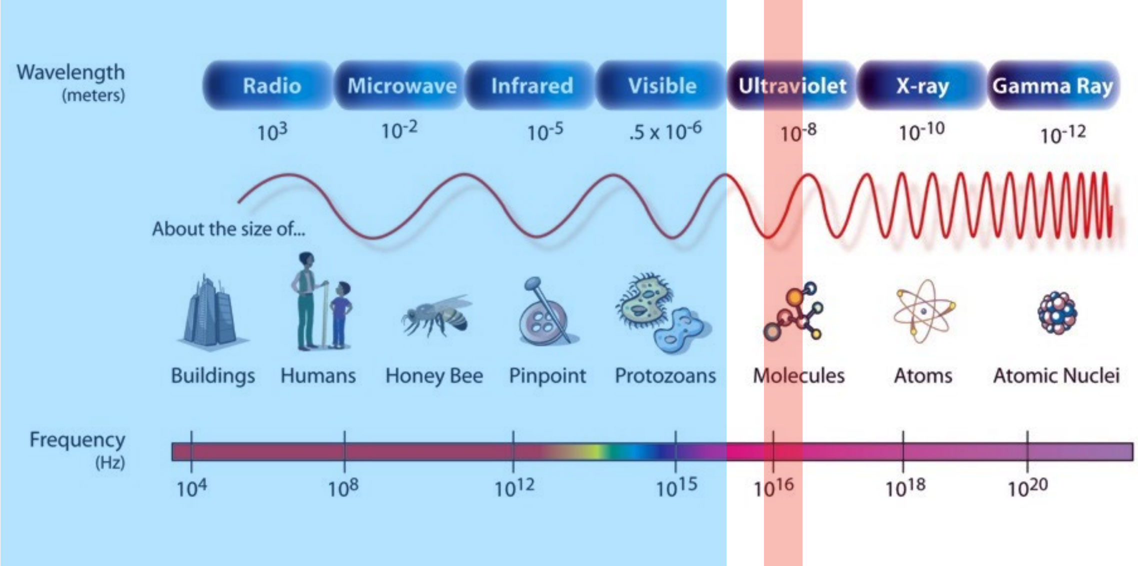
High Volume Semiconductor Foundry-Based Lens Manufacturing

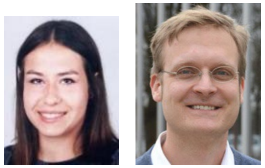


- ➢ Metalenz **announced a partnership** with UMC (major foundry) for high-volume manufacturing of optical lenses using commercial semiconductor processing platforms. UMC is amongst the largest semiconductor foundries in the world .
- ➢ The partnership enables high-volume manufacturing of optical lenses for 3D imaging in applications ranging from smartphones and laptops to IoT (Internet of Things) and automotive sensing.

https://www.forbes.com/sites/sabbirrangwala/2023/07/05/metalenz-pioneers-high-volume-semiconductor-foundry-based-lens-manufacturing/?sh=f5e36d423bde

Extreme Ultraviolet Metalenses





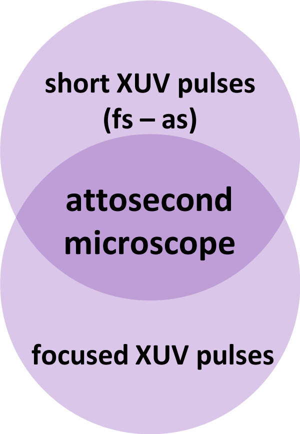
Hana Hampel Martin Schultze

M. Ossiander et al., Science 380, 59–63 (2023)

Extreme ultraviolet radiation

- Why focus XUV?
    - manipulate and observe electron motion in atoms and molecules
    - nonlinear attosecond dynamics
    - XUV semiconductor lithography

- **Goal of this project: design and test a transmitting XUV-focusing metaoptic**



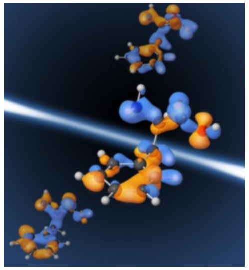
short XUV pulses (fs – as)

attosecond microscope

focused XUV pulses

← time-domain focusing ✓

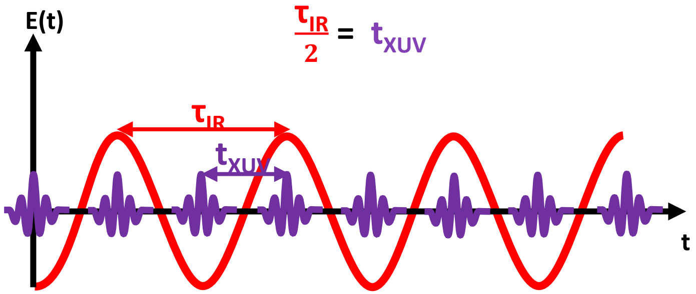
← spatial-domain focusing ✗

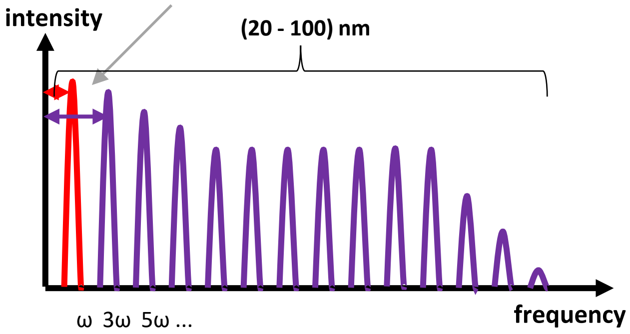


- XUV Sources:
    - synchrotrons
    - free electron lasers
    - tin-droplets plasma
    - high harmonic generation

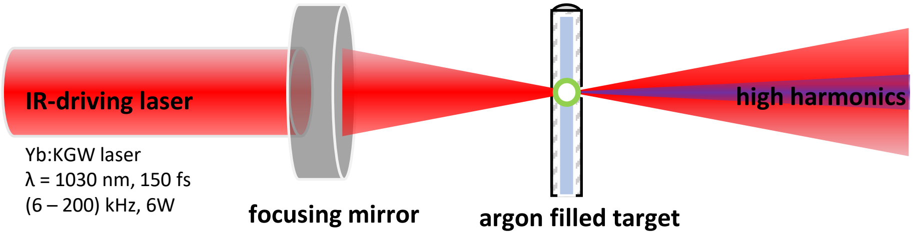
Source: DOI: 10.1126/science.1189401
Source: https://www.cecam.org/workshop-1552.html

High harmonic generation: spectrum



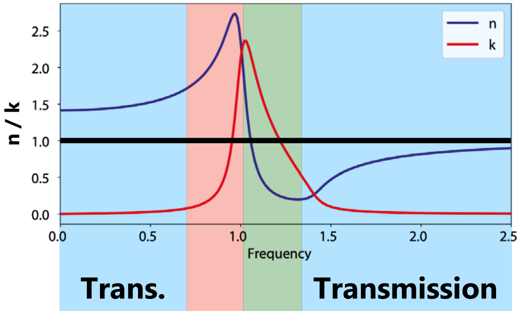


one attosecond pulse is generated every half-cycle of the driving laser
-> extreme ultraviolet harmonics are spaced by two fundamental photon energies (Fourier transform)



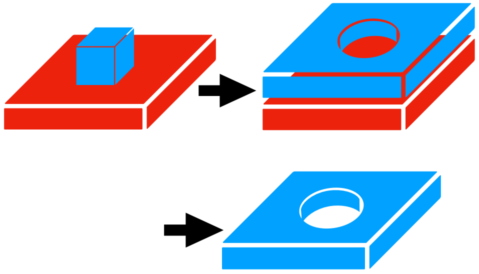
Yb:KGW laser
λ = 1030 nm, 150 fs
(6 – 200) kHz, 6W

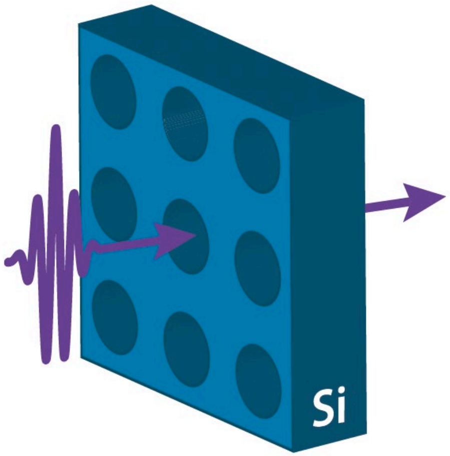
EUV Material Properties



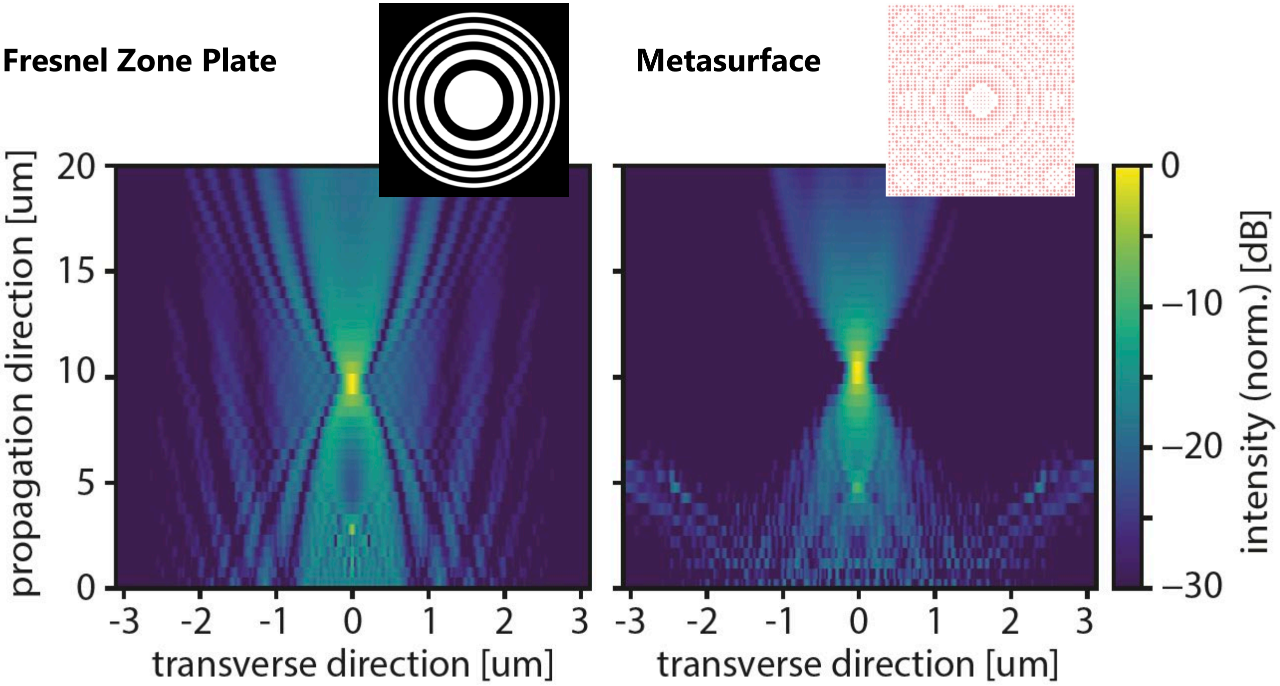
$n_{material} < n_{vacuum}$
→ vacuum suddenly guiding

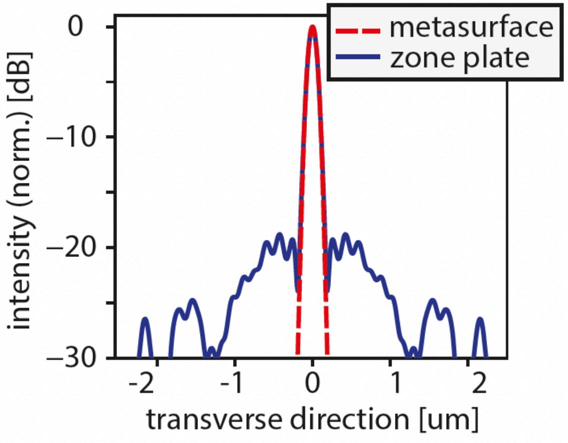
$k_{material} > 0$
→ thin device
→ thin / no substrate





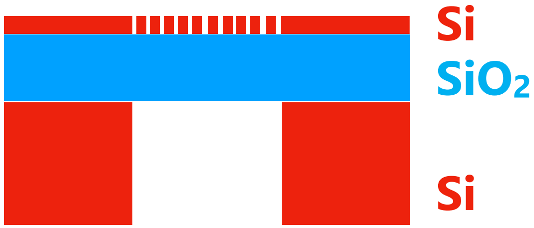
But is it worth it?



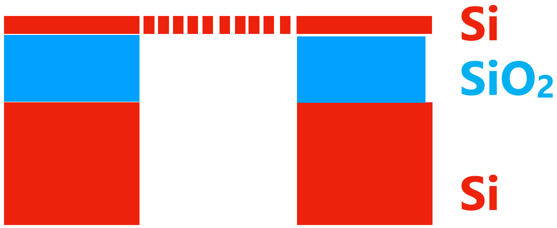


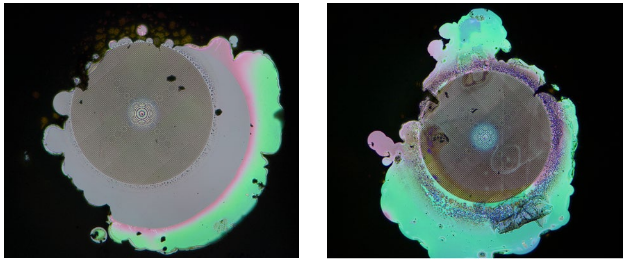
EUV Metasurface Fabrication

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



BHF wet etched





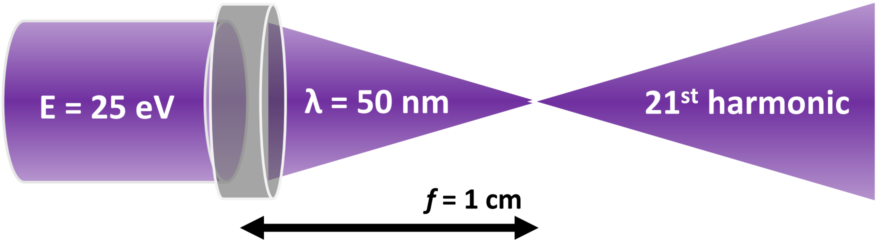
Focussing of XUV radiation

Capasso Group
Harvard School of Engineering and Applied Sciences

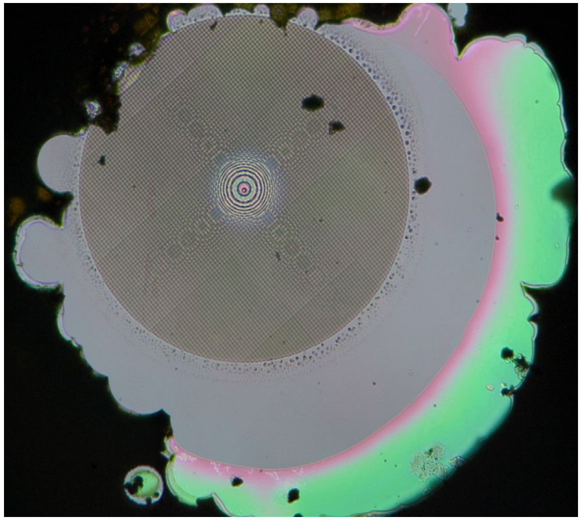
TU Graz

Hana Hampel
Martin Schultze

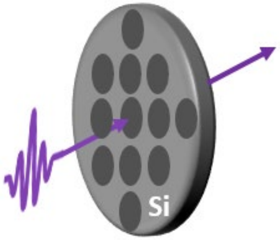
- transmitting metaoptics
  - wavelength-scale structures made of Si
  - optimized for 50 nm radiation:



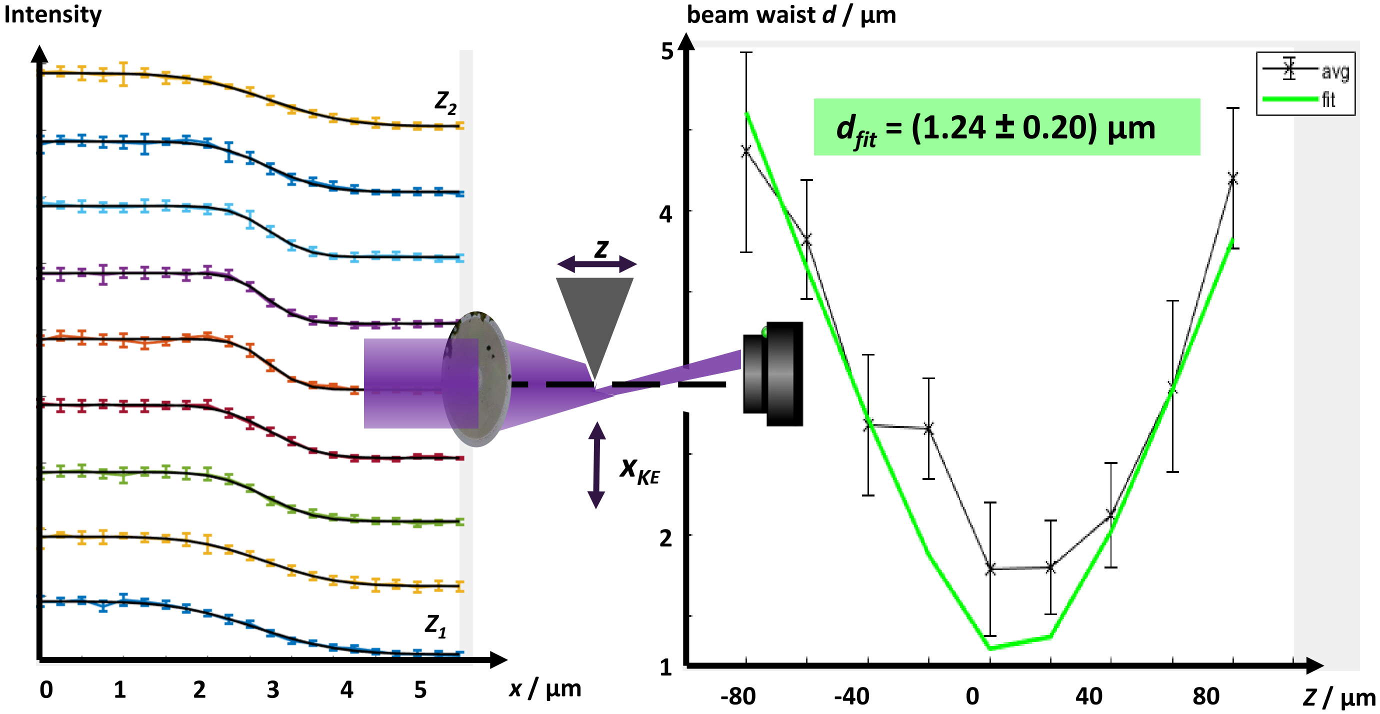
Sample preparation:
Maryna Meretska
Soon Wei Daniel Lim



Numerics and concept:
Marcus Ossiander

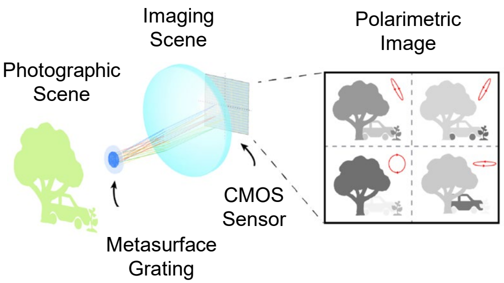


Measurement



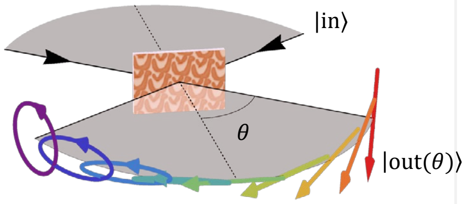
Multifunctional Meta-Optics

Imaging Polarimetry



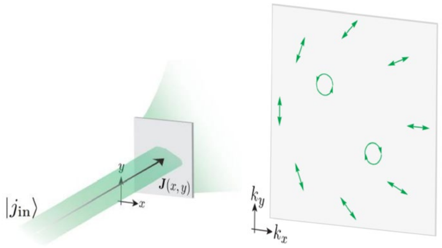
NA Rubin, G D'Aversa, P Chevalier, Z Shi, WT Chen, and F Capasso, *Science*, Vol. 365, Issue 6448, eaax1839 (2019).

Angle-Tunable Birefringence



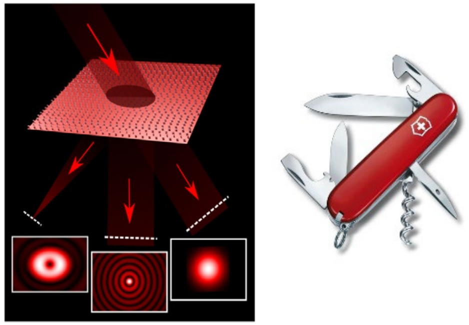
Z. Shi et al., A. Y. Zhu, Z. Li, Y.-W. Huang, W. T. Chen, C.-W. Qiu, F. Capasso, *Science Advances* 6, eaba3367 (2020).

Jones Matrix Holography



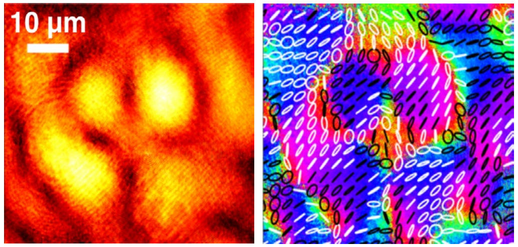
NA Rubin, A Zaidi, AH Dorrah, Z Shi, F Capasso, *Science Advances* 7, eabg7488 (2021).

Multifunct. Wide-Angle Optics



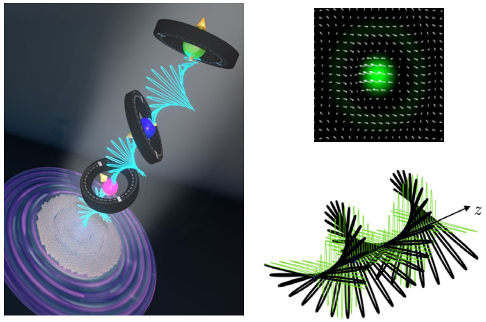
C Spagele, M Tamagnone, D Kazakov, M Ossiander, M Piccardo, F Capasso,, *Nat. Communications* 12, 3787 (2021).

Singularities



S. W. D. Lim, J.-S. Park, M. L. Meretska, A. H. Dorrah, F. Capasso, *Nature Communications* 12, 4190 (2021).

Structured Polarization in 3D



AH Dorrah, NA Rubin, A Zaidi, M Tamagnone, F Capasso, *Nature Photonics* 15, 287 (2021).

Miniature spectrometers

- Recently freeform optics have emerged as a potential solution – these are off-axis, non-rotationally symmetric components
- Examples include e.g. toroidal gratings, aspherical off-axis mirrors
- Difficult to fabricate and generally bulky/expensive

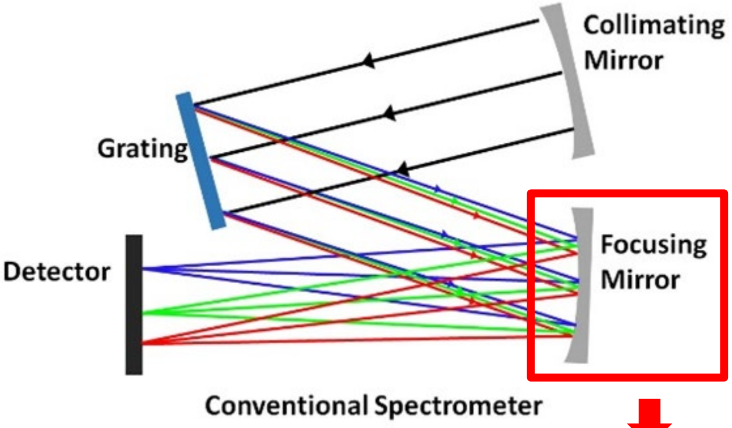
Diamond machining of off-axis mirrors

Rotationally symmetric, non-standard shapes

Other complex shapes and concave/toroidal gratings

Meta-spectrometers: Making good use of Chromatic Effect

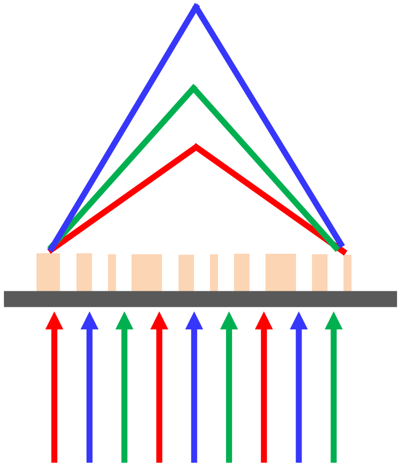
- ➢ Conventional grating-based spectrometers



Achromatic reflective focusing lens

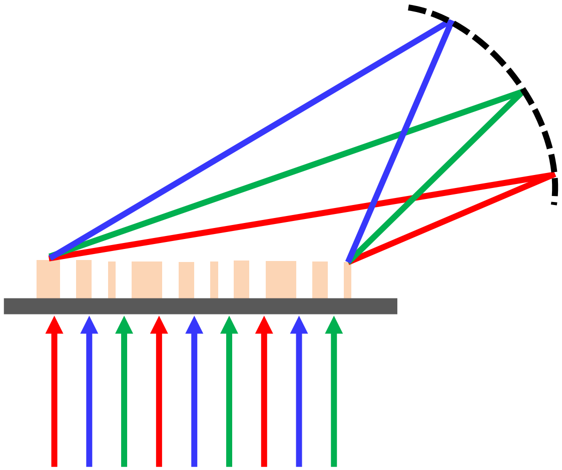
- angular dispersion

- ➢ On-axis focusing metalens



- longitudinal dispersion

- ➢ Off-axis focusing metalens

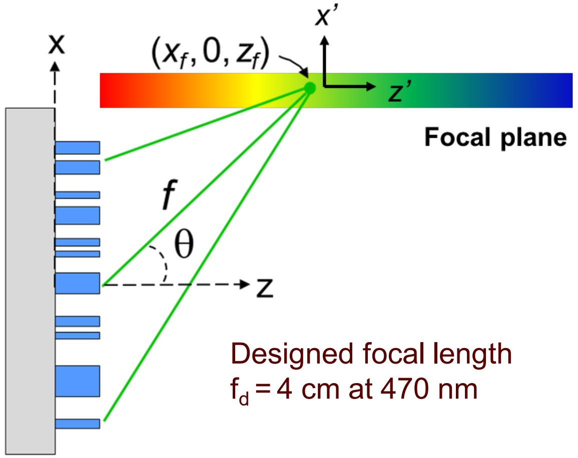


- angular dispersion + longitudinal dispersion

- ➢ 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.

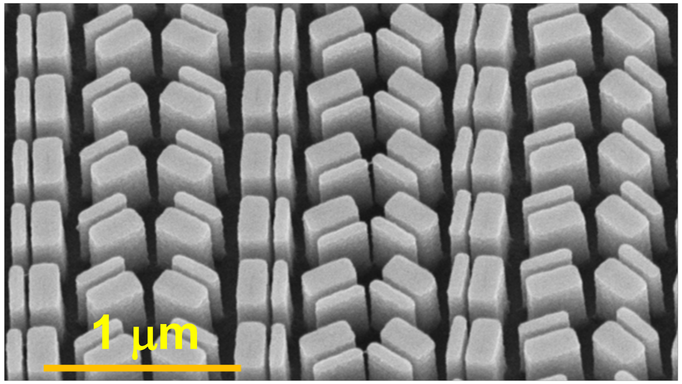
Aberration-corrected metalens spectrometer

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



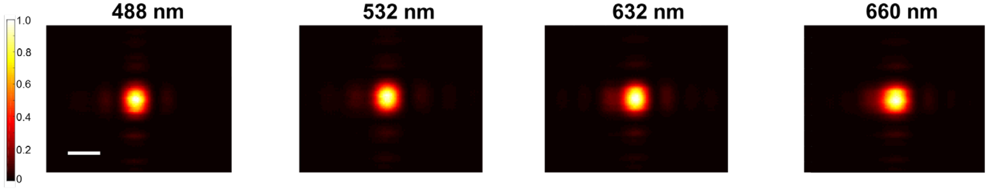
Designed focal length $f_d = 4$ cm at 470 nm

- Coupled TiO_2 waveguide for fine tuning dispersion

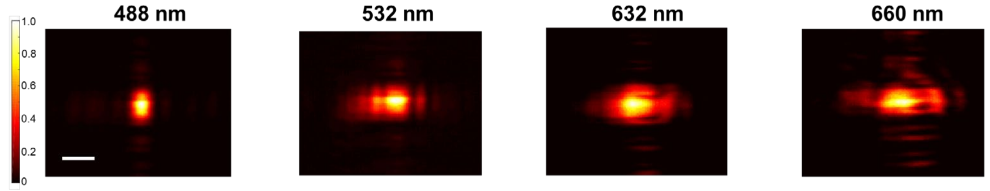


- Measured focal spots (FWHM ~ 56 μm)

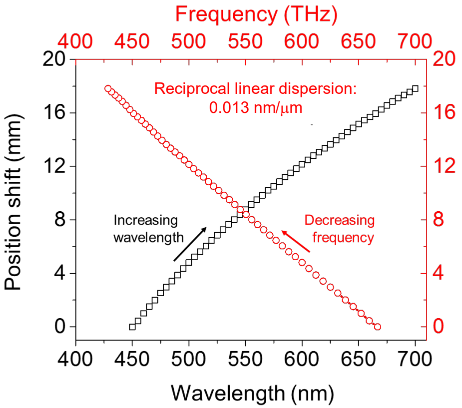
Dispersion engineered metalens



Without dispersion engineering



- 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

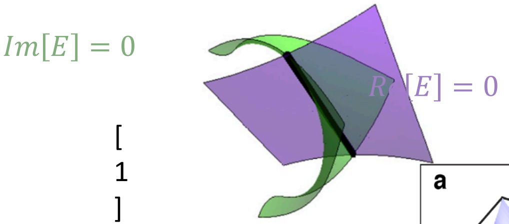
Light is subject to the diffraction limit.

There is a smallest angle or volume it can be localized in.

There is no diffraction limit for dark.

Singularities can be arbitrarily localized.

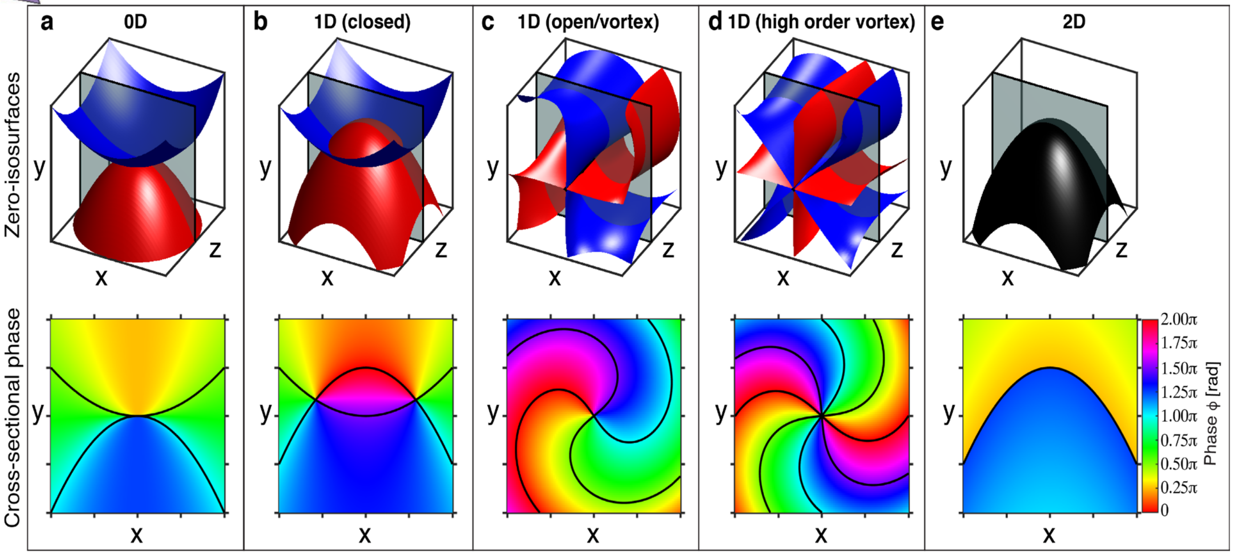
Structuring Dark via Phase Singularities



[1]

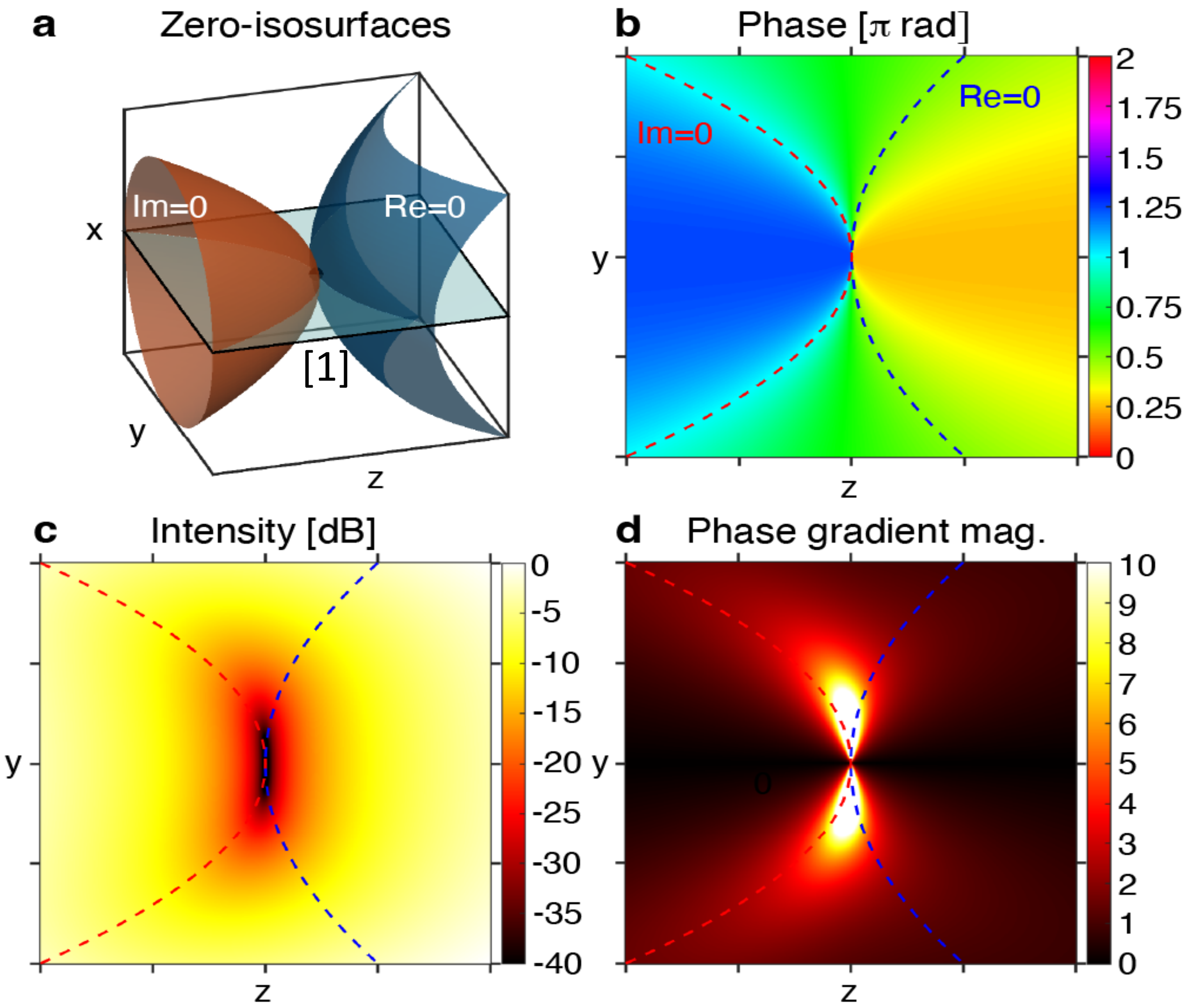
- 1D first-order singularities are robust against small field perturbations.
- 1D first-order singularity existence is preserved under small deformations or displacements of the zero-surfaces (topologically-protected).

- 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.

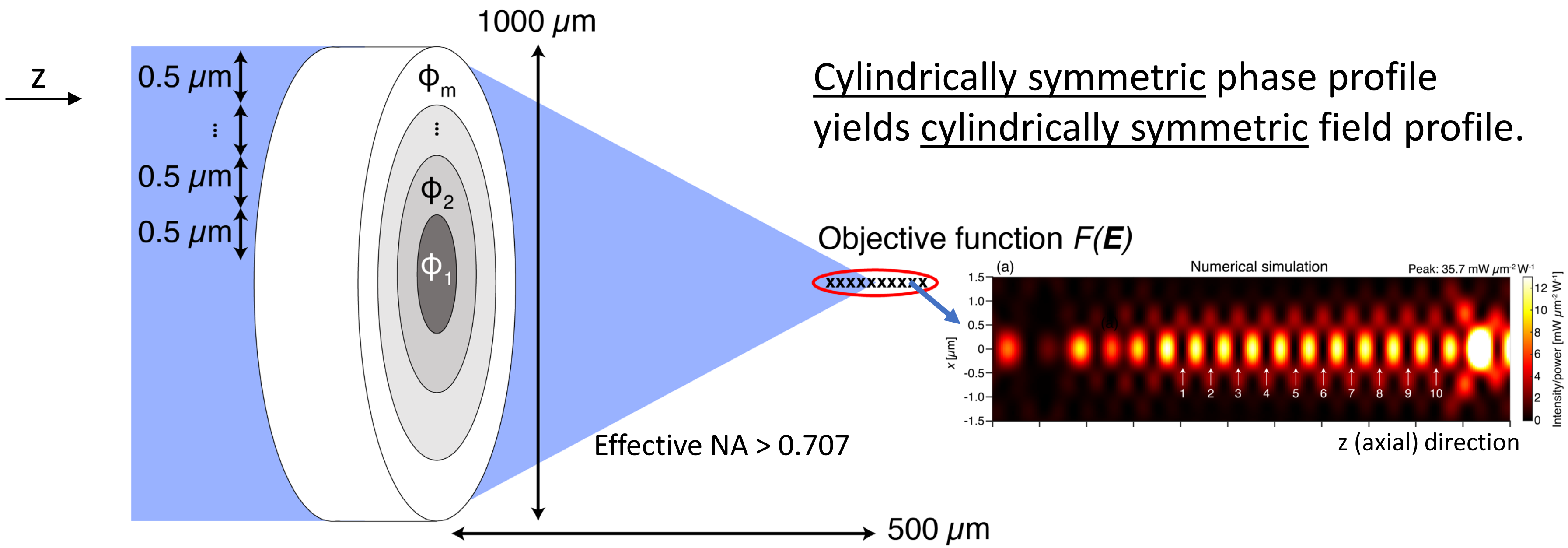


Our Recipe for sheet singularities: *maximize phase gradient orthogonal to desired sheet!*

Point Singularities



Inverse design of point singularities



<u>Cylindrically symmetric</u> phase profile yields <u>cylindrically symmetric</u> field profile.

- Design strategy:
  - Step 1: Produce point singularities at each position.
  - Step 2: Equalize optical environment across positions.

S. D. Lim, J-S. Park, D. Kazakov, C. M Spaegele, A. H Dorrah, M. L Meretska, and F. Capasso Nature Communications, 14, 3237 (2023.

Capasso Group
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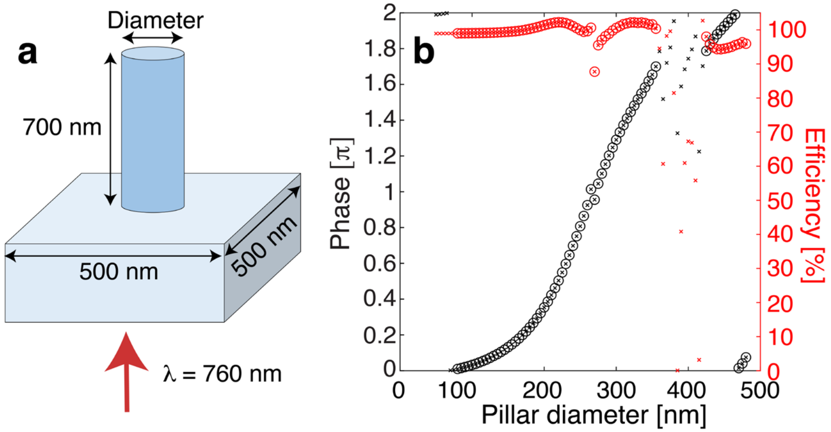
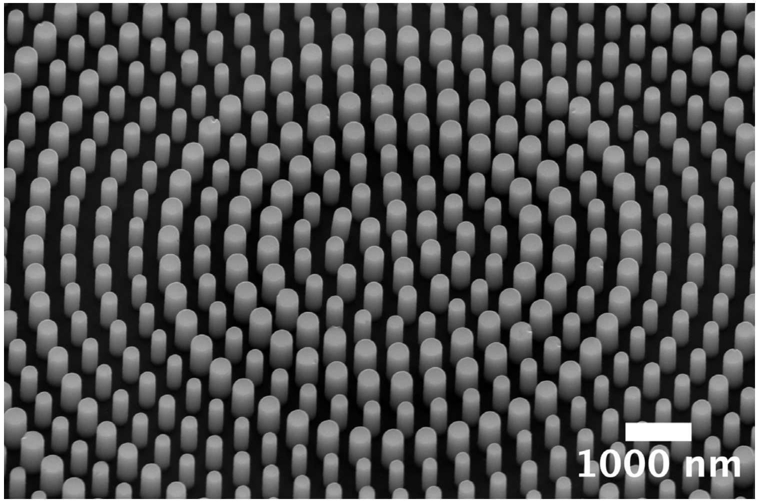
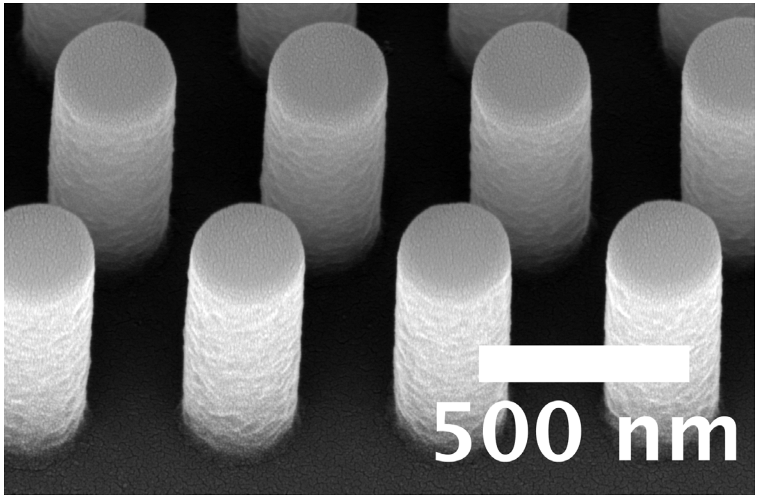
Experimental realization

- Phase-only metasurface using TiO_2 nanopillars on SiO_2.
- Protocol [1]:
    1. Electron beam lithography to produce nano-holes.
    2. Backfill of holes with TiO_2 using atomic layer deposition.
    3. Etch back of excess TiO_2 with reactive ion etching.
    4. Deposition of gold aperture mask to eliminate stray light.



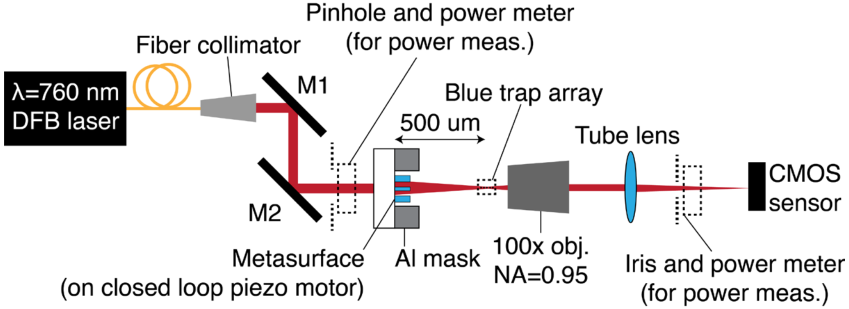


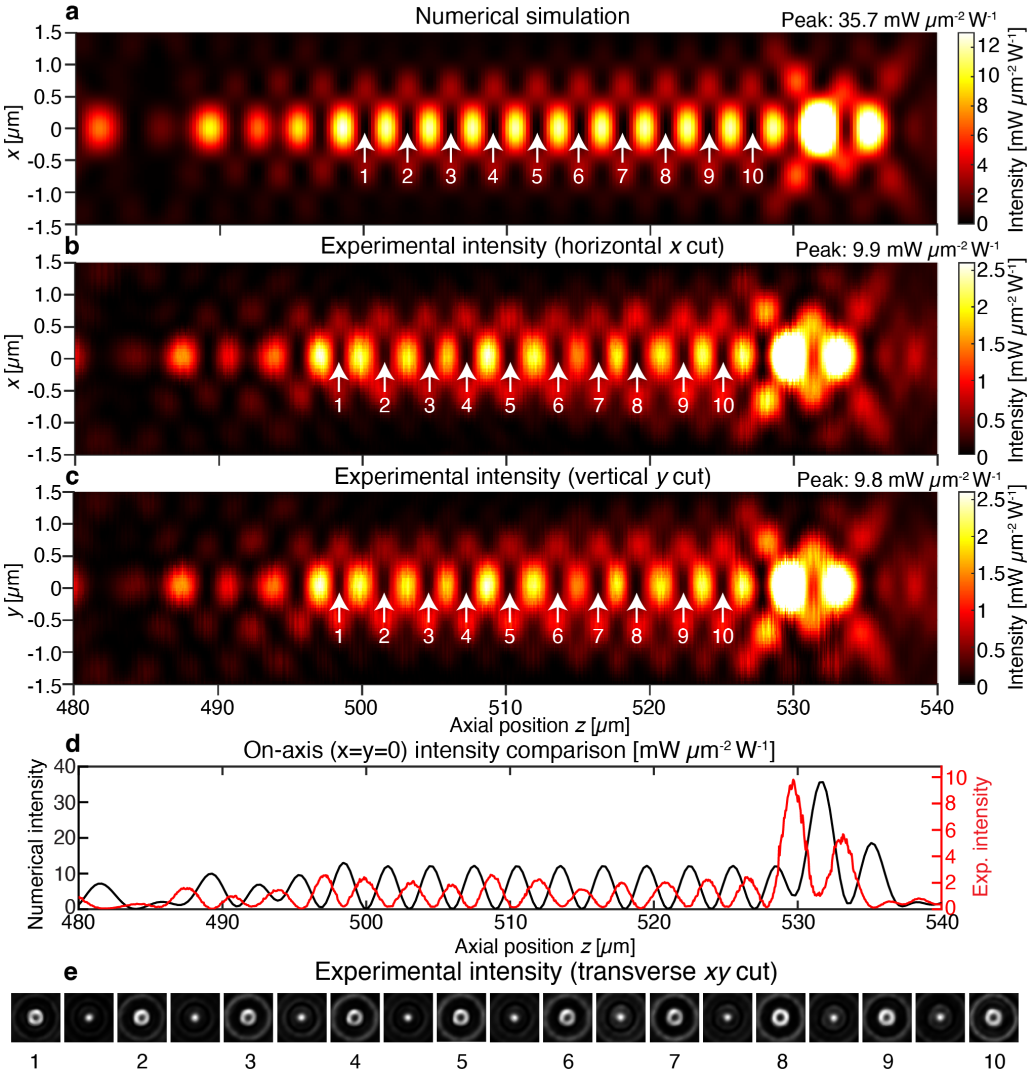


[1] R. C. Devlin, M. Khorasaninejad, W. T. Chen, J. Oh, and F. Capasso, Broadband high-efficiency dielectric metasurfaces for the visible spectrum, *Proc. Natl. Acad. Sci. USA* **113**, 10473–10478 (2016).

Experimental results

Experimental setup:





- Slight axial displacement due to $\lambda = 760.9\ \mathrm{nm}$ used instead of target $\lambda = 760\ \mathrm{nm}$.

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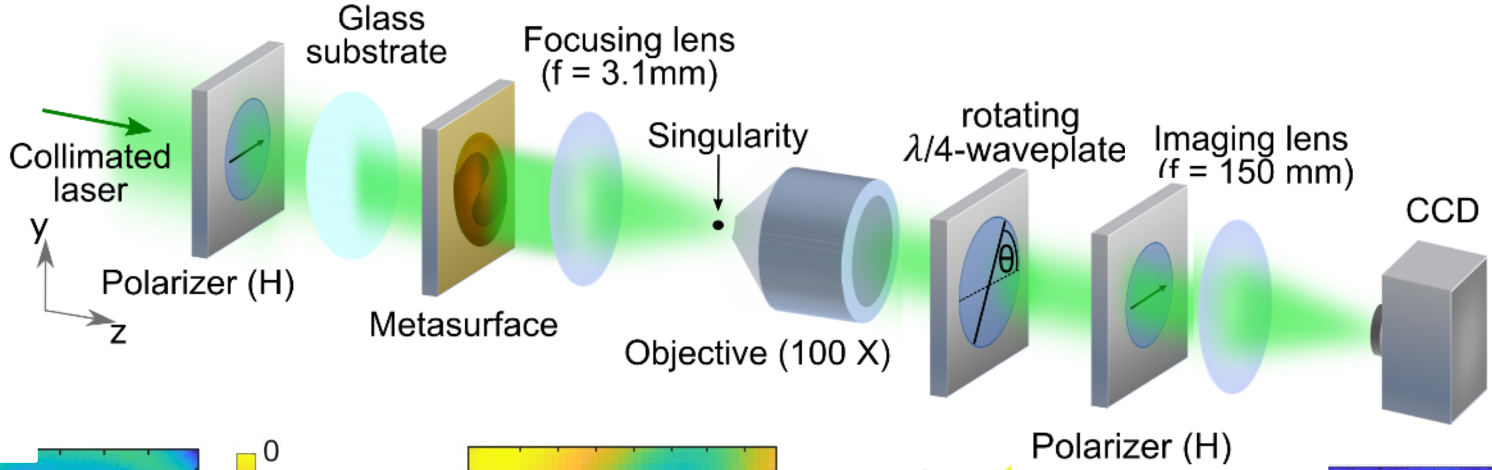
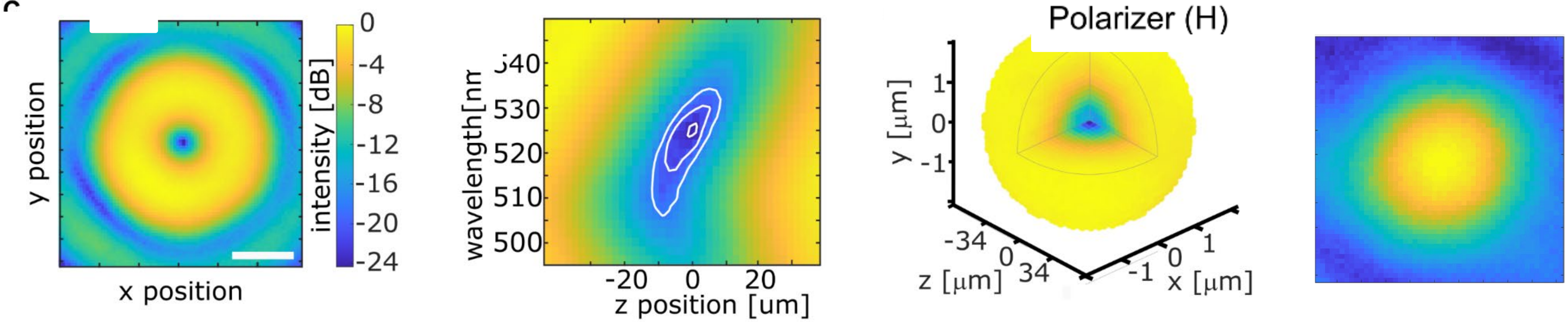
Topologically Protected Phase and Polarization Singularity





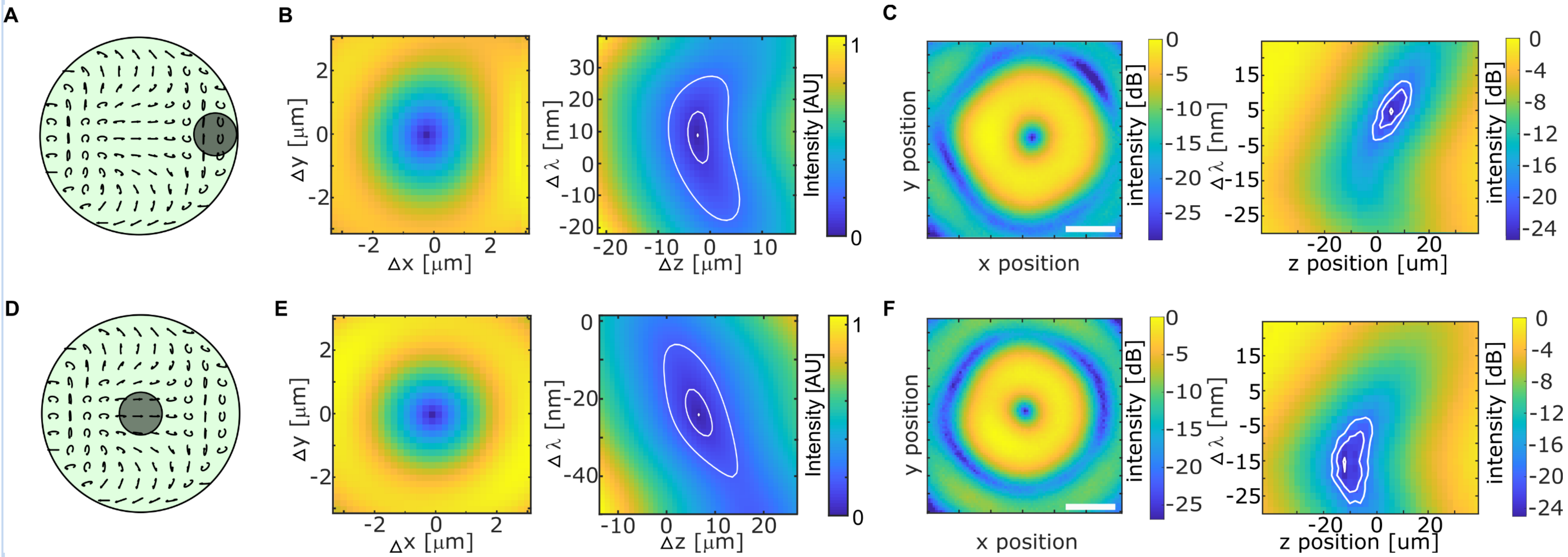
C.M. Spaegele, M. Tamagnone, S.W.D. Lim, M. Ossiander, M.L. Meretska & F. Capasso. *Science Advances* **9**, 24 (2023)

Topological protection

Perturbation

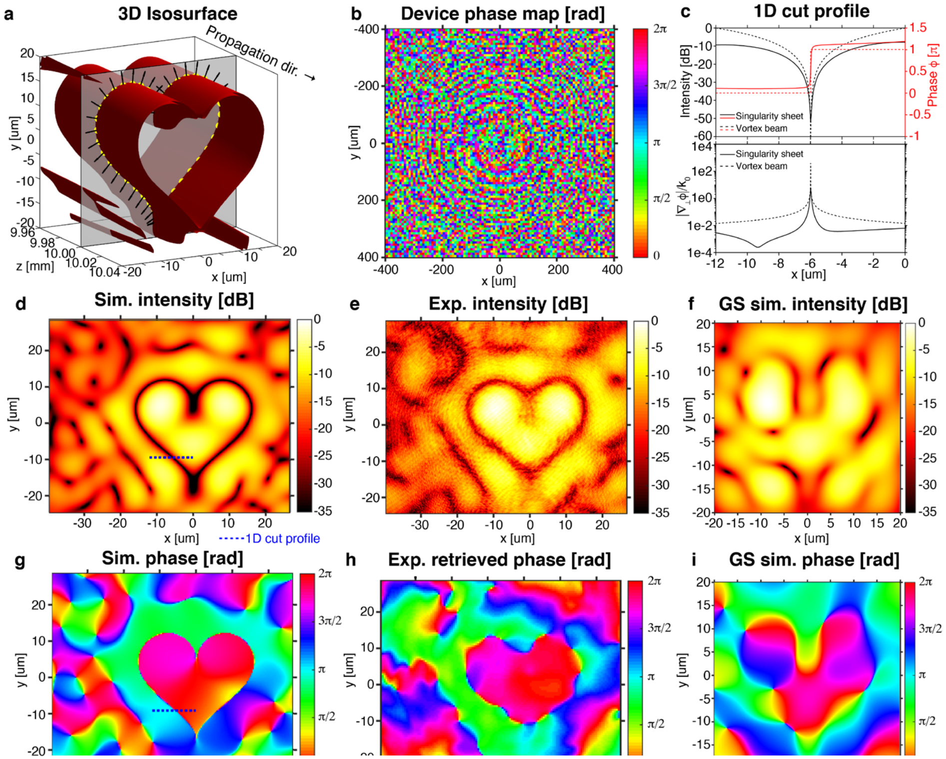
Simulation

Experiment

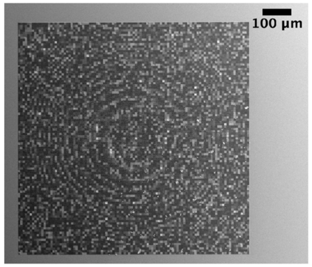


Sheet phase singularities

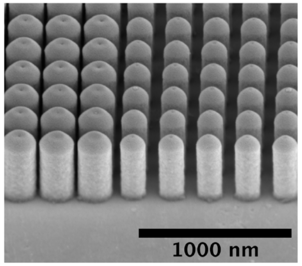
- Sheet singularity with heart-shaped cross-section designed using phase gradient maximization and fabricated.
    - For 532 nm wavelength.
    - Metasurface platform: TiO_2 nanopillars on SiO_2
- Fidelity and contrast attained is superior to that obtained using the Gerchberg-Saxton (GS) algorithm.



Full metasurface



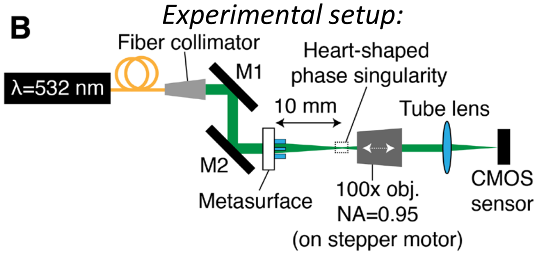
Superpixel zoom in



Soon Wei Daniel Lim, Joon-Suh Park, Maryna L. Meretska, Ahmed H. Dorrah, and F. Capasso., Nature Communications, 12, 4190 (2021)

3D singularity sheet structure flythrough

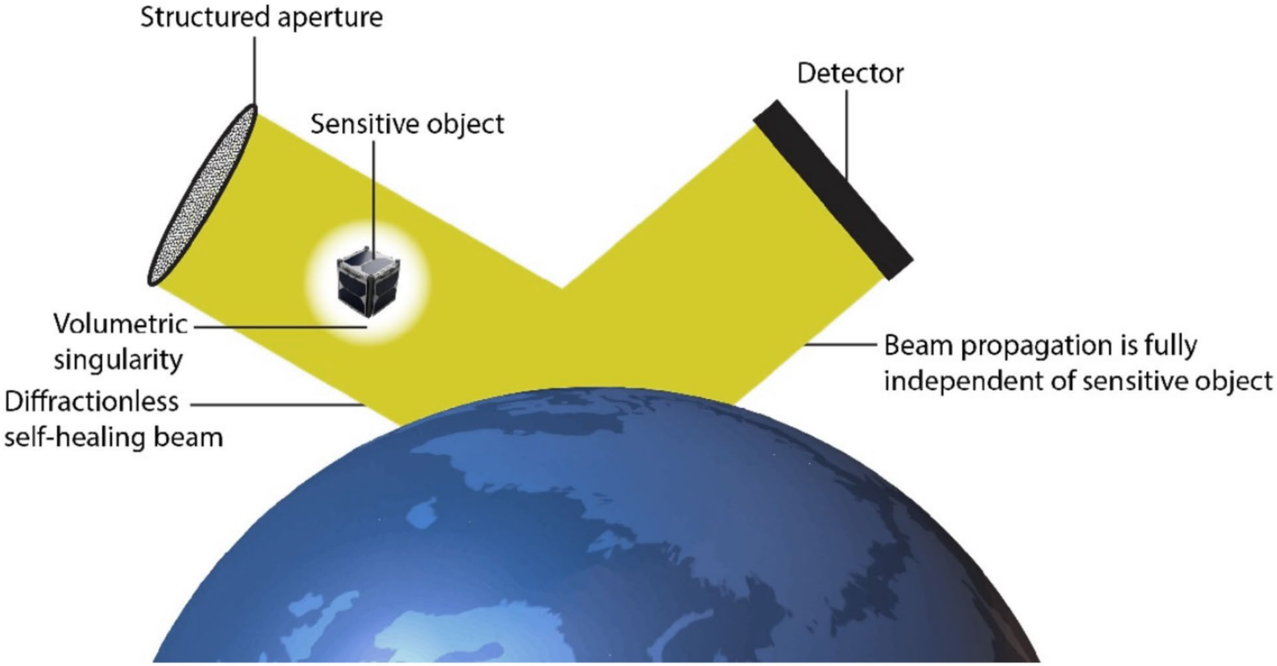
Experimental setup:



- 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.

Soon Wei Daniel Lim, Joon-Suh Park, Maryna L. Meretska, Ahmed H. Dorrah, and F. Capasso., Nature Communications, 12, 4190 (2021)

Structuring dark around obstacles



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**

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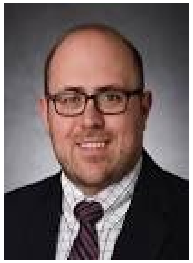
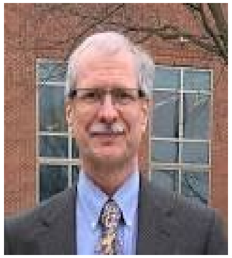
Raphael Pestourie, MIT


Prof. Steve Johnson, MIT


Sawyer D. Campbell, PSU


Prof. Douglas Werner, PSU


Paulo Dainese, Corning

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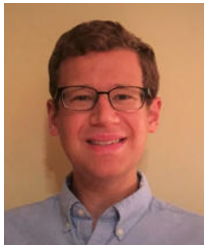

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