Flat and Conformal Optics Based on Dielectric Metasurfaces

Presented by:


OSA
Optical
Material Studies
Technical Group

- Mission: Networking and activities related to Optical Materials

- Webinars, seminars & special events (*e.g.* Special lunch presentation, poster session, networking events at FiO, CLEO conferences)

- You are welcome to join the committee and propose new activities

- Contact: Garo Khanarian, gkhanarian@gmail.com
  tel: 908 868 4546(M)

- More information at: www.osa.org/opticalmaterialstudiesTG

OSA Optical Material Studies Technical Group

Committee

Name	Affiliation	Title
Garo Khanarian	BASF	Chair
Stephen H. Foulger	Clemson University	Vice Chair
David J. DiGiovanni	OFS Laboratories	Advisor
Mark G. Kuzyk	Washington State University	Advisor
Robert A. Stegeman	Nuburu	Hot Topics
Robert A. Norwood	University of Arizona	Incubator Organizer
Shekhar Guha	US Air Force Research Laboratory	Networking Organizer
Wei Lee	National Chiao Tung University	Optical Groups Liaison
Yichen Liang	MS&T	Social Media Organizer
Ho Wai Howard Lee	Baylor University	Webinar Organizer
Zhi M. Liao	Lawrence Livermore National Laboratory	Webinar Organizer

OSA Optical Material Studies Technical Group

Webinar

"Flat and Conformal Optics Based on Dielectric Metasurfaces"

by Prof. Andrei Faraon, Caltech on Wednesday November 9th , 2016 at 3 PM , EST.

Andrei Faraon, ***California Institute of Technology***

OSA Optical Material Studies Technical Group

Webinar

" Material Science View of Grinding and Polishing of Laser Glass Optics"

by Dr. Tayyab Suratwala, Lawrence Livermore Lab, December 2, 2016 12:00 noon EST

Tayyab Suratwala, ***Lawrence Livermore National Laboratory***

OSA Optical Material Studies Technical Group

"Flat and Conformal Optics Based on Dielectric Metasurfaces"

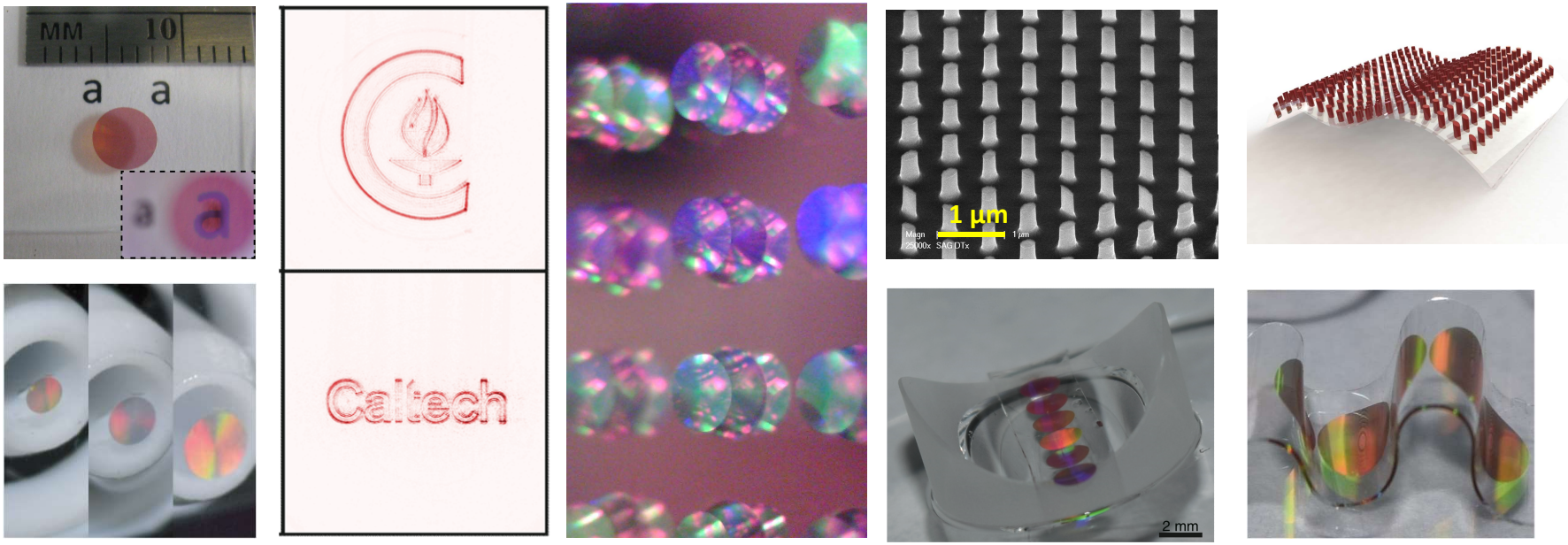
by Prof. Andrei Faraon, Caltech on Wednesday November 9th , 2016 at 3 PM , EST.

Andrei Faraon, *California Institute of Technology*

Biography of speaker:

Dr. Andrei Faraon is an Assistant Professor of Applied Physics, Materials Science and Medical Engineering at California Institute of Technology. After earning a B.S. degree in physics with honors in 2004 at California Institute of Technology, he received his M.S. in Electrical Engineering and PhD in Applied Physics both from Stanford University in 2009. At Stanford, Dr. Faraon was involved with seminal experiments on quantum optics using single indium arsenide quantum dots strongly coupled to photonic crystal cavities in gallium arsenide. After earning his PhD, Dr. Faraon spent three years as a postdoctoral fellow at Hewlett Packard Laboratories. At HP he was involved with pioneering experiments on diamond quantum photonic devices coupled to solid-state spins. He demonstrated the first nano-resonators coupled to single nitrogen vacancy centers in mono-crystalline diamond.

Flat and Conformal Optics With Dielectric Metasurfaces



Andrei Faraon

T.J. Watson Laboratory of Applied Physics & Kavli Nanoscience Institute

OSA Webinar, November 9 2016

Caltech

Acknowledgements

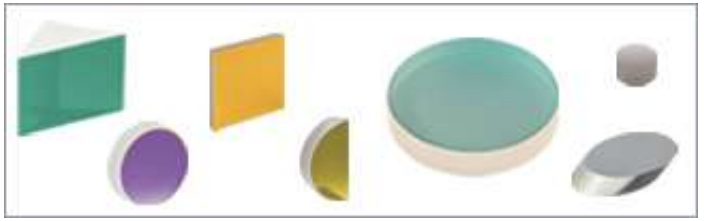
Faraon group: Dr. Amir Arbabi, Yu Horie, Mahsa Kamali, Ehsan Arbabi, Leon Ding (UG), Alex Ball (UG)

Collaborators: Dr. David Fattal (HP/Leia Inc.), Dr. Seunghoon Han (Samsung), Dr. Mahmood Bagheri (JPL), Prof. W.E. Moerner (Stanford), Prof. Gary Brooker (Hopkins), Alan Willner (USC), Oscar Bruno (Caltech)

Free space optical elements

Lenses

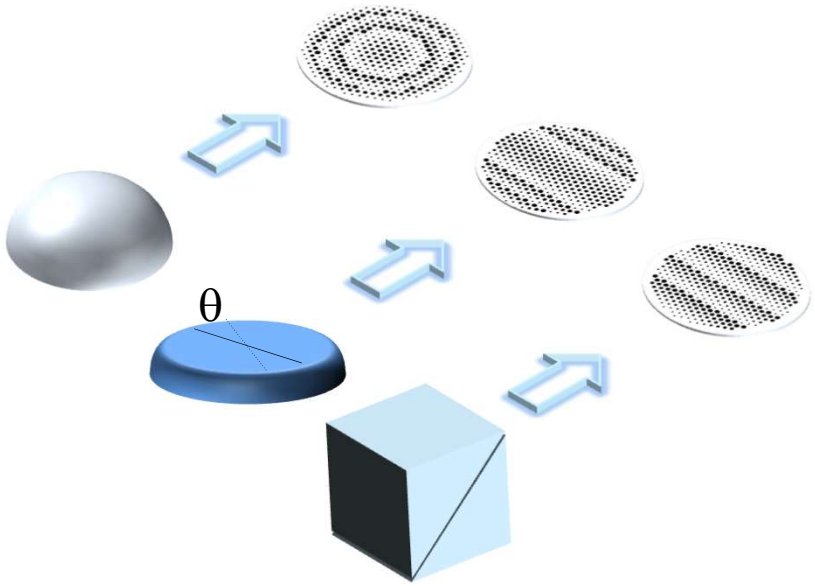
Mirrors



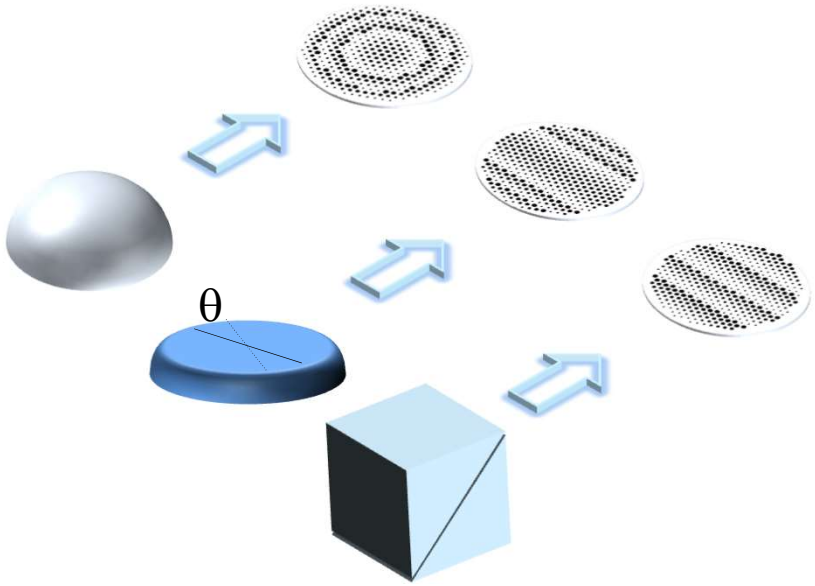
Beam-splitter

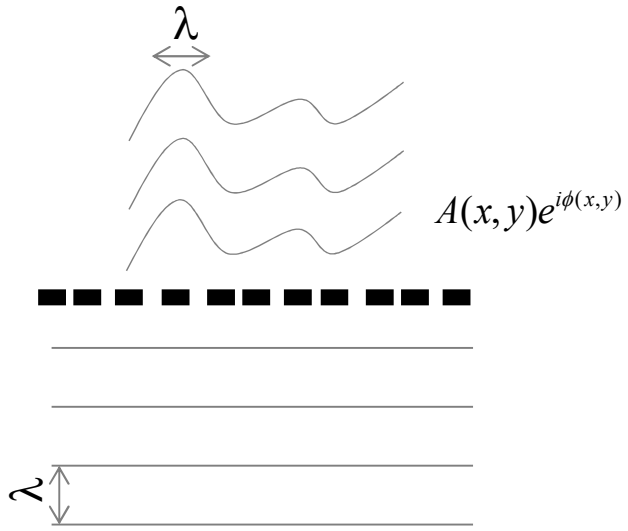
Polarizers

Flat optics: a new paradigm for optical systems

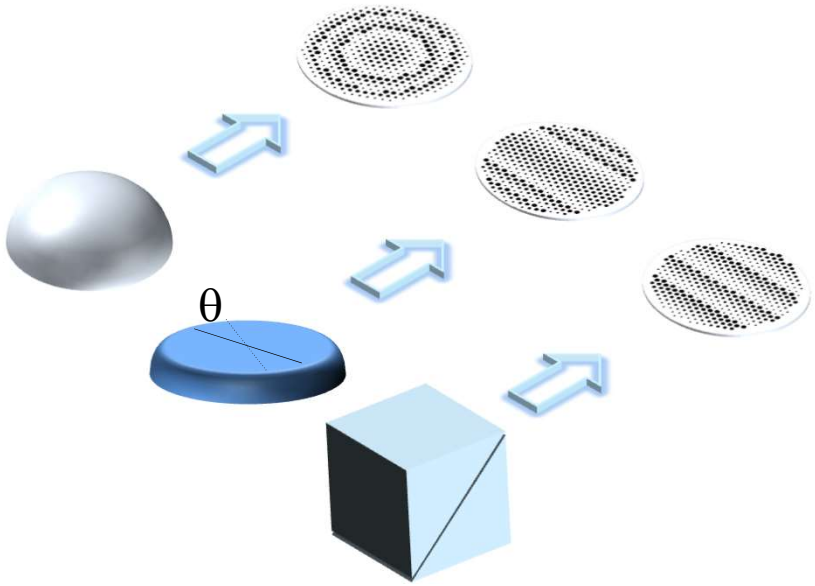


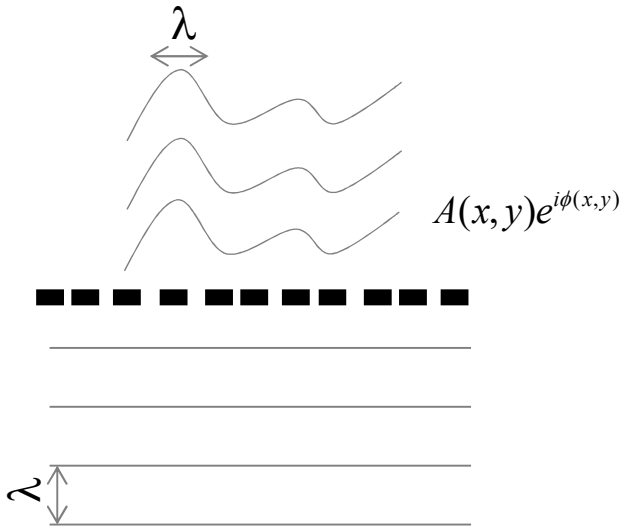
Flat optics: a new paradigm for optical systems

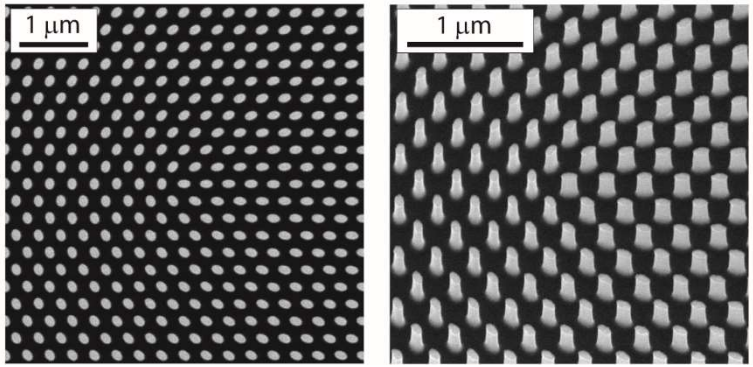




Flat optics: a new paradigm for optical systems







Caltech

Vertical integration of optical components

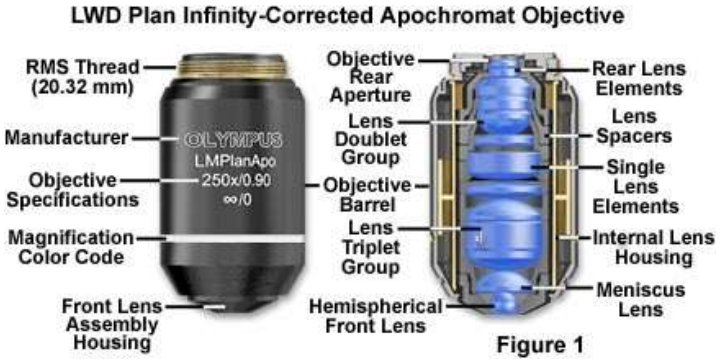


Figure 1

Vertical integration of optical components

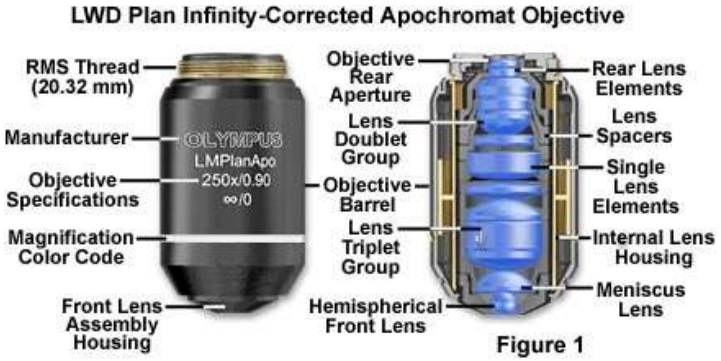
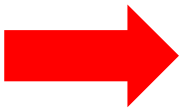
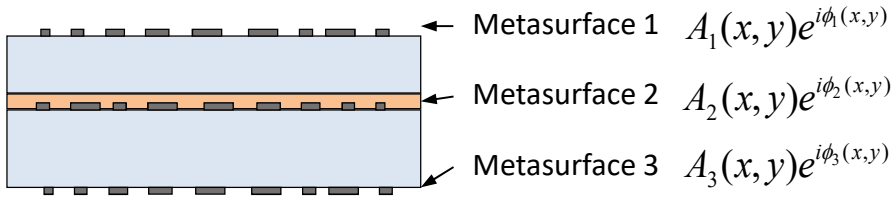
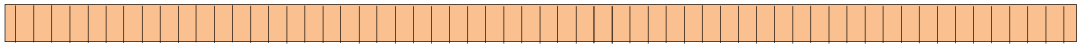


Figure 1





Vertical integration with electronics

Image Sensor 

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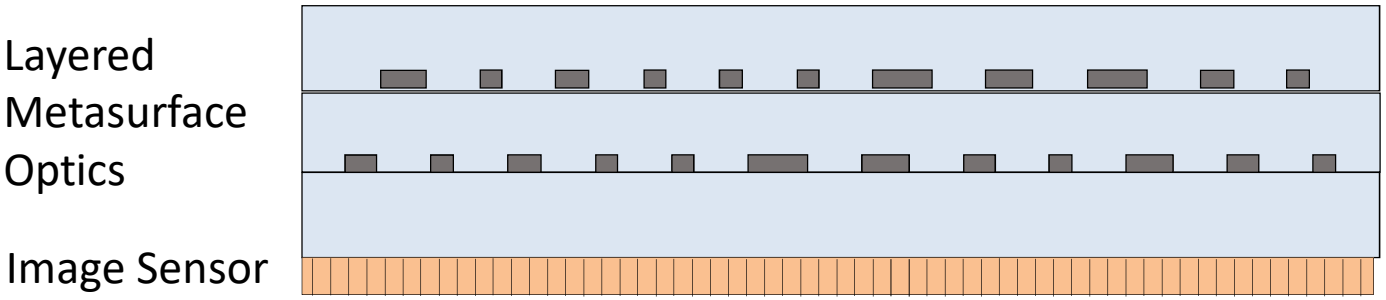

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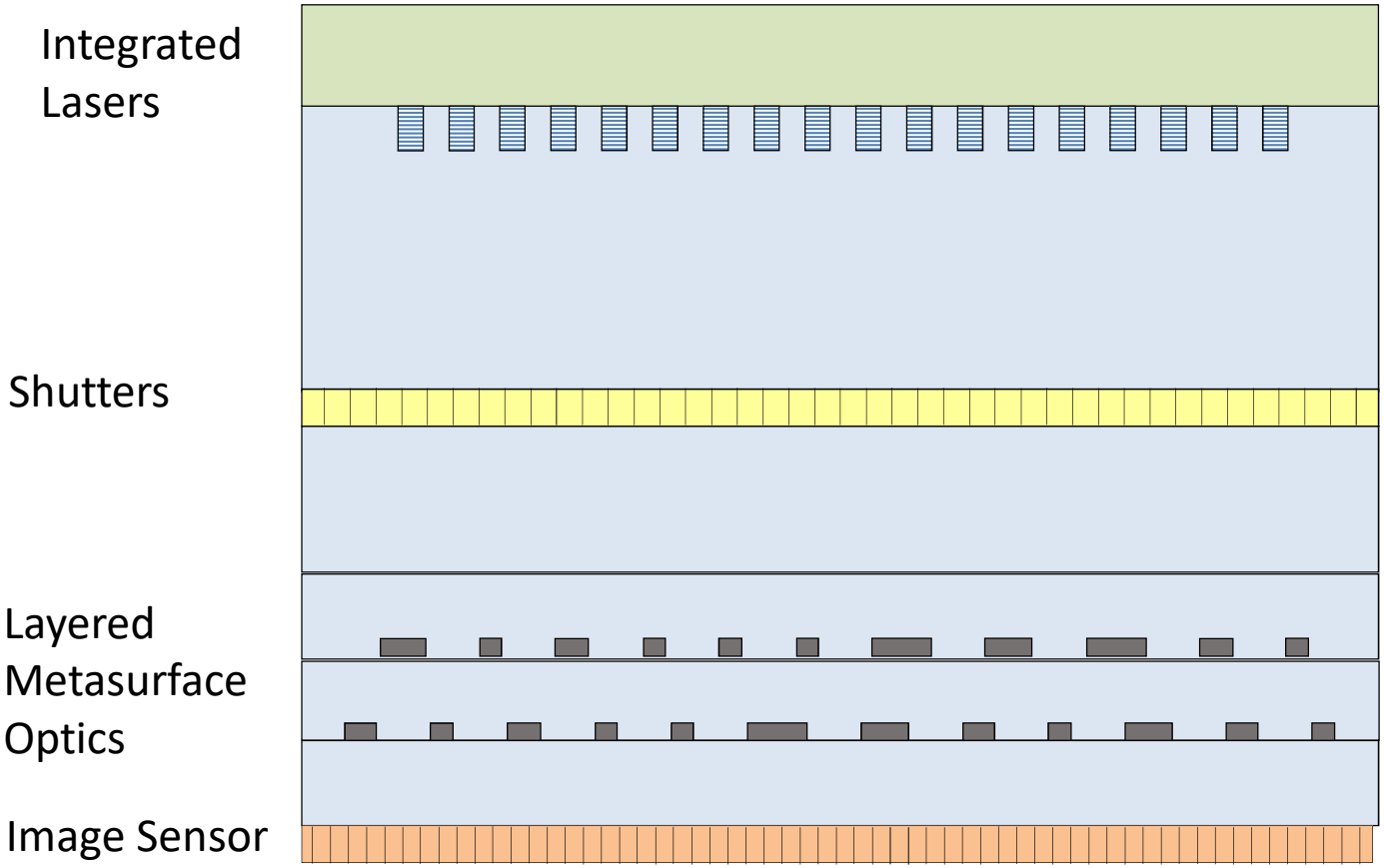
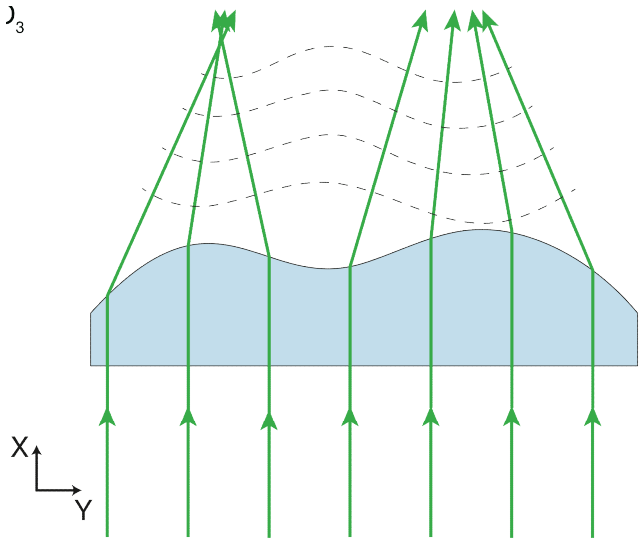


Conformal optics



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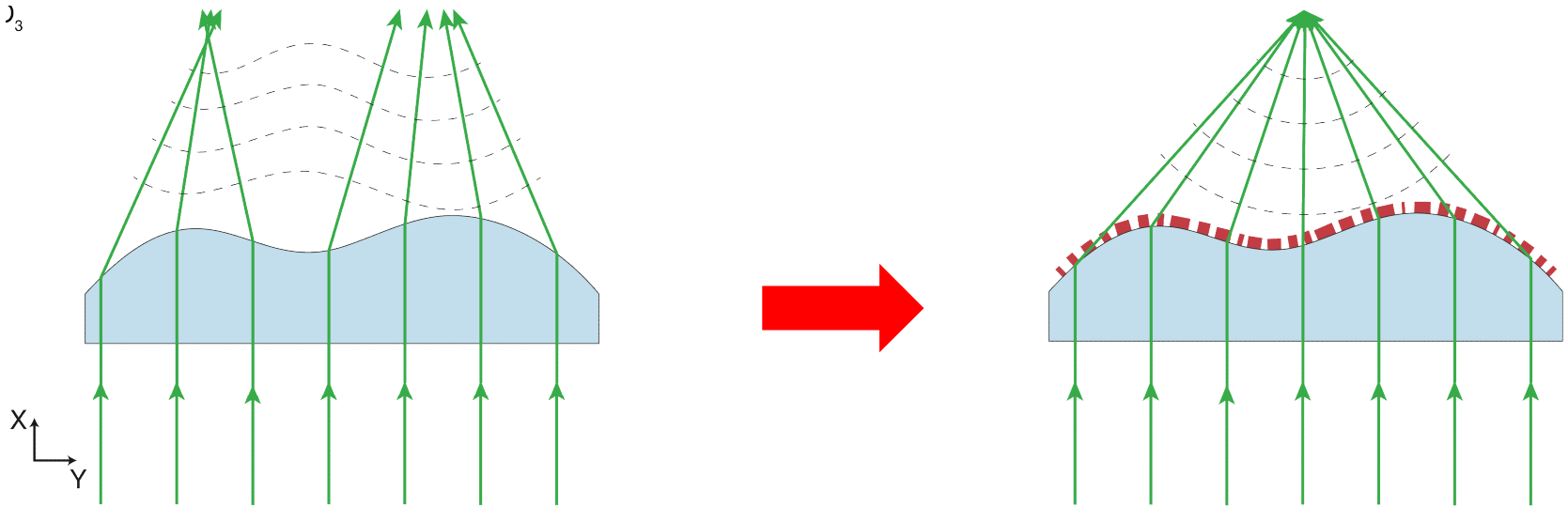
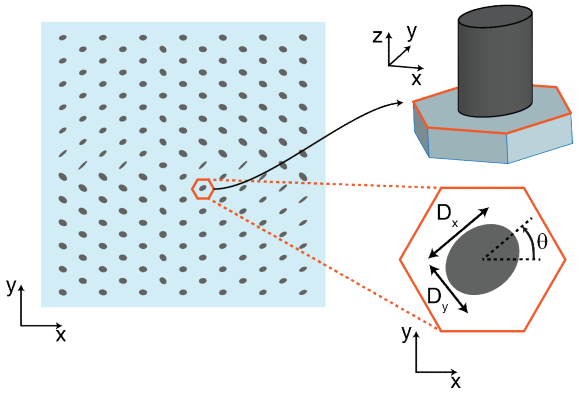


Outline

Outline

Metasurfaces for complete
phase and polarization control



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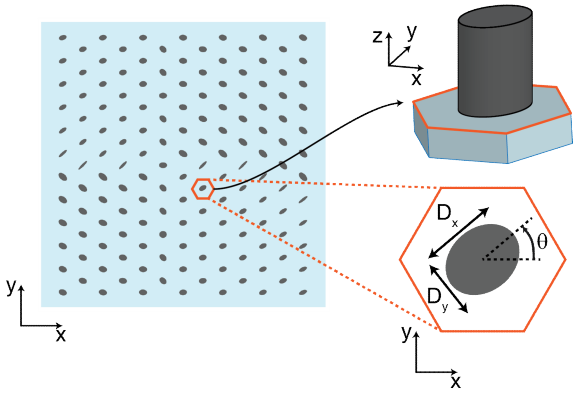
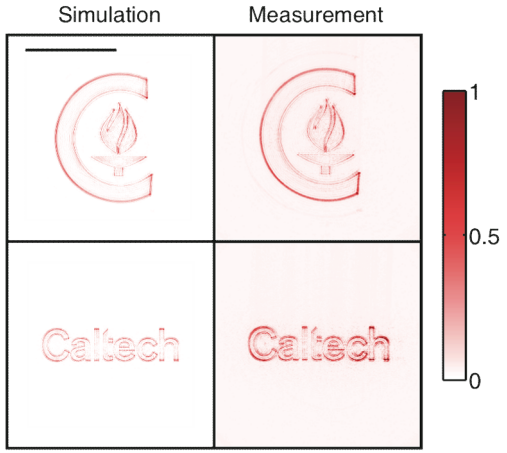


Arbitrary polarization/phase plates



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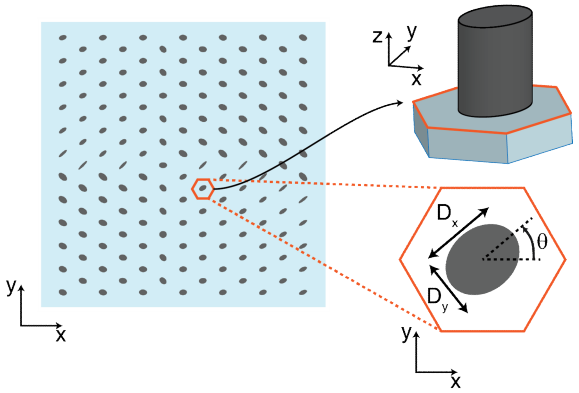
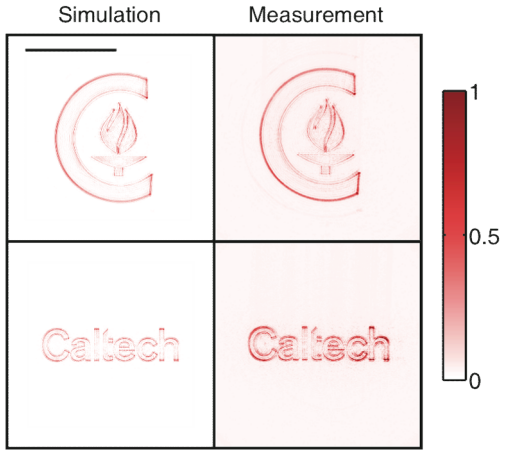
Metasurfaces for complete phase and polarization control



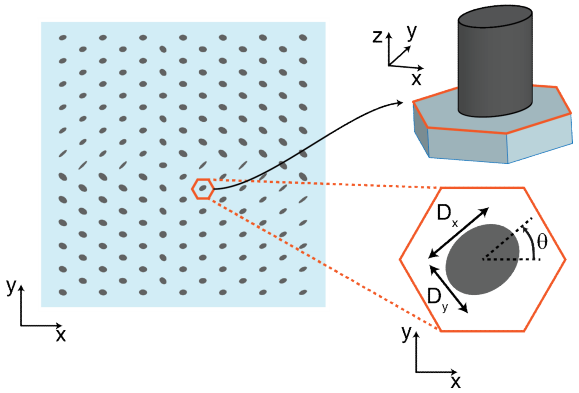
Arbitrary polarization/phase plates



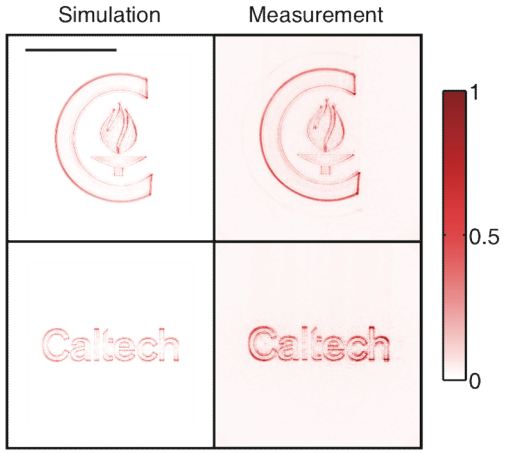
APPLICATIONS

Outline

Metasurfaces for complete phase and polarization control



Arbitrary polarization/phase plates

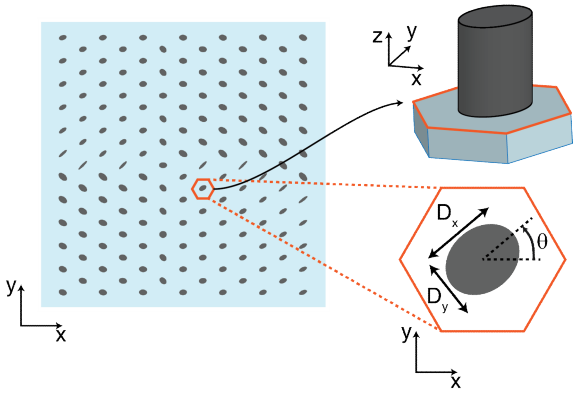


APPLICATIONS

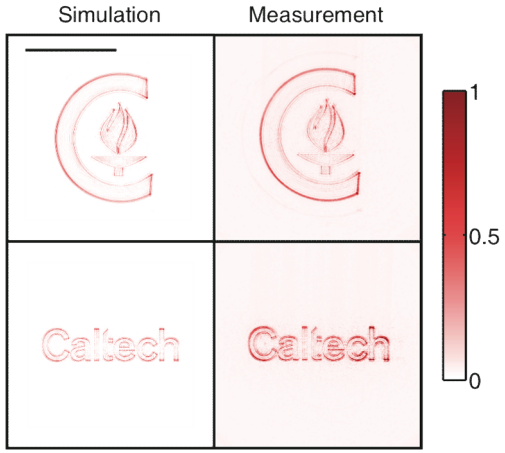
Microscopy

Outline

Metasurfaces for complete phase and polarization control



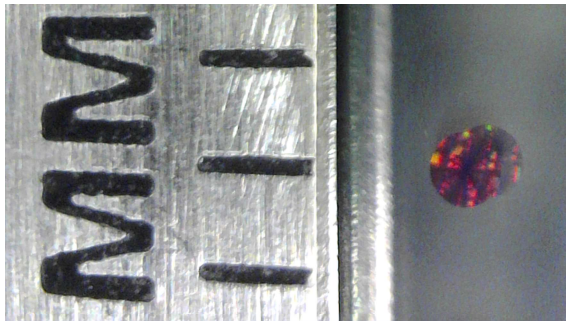
Arbitrary polarization/phase plates



APPLICATIONS

Microscopy

Ultra-Compact Camera Lenses



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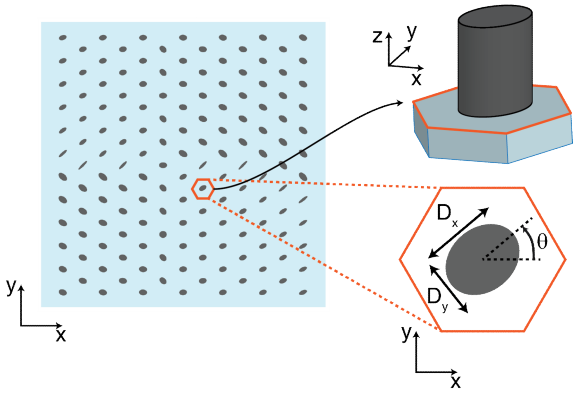
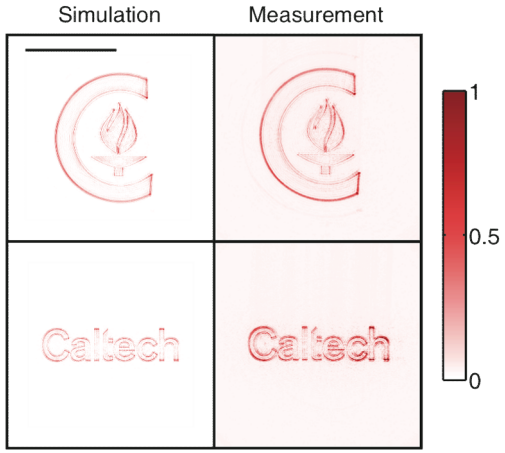
Metasurfaces for complete phase and polarization control

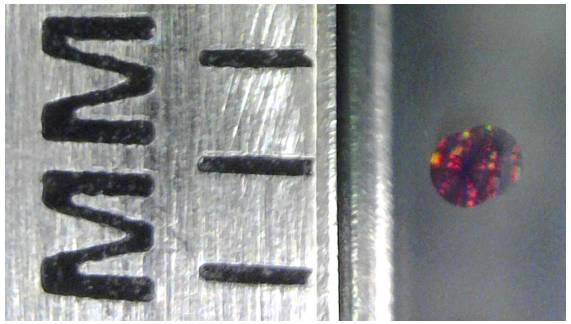


Arbitrary polarization/phase plates



APPLICATIONS

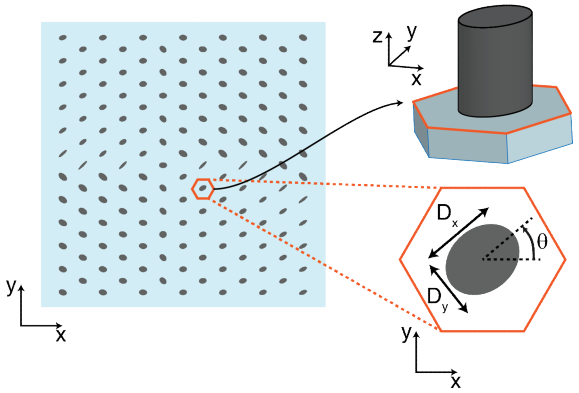
Microscopy Ultra-Compact Camera Lenses Retroreflector



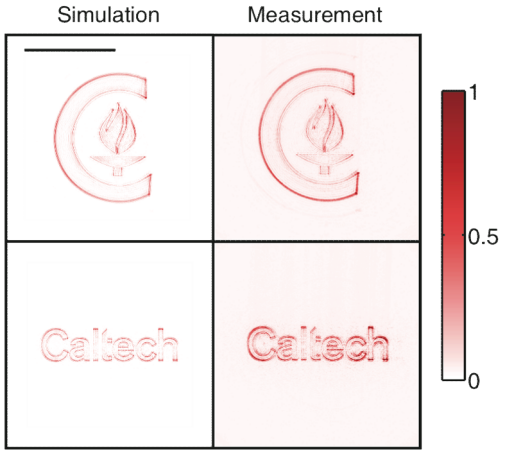
Caltech

Outline

Metasurfaces for complete phase and polarization control

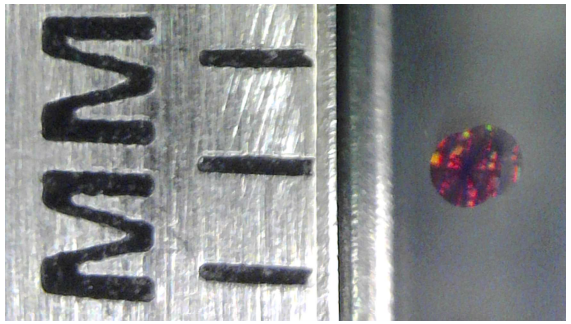


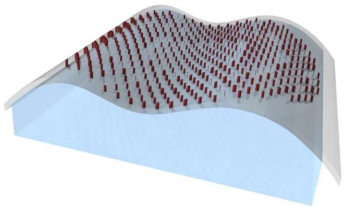
Arbitrary polarization/phase plates



APPLICATIONS

Microscopy Ultra-Compact Camera Lenses Retroreflector Conformal Optics

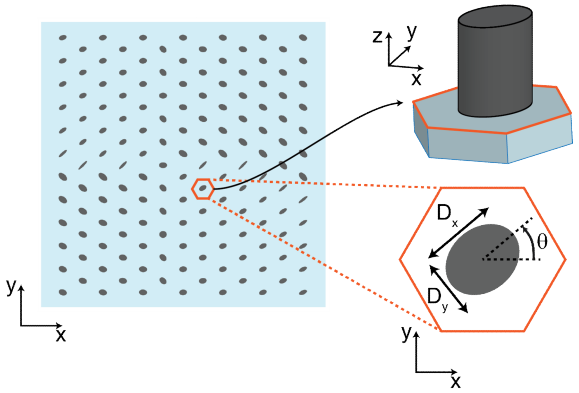




Caltech

Outline

Metasurfaces for complete phase and polarization control



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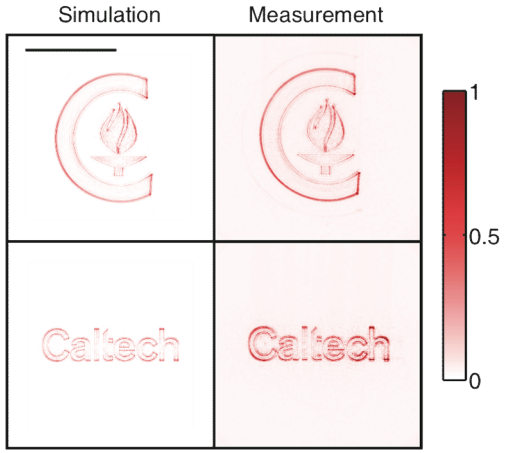
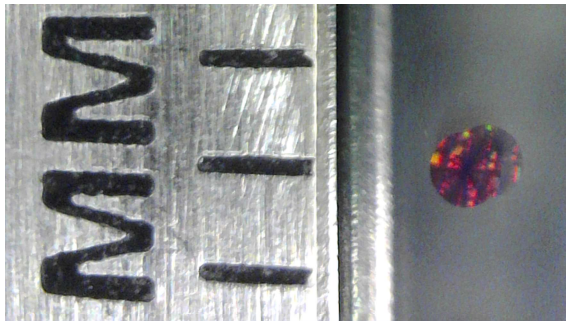
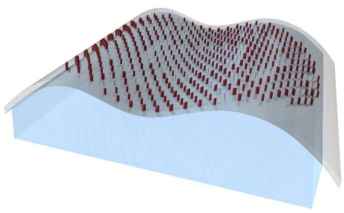
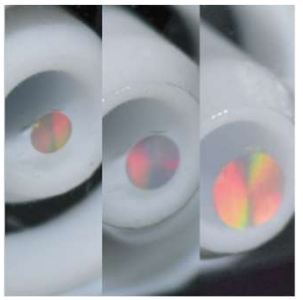


APPLICATIONS

Microscopy Ultra-Compact Camera Lenses Retroreflector Conformal Optics Tunable Lenses







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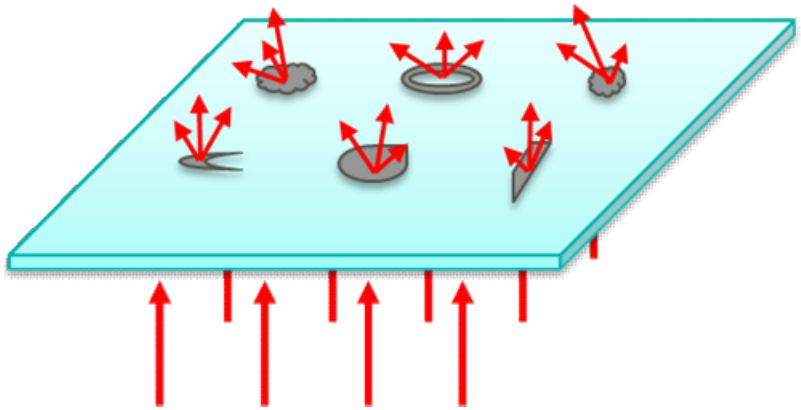
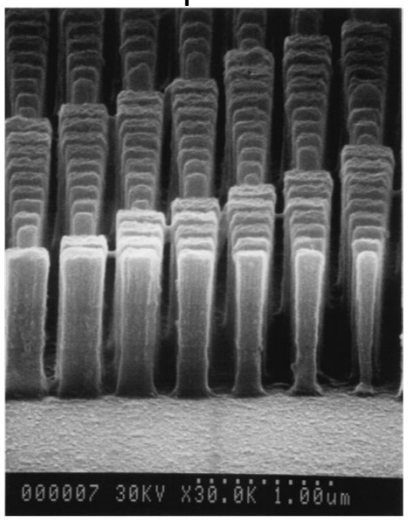
Optical Dielectric Metasurfaces



Optical metasurfaces are 2D planar arrays of subwavelength meta-atoms/scatterers

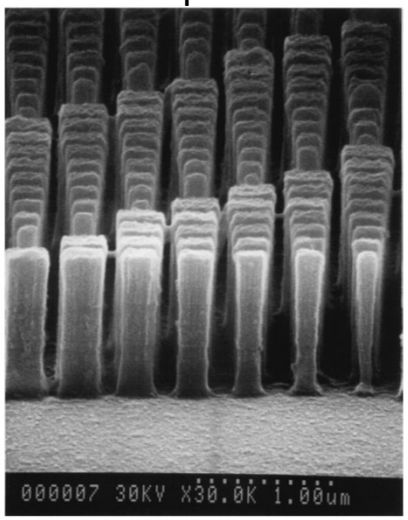
Provide spatially varying optical (polarization&phase) response by proper selection of the scatterers.

TiO2 nanoposts



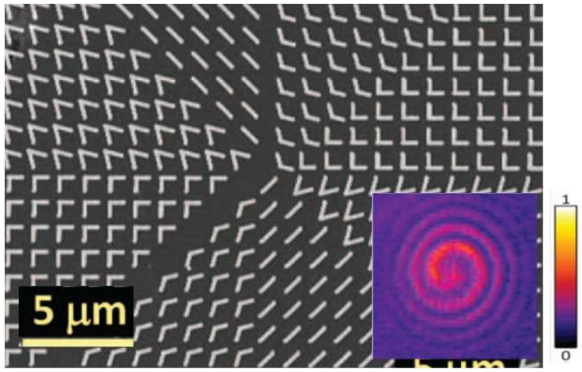
Lallane et al, J. Opt. Soc. Am. A, (1999)

TiO2 nanoposts



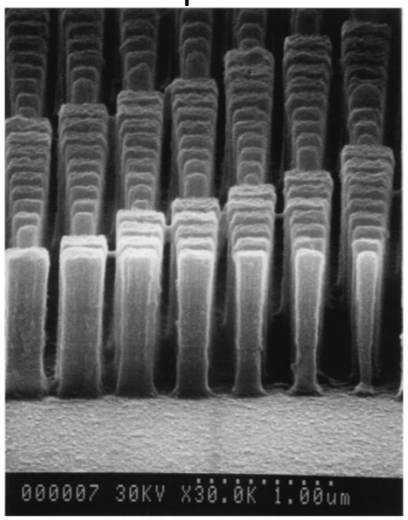
Lallane et al, J. Opt. Soc. Am. A, (1999)

Plasmonic antennas



N. Yu et al., Science(2011)

TiO2 nanoposts



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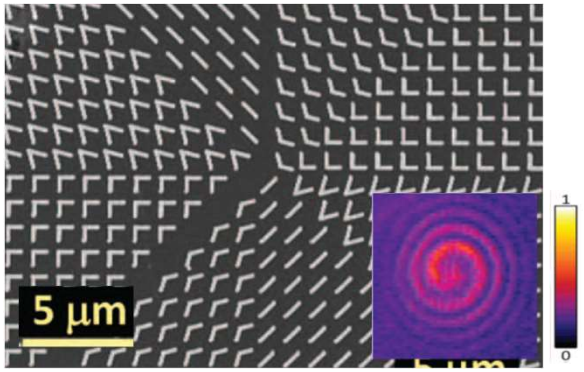
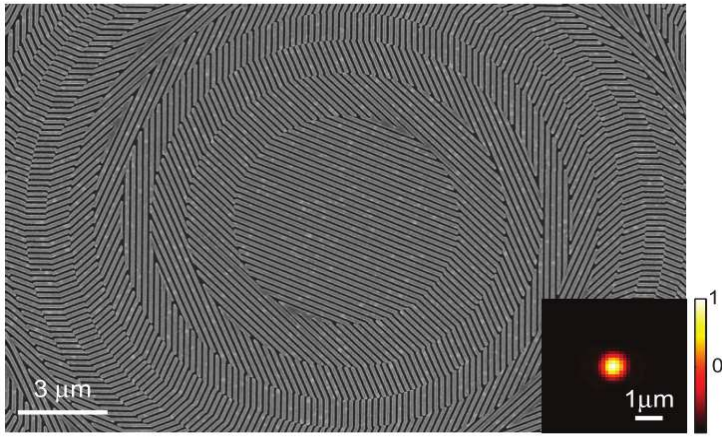


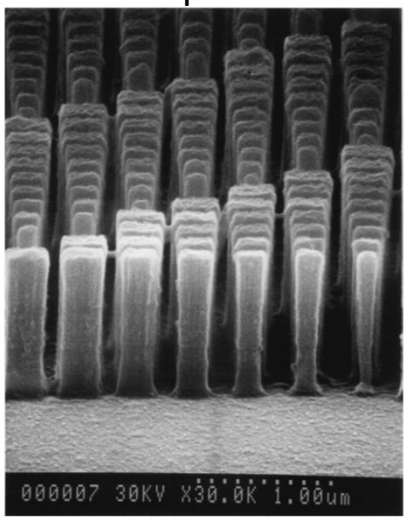
N. Yu et al., Science(2011)

Silicon bars



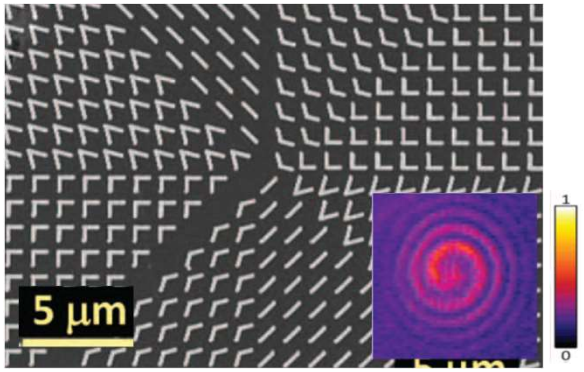
D. Lin *et al.*, Science (2014)

TiO2 nanoposts



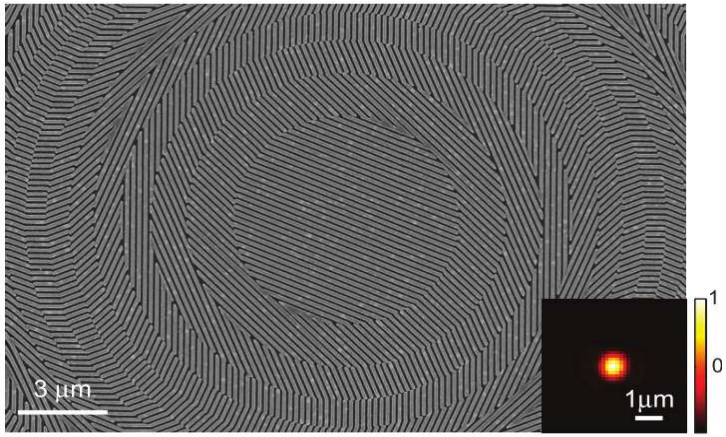
Lallane et al, J. Opt. Soc. Am. A, (1999)

Plasmonic antennas



N. Yu et al., Science(2011)

Silicon bars



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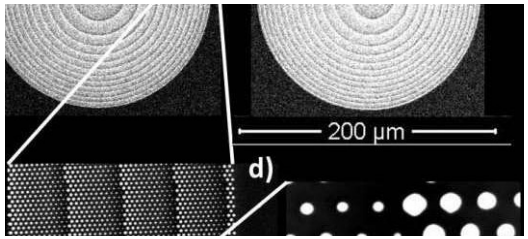
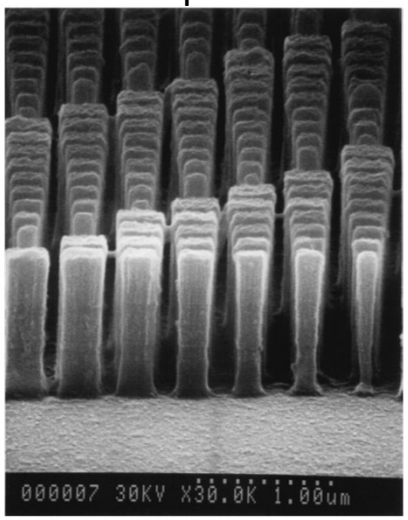
Si nanoposts



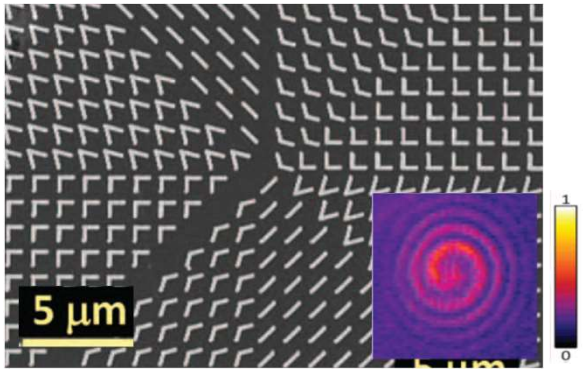
Vo et al, IEEE PTL, (2014)

TiO2 nanoposts



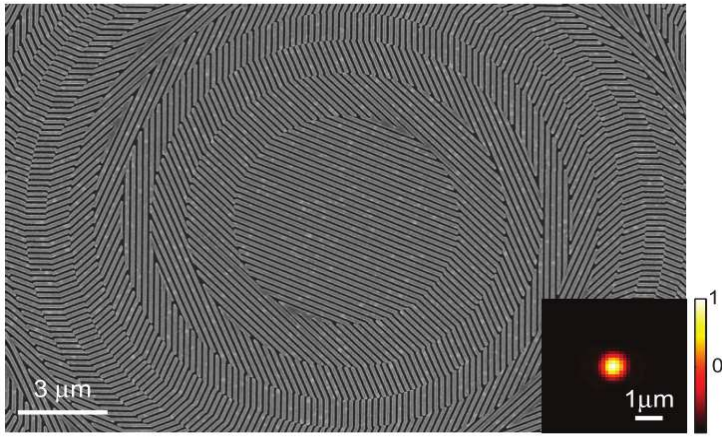
Lallane et al, J. Opt. Soc. Am. A, (1999)

Plasmonic antennas



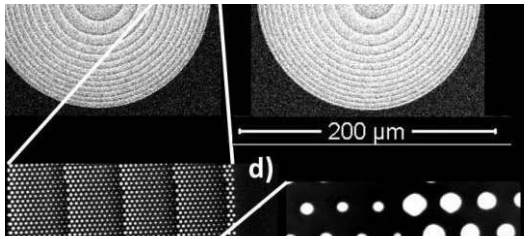
N. Yu et al., Science(2011)

Silicon bars



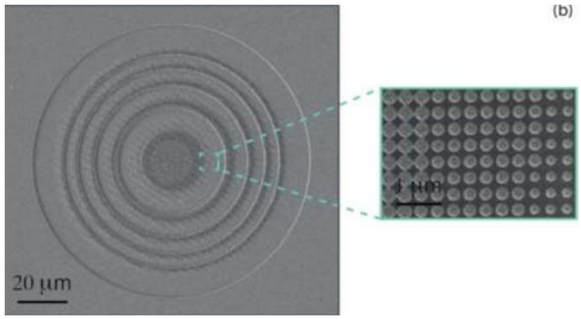
D. Lin *et al.*, Science (2014)

Si nanoposts



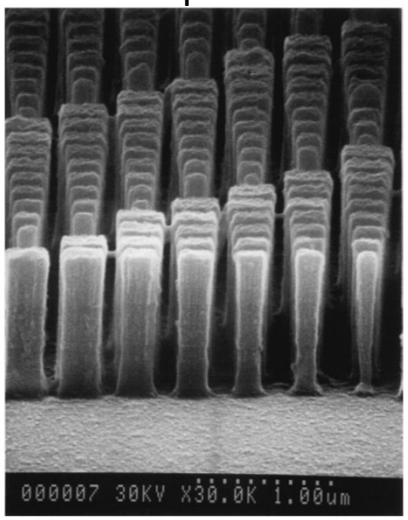
Vo et al, IEEE PTL, (2014)

SiN nanoposts



Zhan et al, ACS Photonics, (2015)

TiO2 nanoposts



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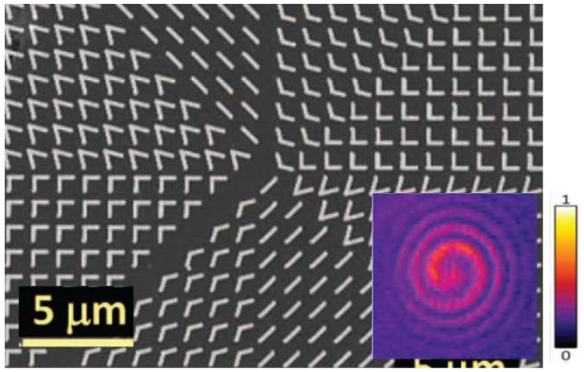

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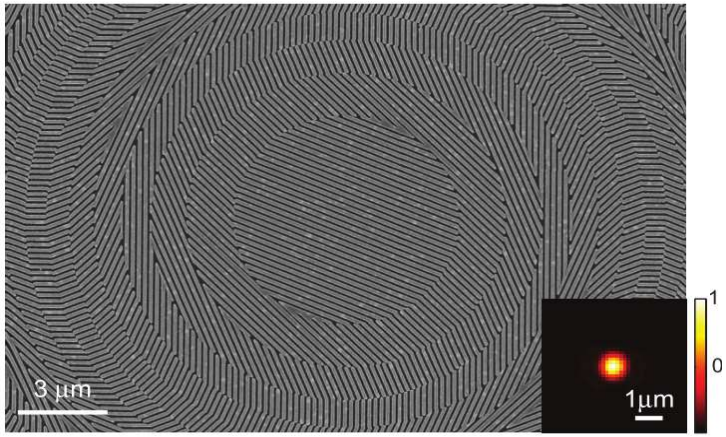

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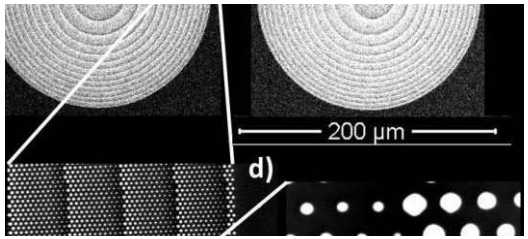

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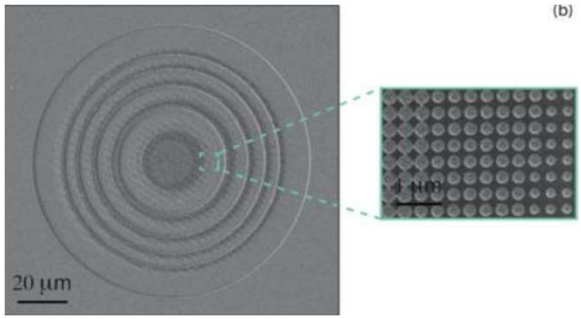

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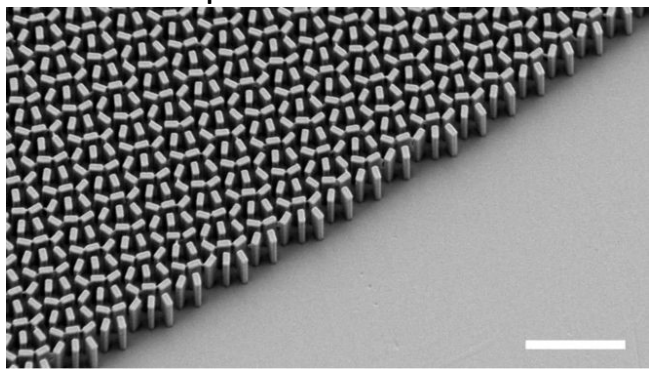
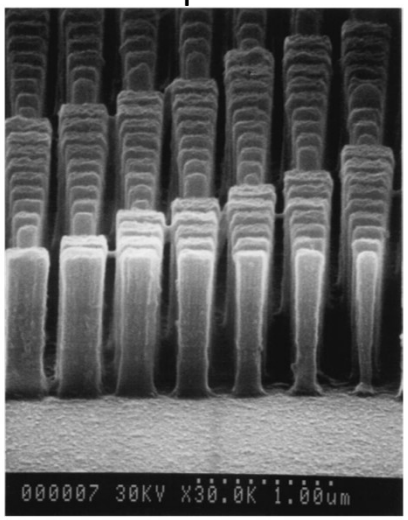


Khorasaninejad et al, Science (2016)

TiO2 nanoposts



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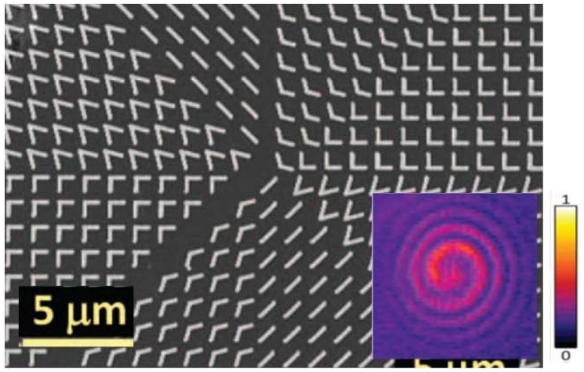

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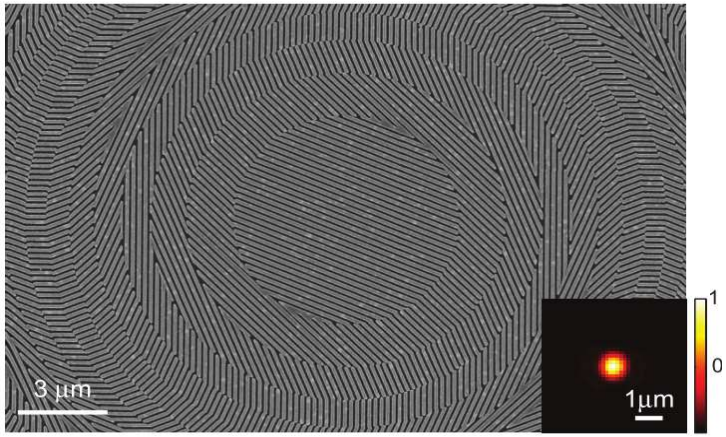

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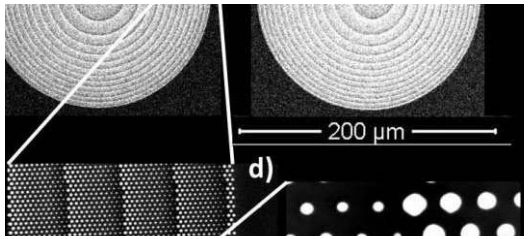

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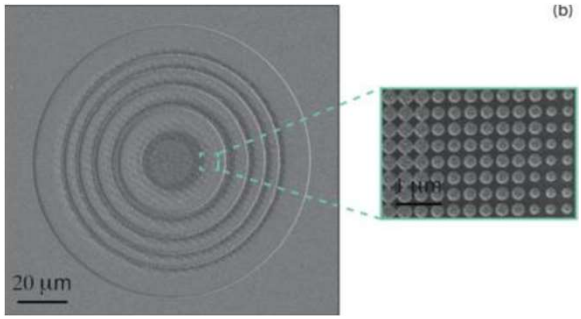

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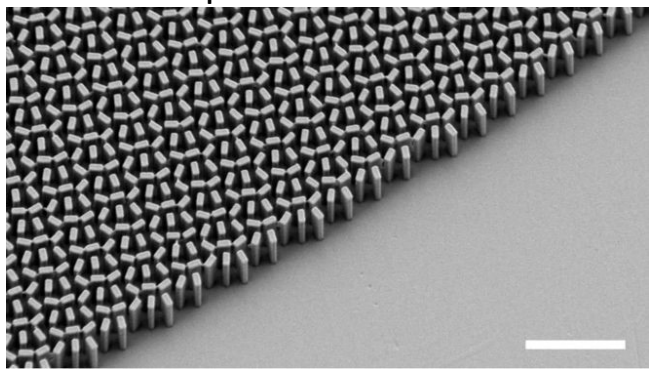
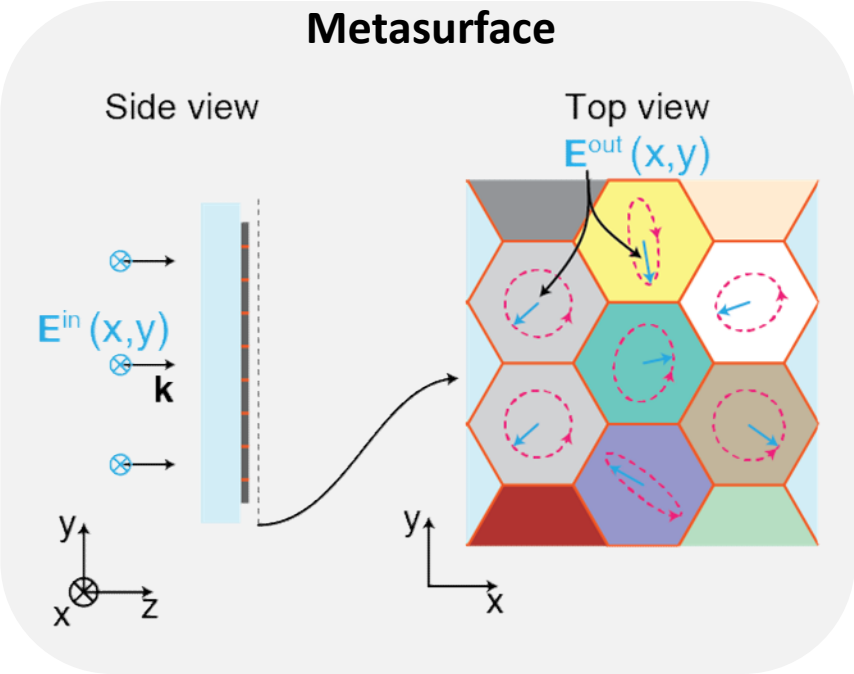


Khorasaninejad et al, Science (2016)

See review: Jahani and Jacob, Nature Nanotechnology 11, 23–36 (2016)

Complete phase and polarization control



A. Arbabi *et al.* ***Nature Nanotechnology,*** 10, 937–943 (2015)

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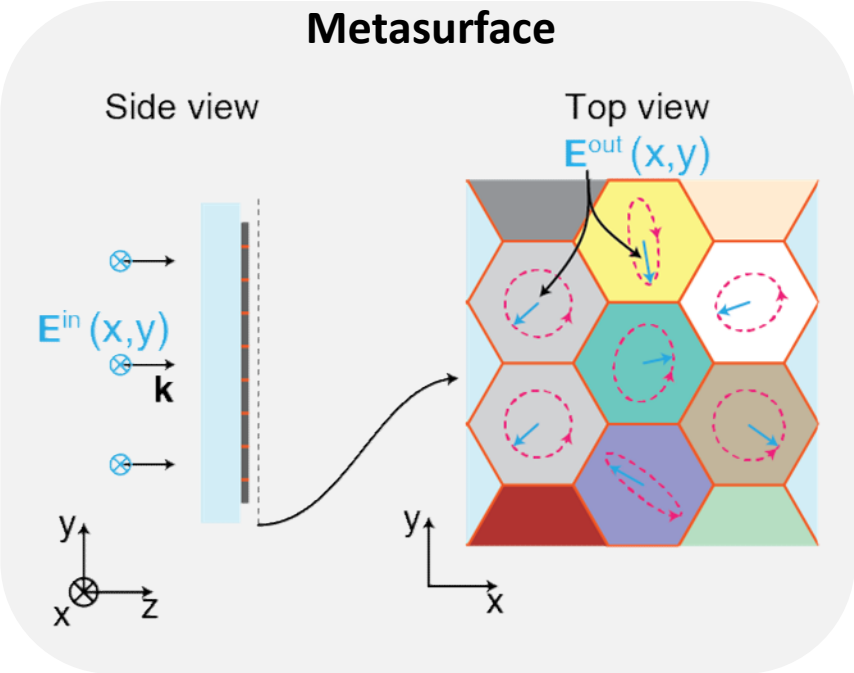

- Any desired output phase and polarization can be generated at each pixel
- High efficiency > 90%
- Subwavelength pixel size < $\lambda/2$

Caltech

A. Arbabi *et al.* ***Nature Nanotechnology,*** 10, 937–943 (2015)

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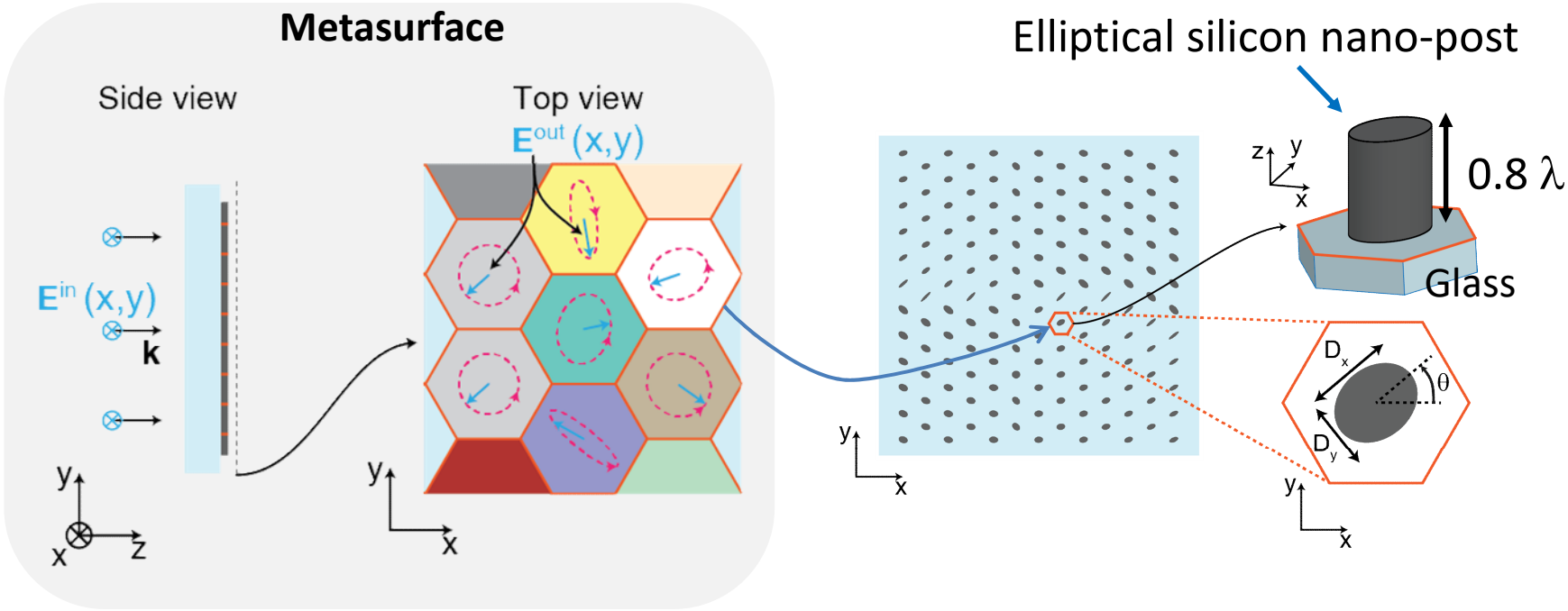

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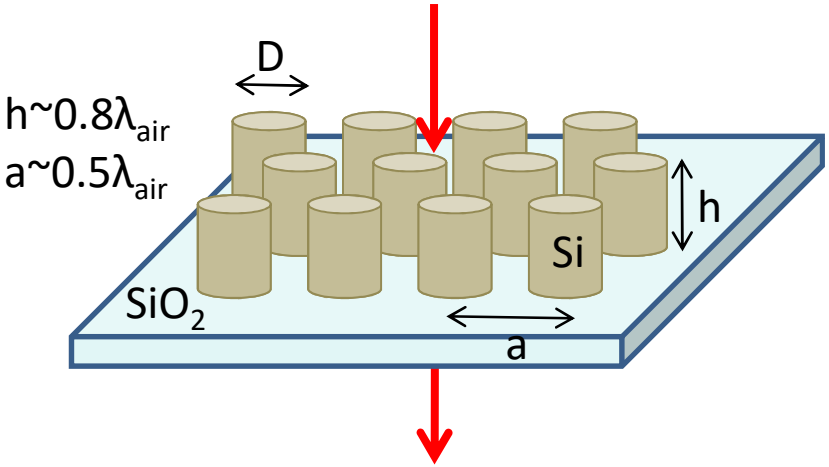
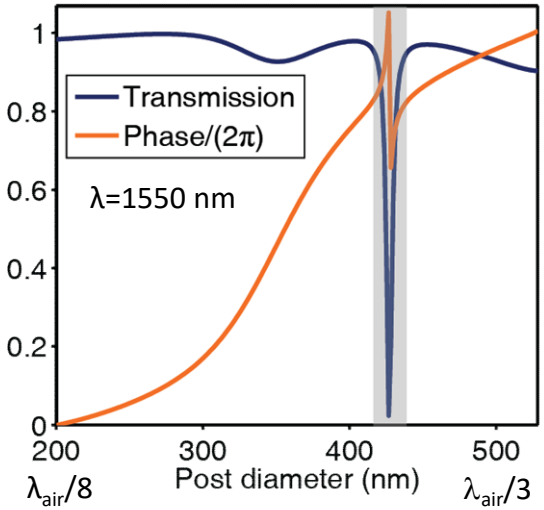
Caltech

A. Arbabi *et al.* ***Nature Nanotechnology,*** 10, 937–943 (2015)

Phase-only control

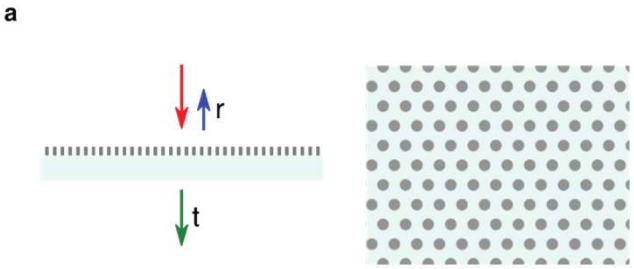




- Polarization insensitive
- Full phase control with high transmission
- Freedom to design any element to control optical wavefront

Fattal et al, Integrated Photonics Research, Silicon and Nanophotonics, ITuD2, 2011
Vo et al, IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 26, NO. 13, JULY 1, 2014

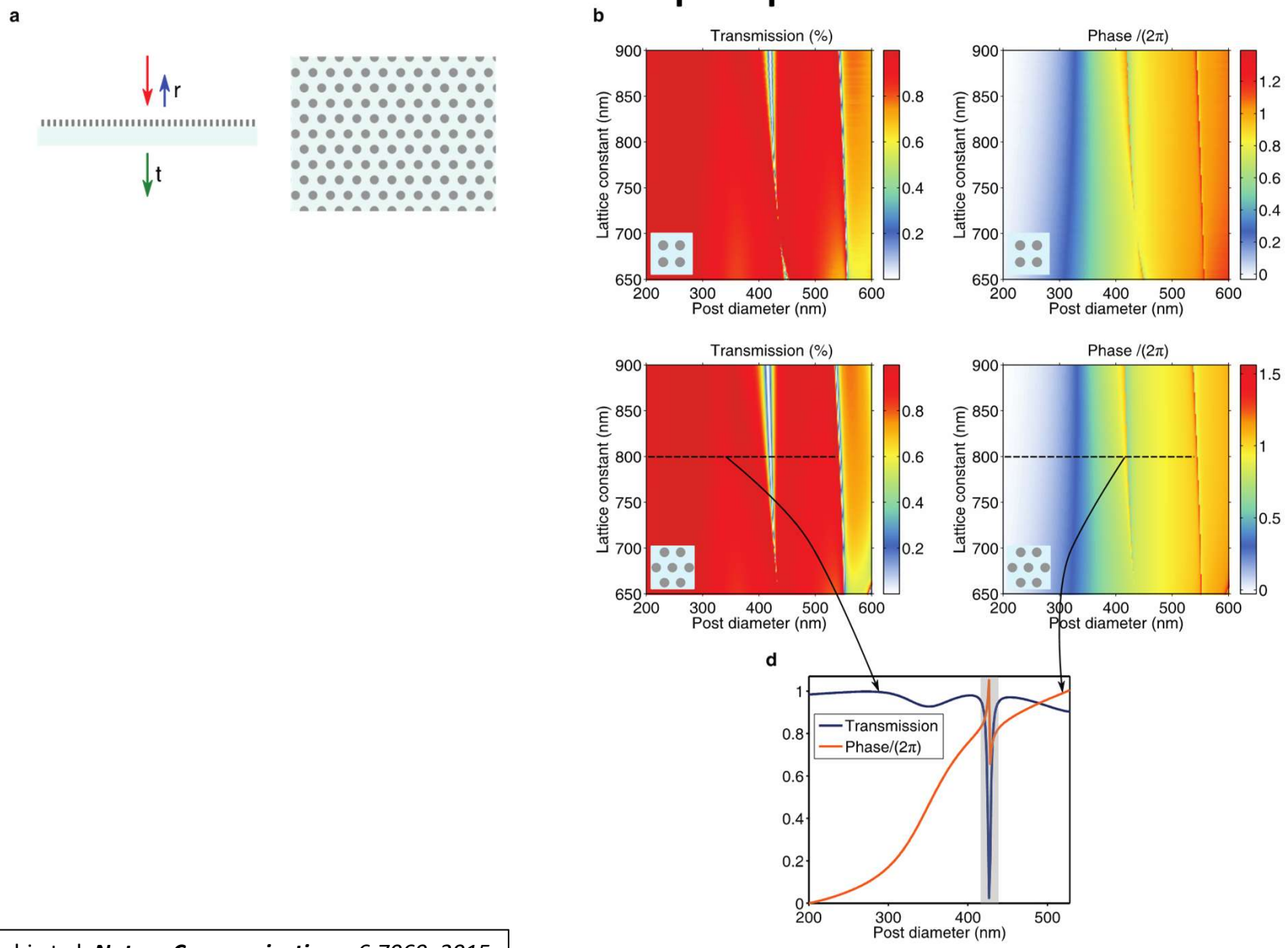
Transmission properties



Arbabi et al, ***Nature Communications**, 6:7069, 2015*

Caltech

Transmission properties



Arbabi et al, ***Nature Communications***, *6:7069, 2015*

Caltech

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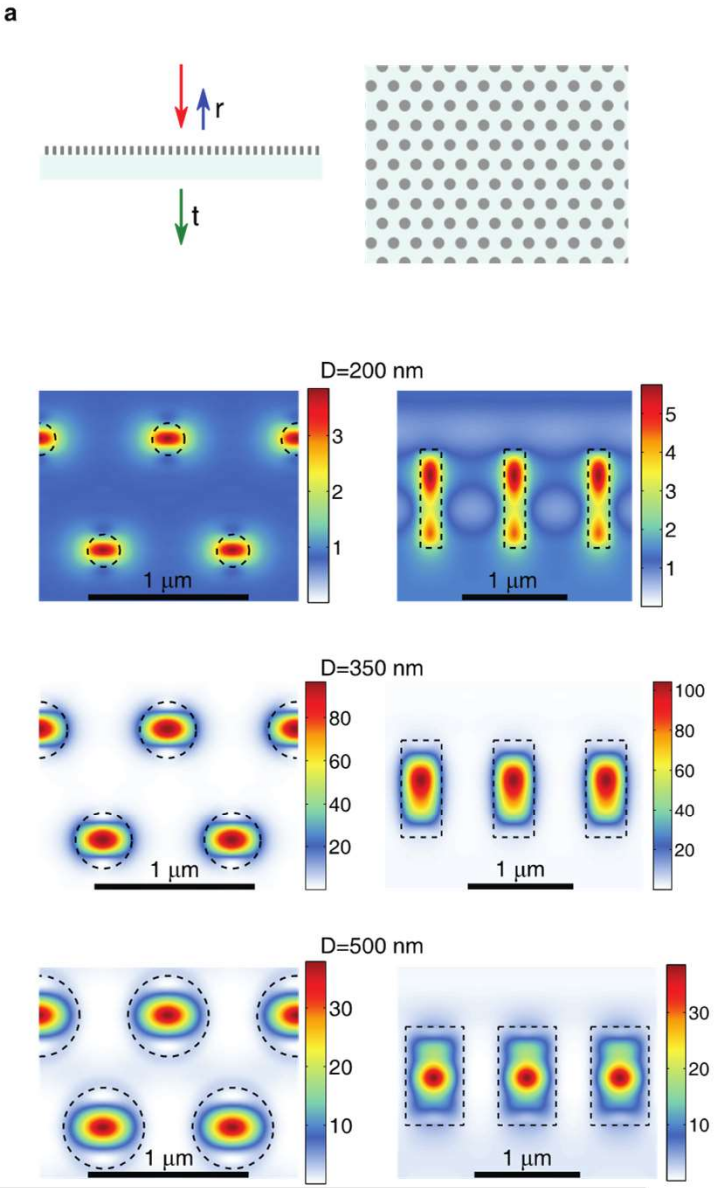
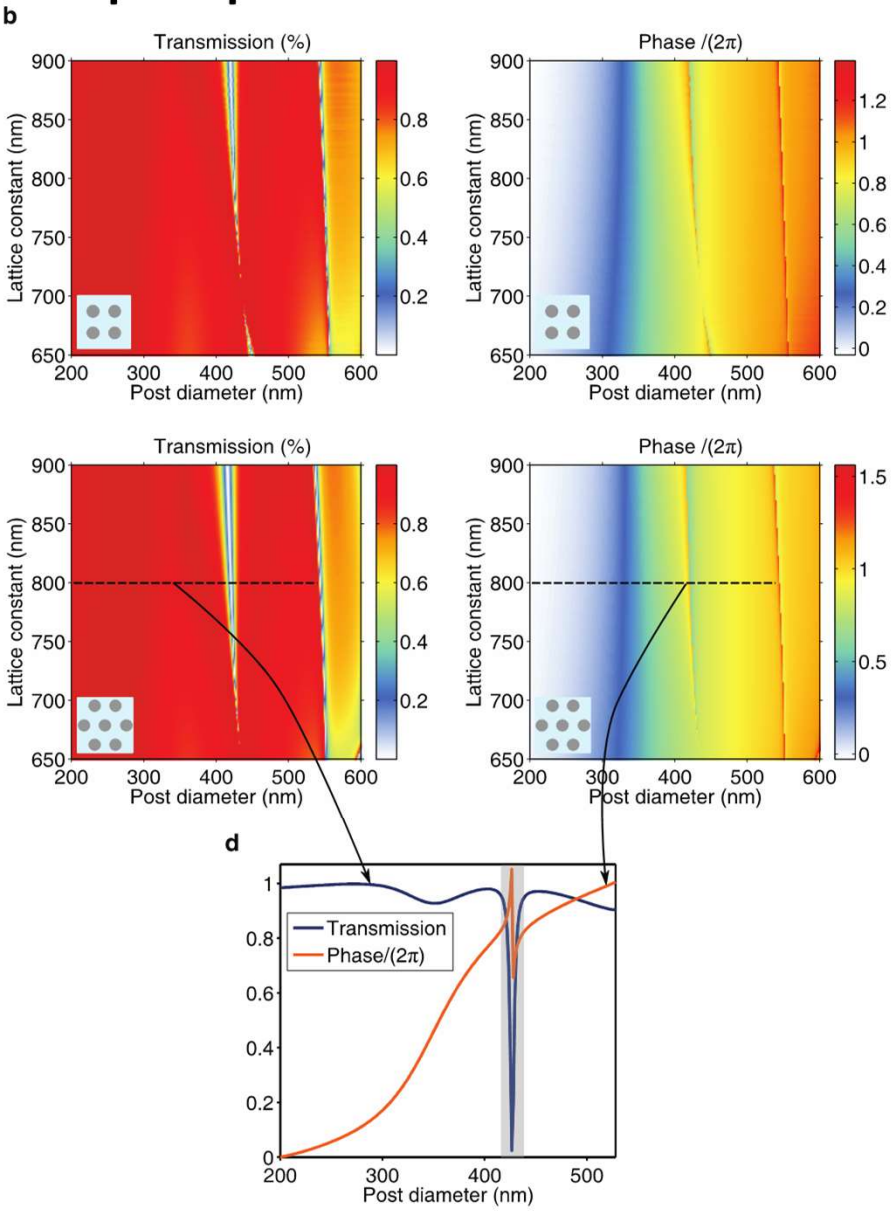
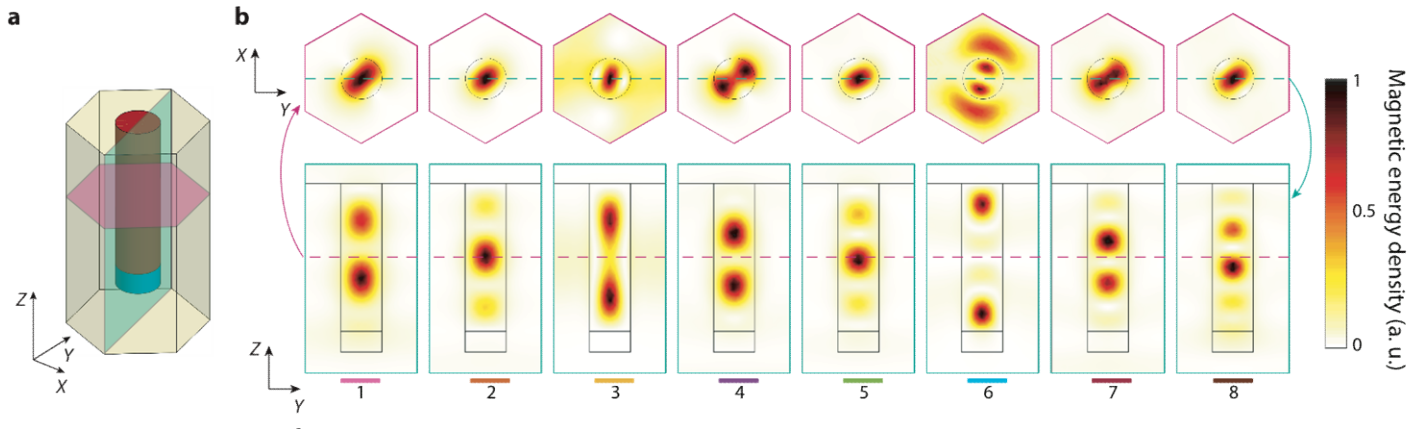




Arbabi et al, ***Nature Communications***, *6:7069, 2015*

Nano-posts as multi-mode antennas



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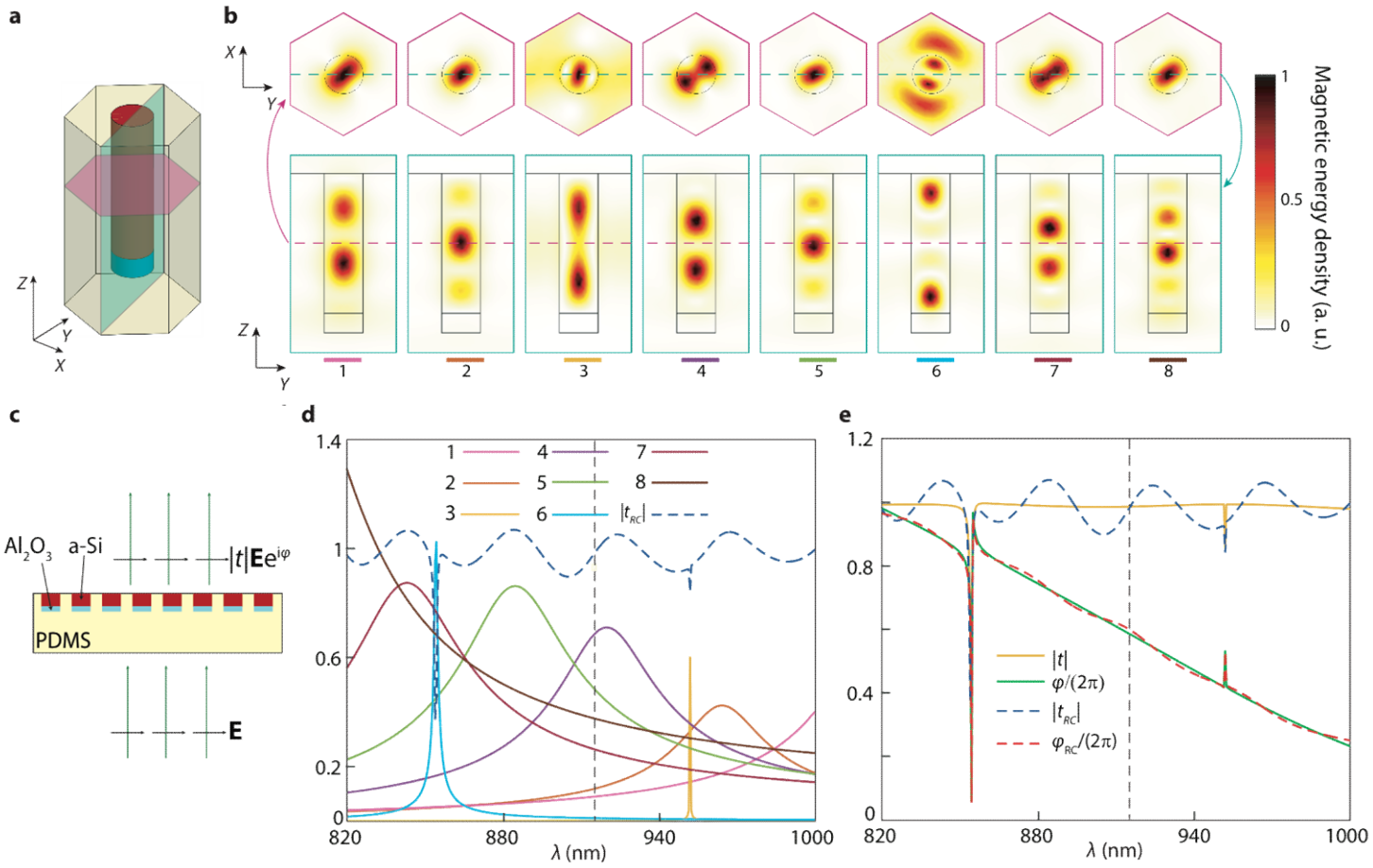
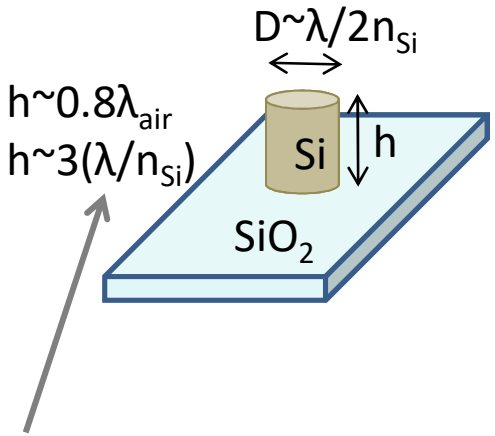
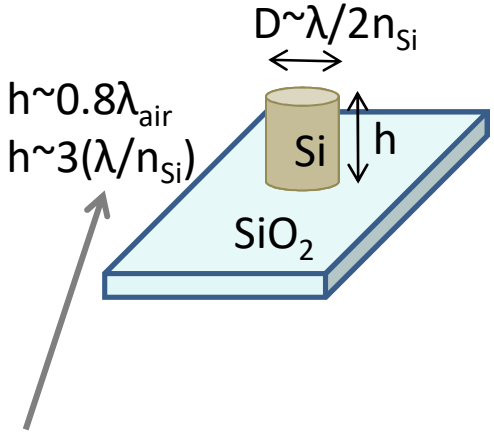


Properties of high index nano-posts



Multi-mode post ensures a rich set of scattering properties that can be engineered

Properties of high index nano-posts



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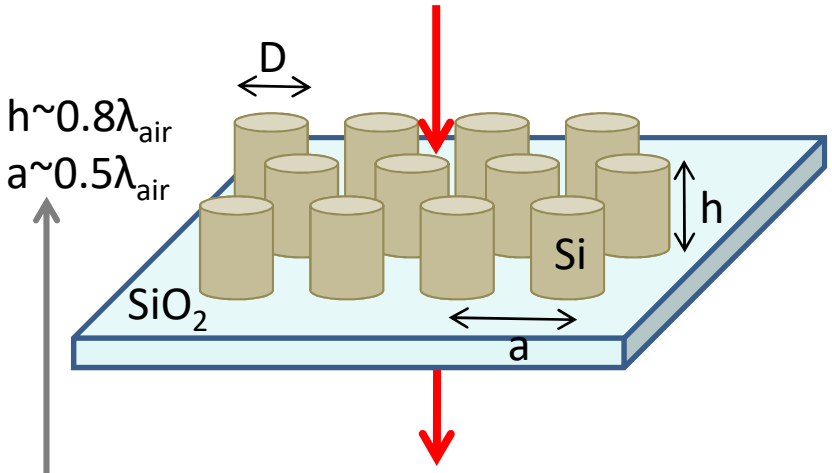
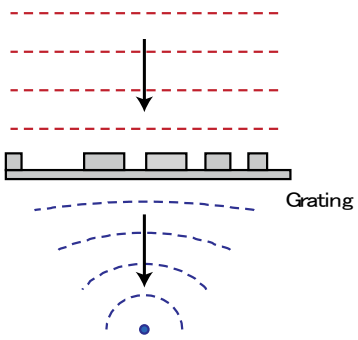


Sub-wavelength lattice ensures that the final structure diffracts only in 0th order

Polarization Insensitive Lens

- Spherical phase profile

$$\phi(x,y) = \phi_0 + \frac{2\pi}{\lambda}\left(f - \sqrt{x^2+y^2+f^2}\right)$$



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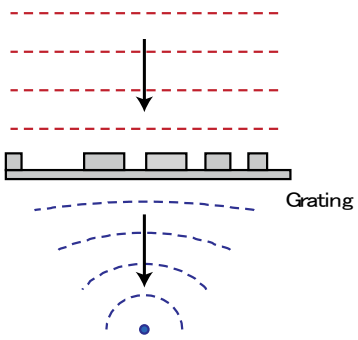

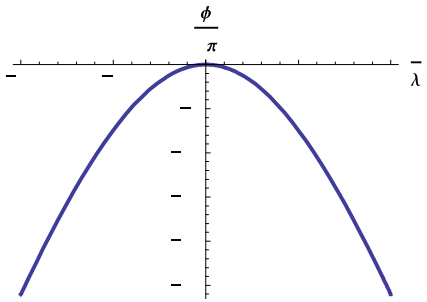

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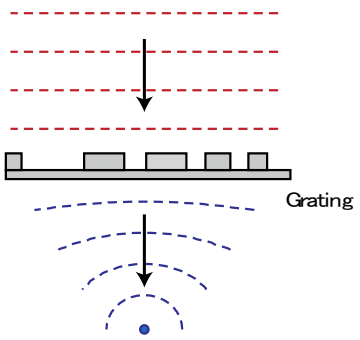

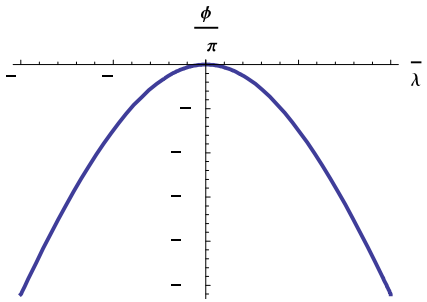

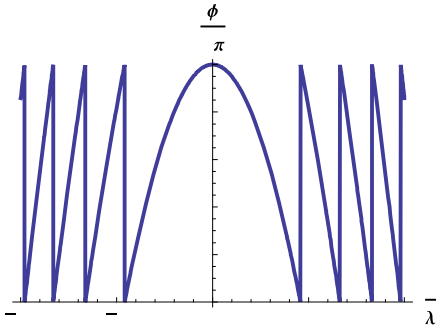

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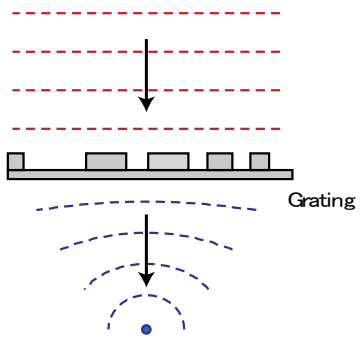

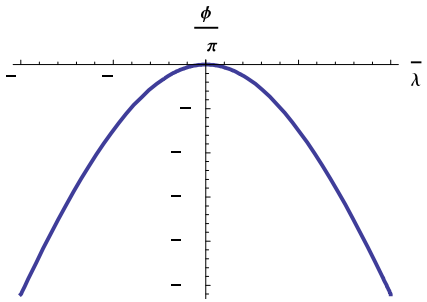

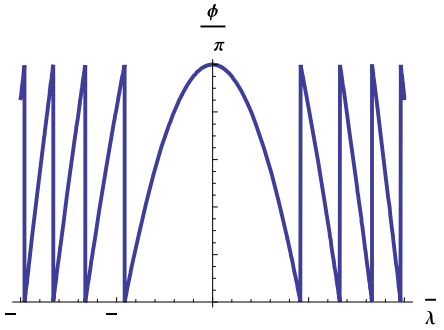

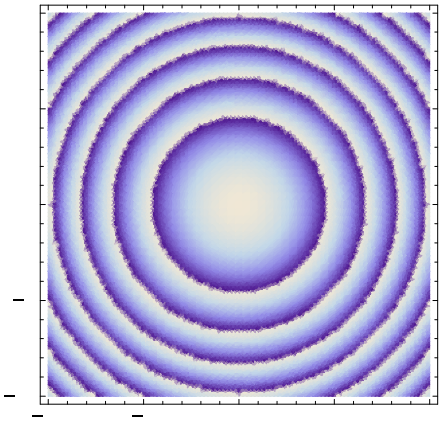

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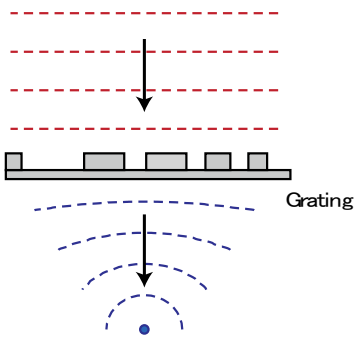

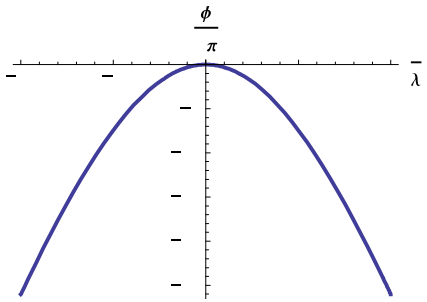

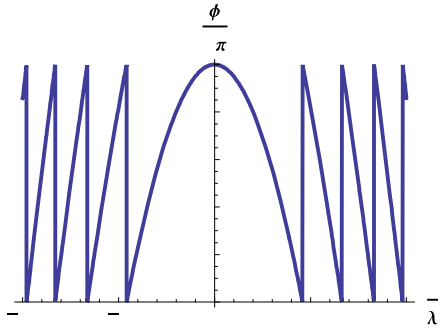

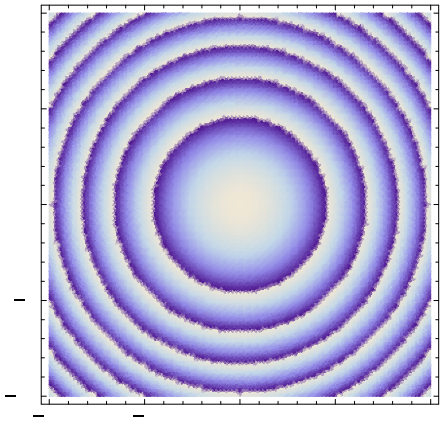

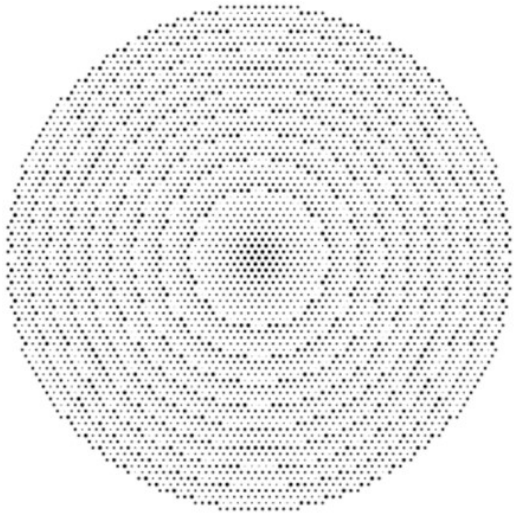

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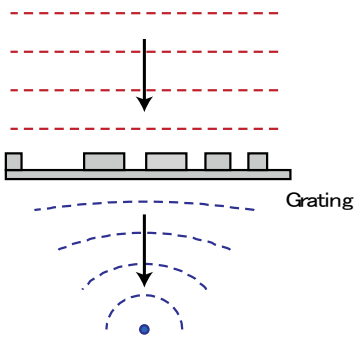
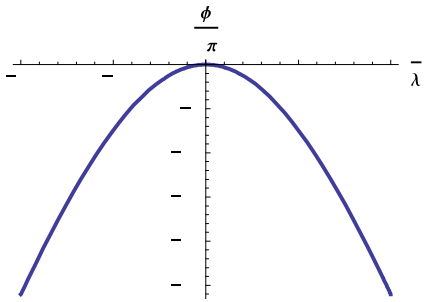
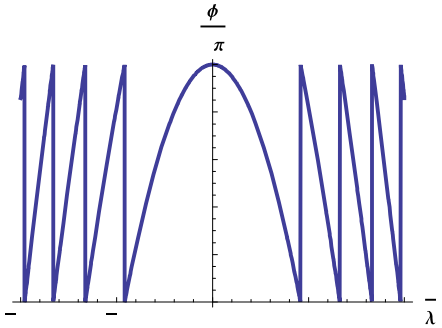
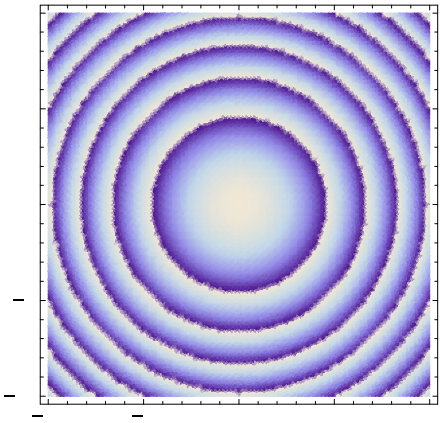
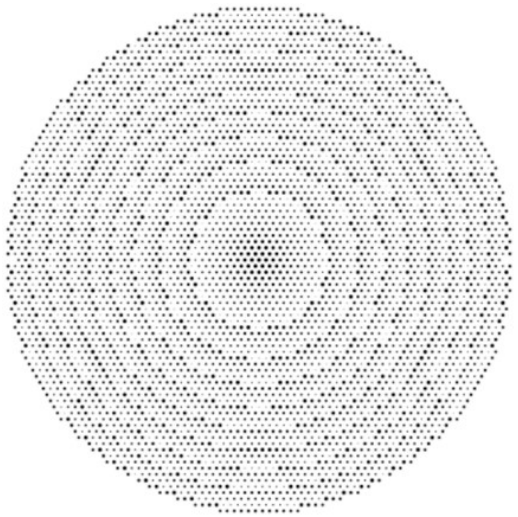
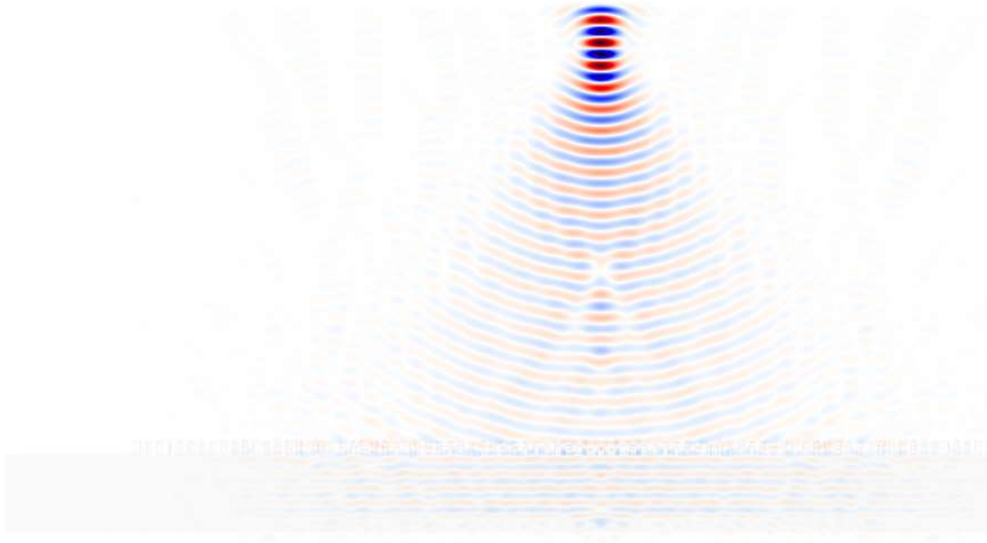










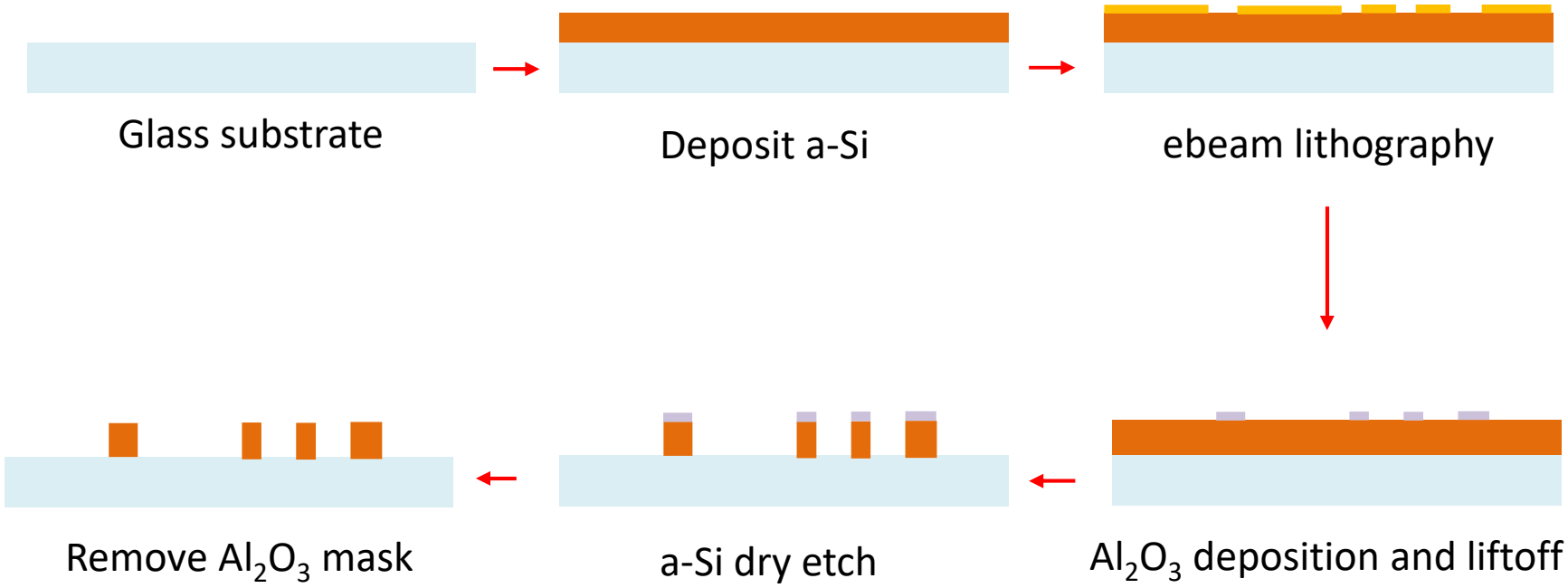


Air

Si posts

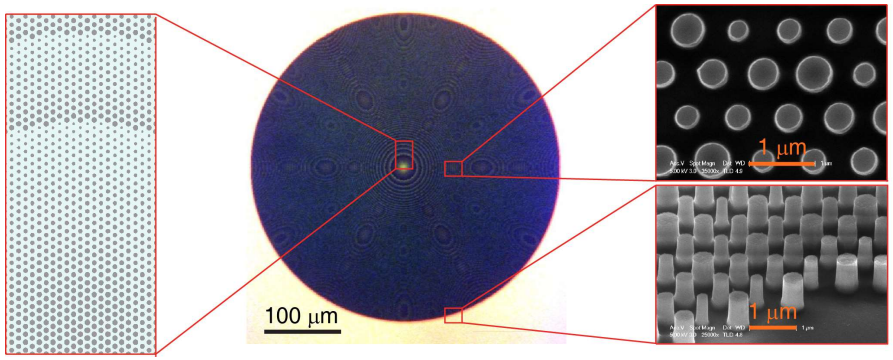
SiO_2

Fabrication Process

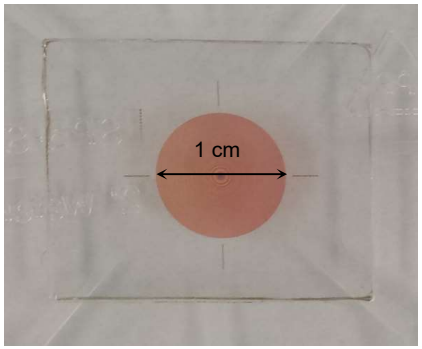


Polarization insensitive lenses

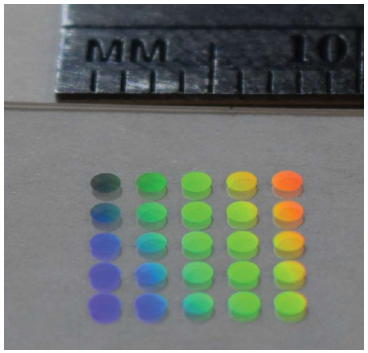
For 1550nm



For 590nm

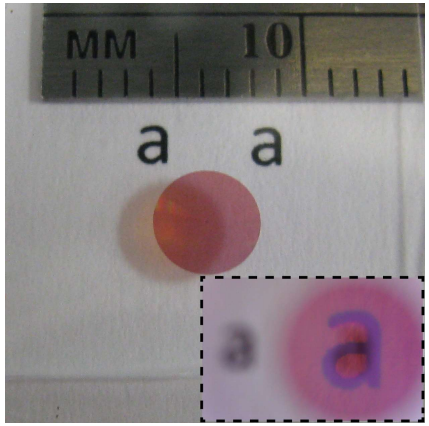


For 4800nm



Features:

- Focal length as small tens of microns
- Visible & infrared (590nm-4800nm) demonstrated
- Diffraction limited with NA up to 0.9
- Up to 90% efficient



- Demo Lens: D=4mm, f=7mm
- 360nm high posts, 320nm lattice period, design λ=650nm

A. Arbabi *et al.* ***Nature Communication*** 6, 7069 (2015)
A. Arbabi *et al.*, ***Optics Express*** *Vol. 23, Issue 26, pp. 33310-33317 (2015)*

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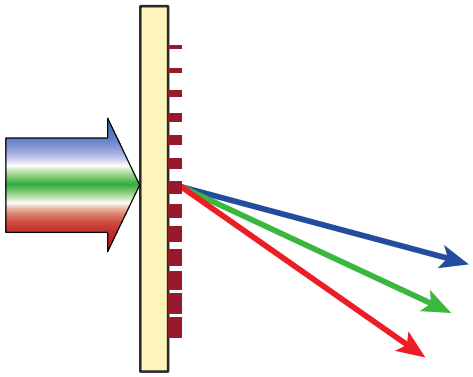
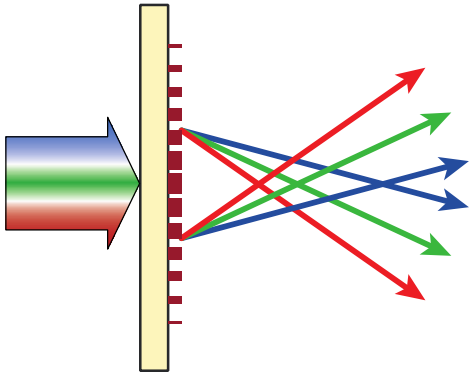
Dispersion of metasurface lenses

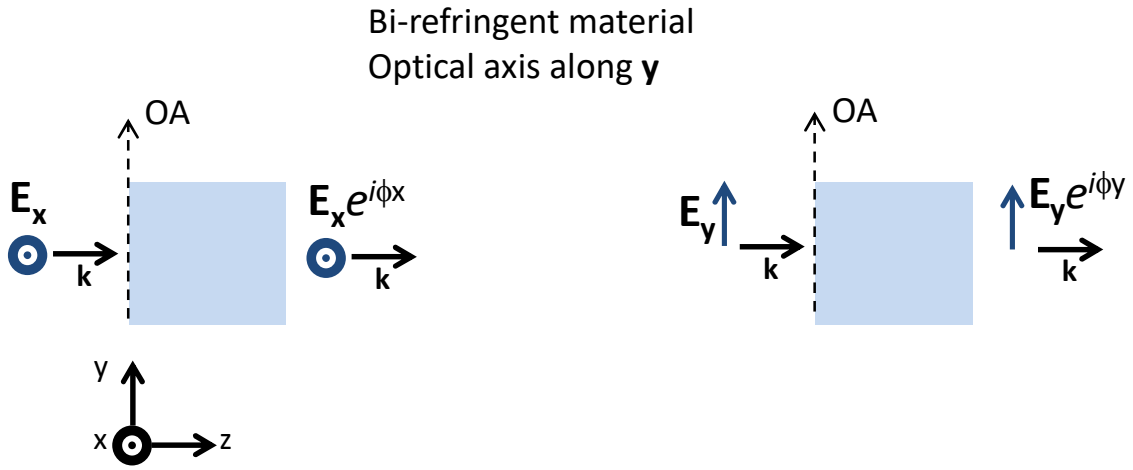


$d\theta/d\lambda = \tan(\theta)/\lambda$



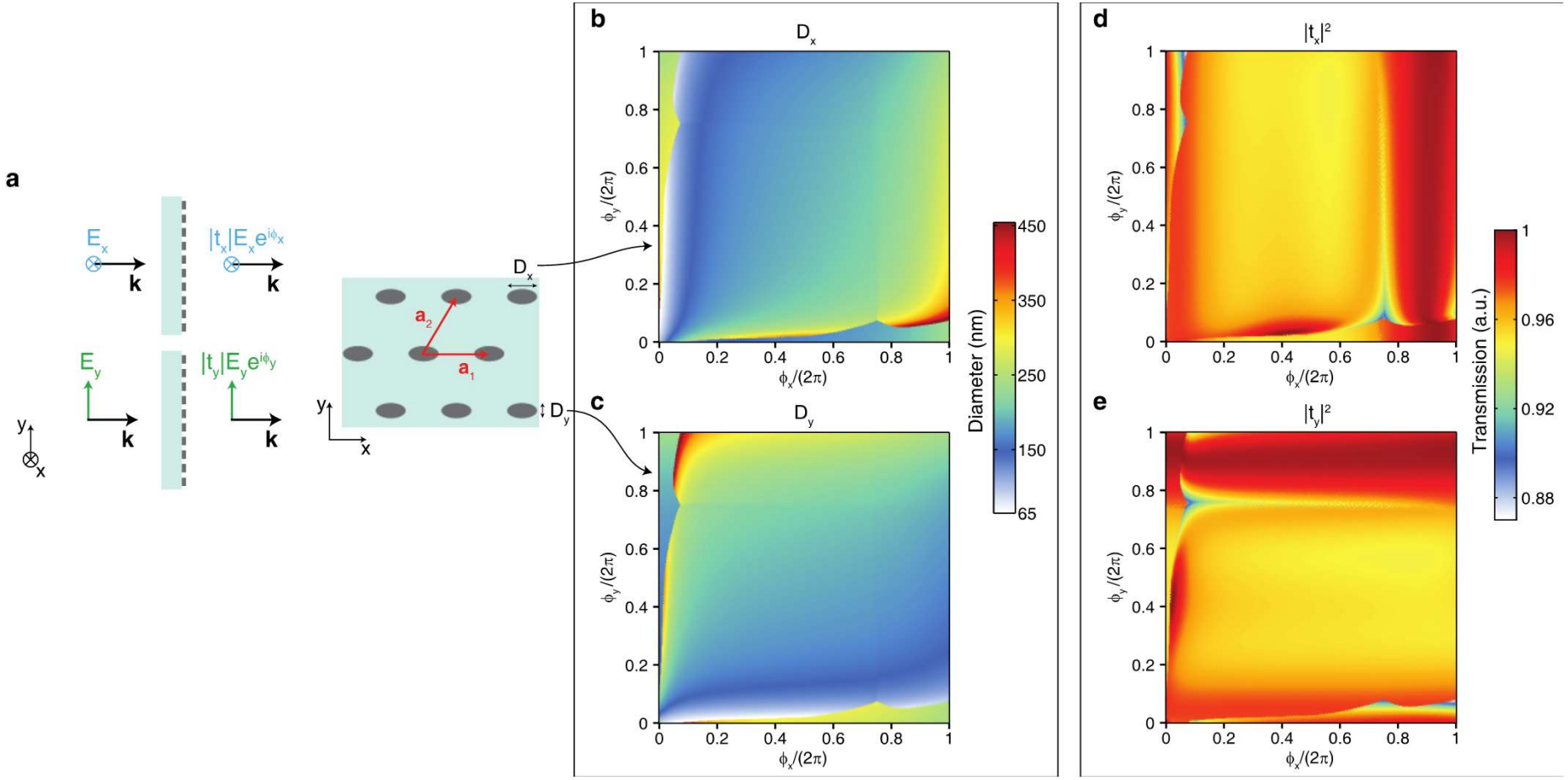
$df/d\lambda = -f/\lambda$

Complete polarization and phase control
- ***must control the birefringence*** -

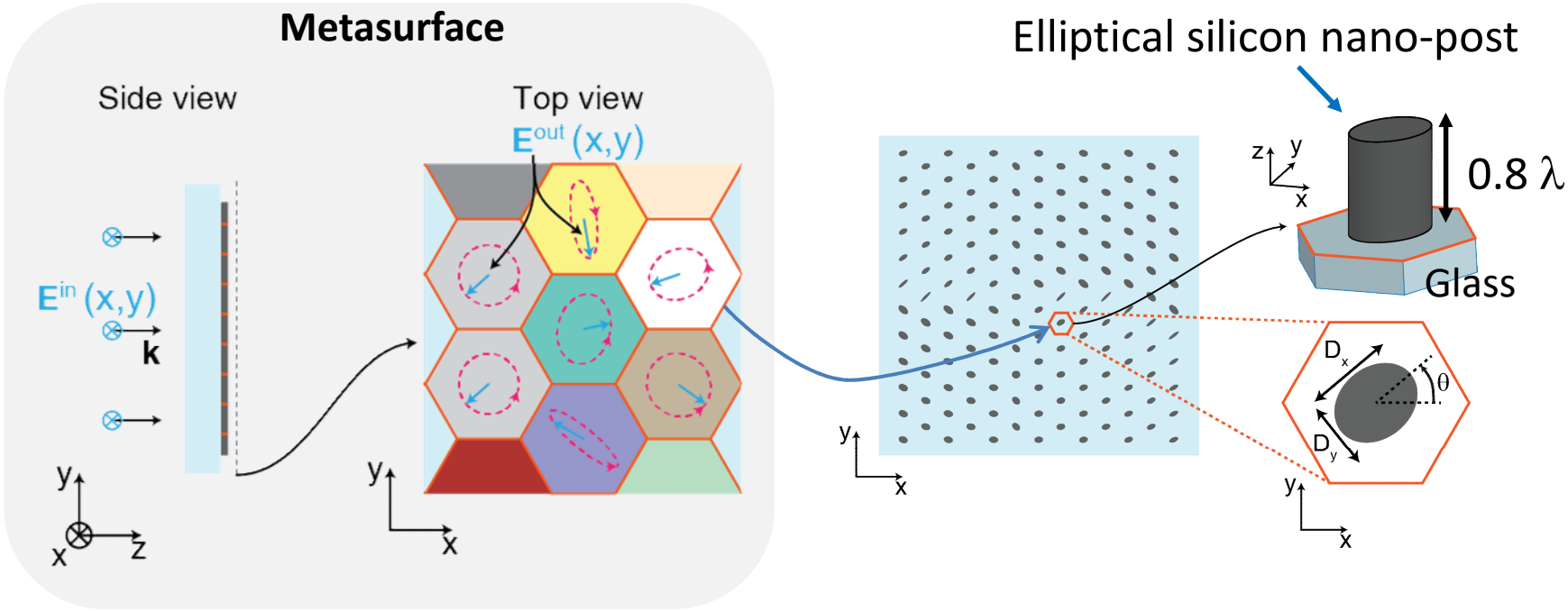


- Complete control means:
  - Ability to adjust both ϕ_x and ϕ_y and between 0 and 2π
  - Ability to rotate the optical axis

Birefringence control with elliptical posts



Complete phase and polarization control



- Any desired output phase and polarization can be generated at each pixel
- High efficiency > 90%
- Subwavelength pixel size < λ/2

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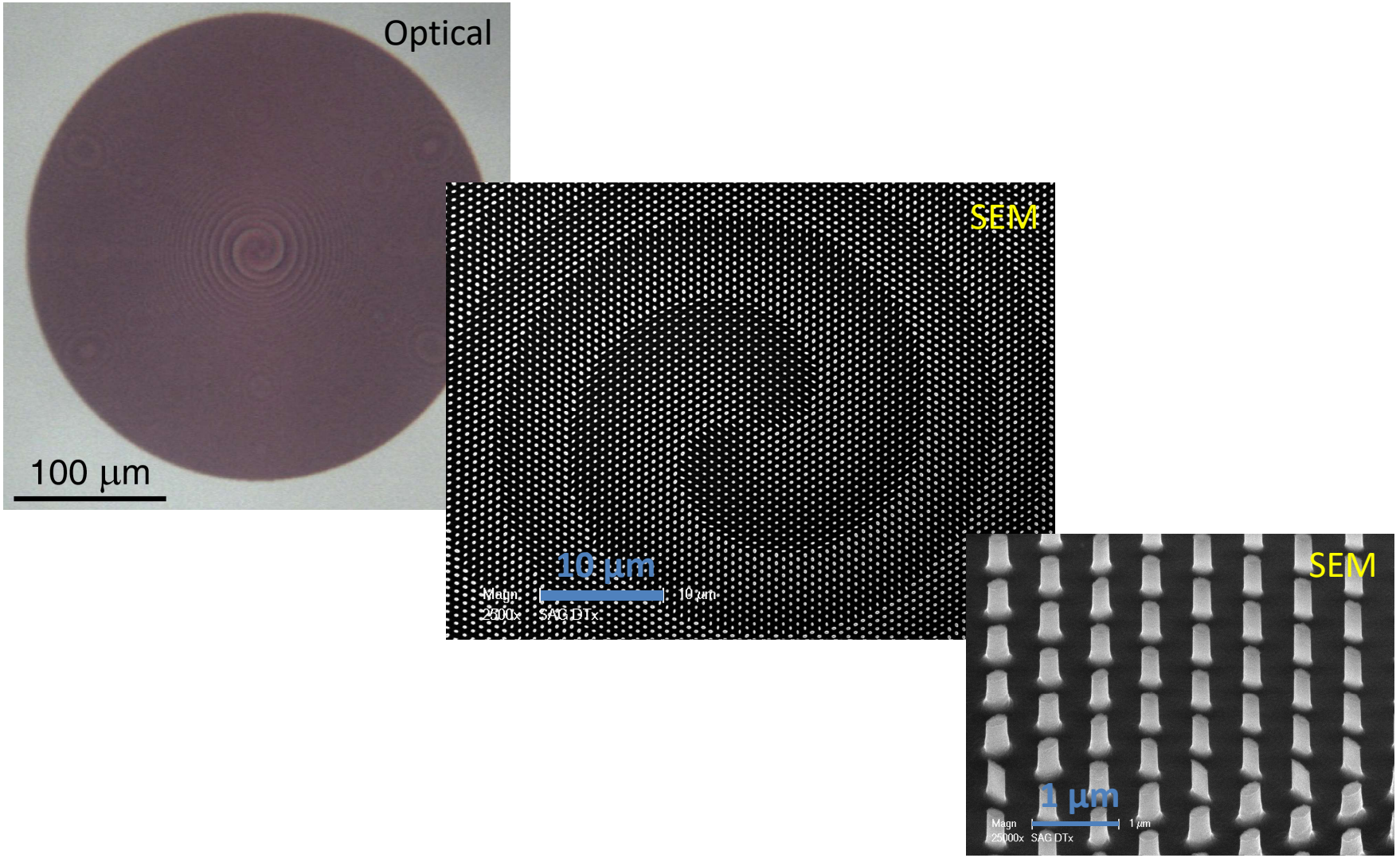
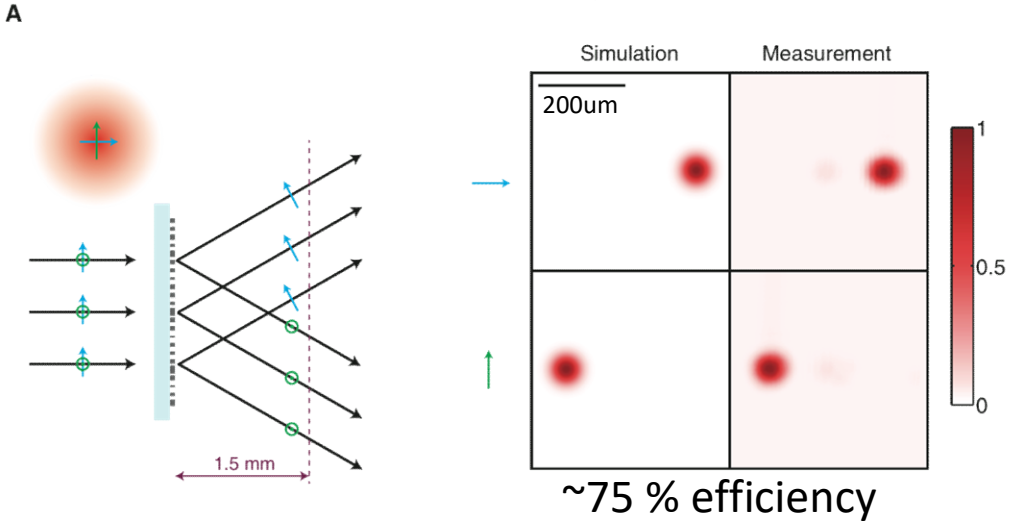
A. Arbabi *et al.* ***Nature Nanotechnology,*** 10, 937–943 (2015)

Devices with Phase and Polarization Control

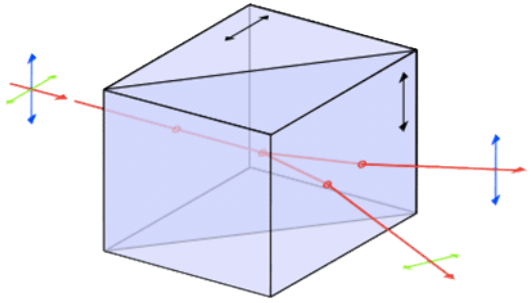


Polarizing beam splitter/focuser



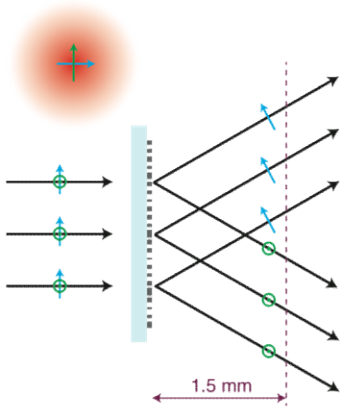
~75 % efficiency

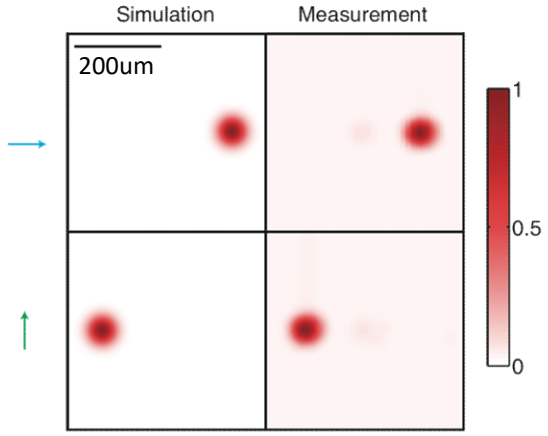
Equivalent to
Wollaston Prism



Polarizing beam splitter/focuser

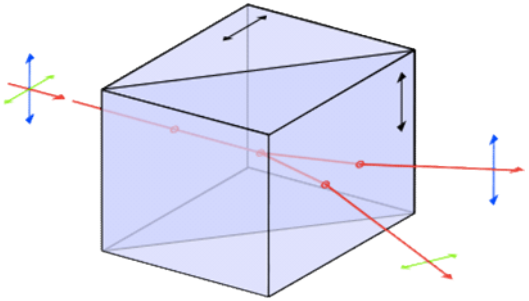
A

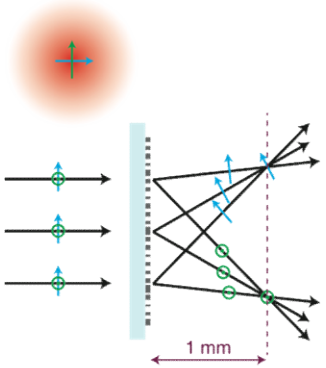


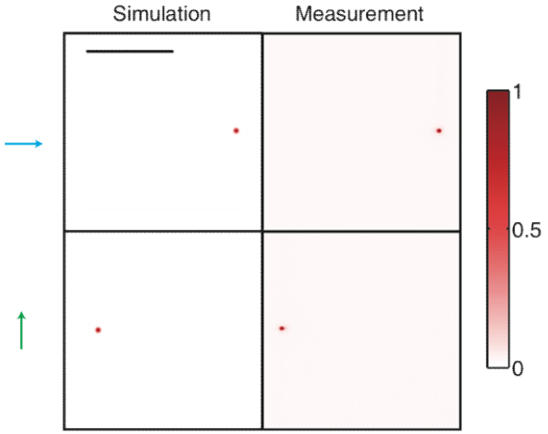


~75 % efficiency

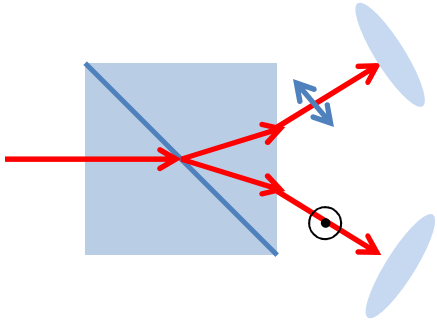
Equivalent to Wollaston Prism



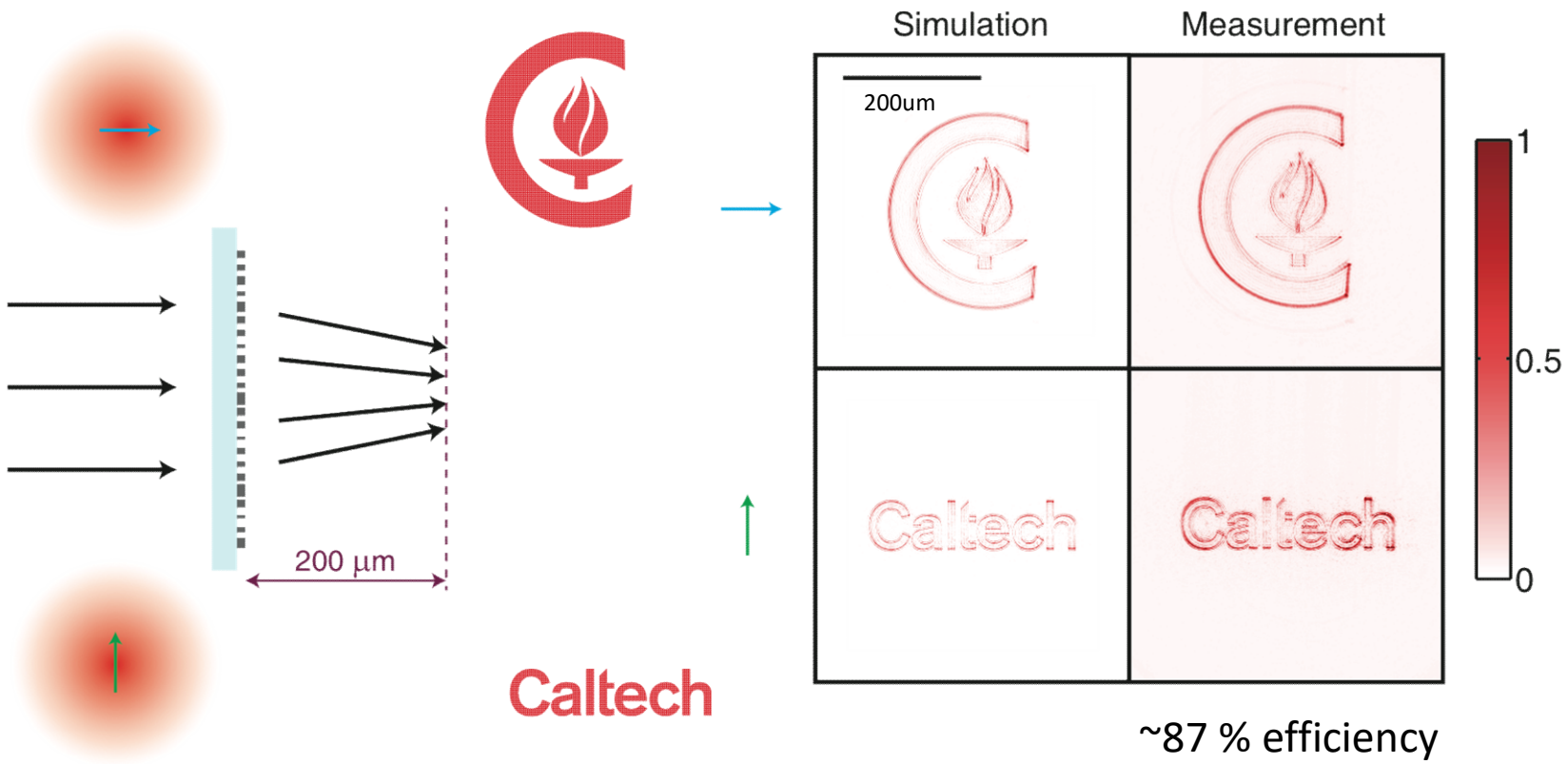




Equivalent to Wollaston Prism and two lenses



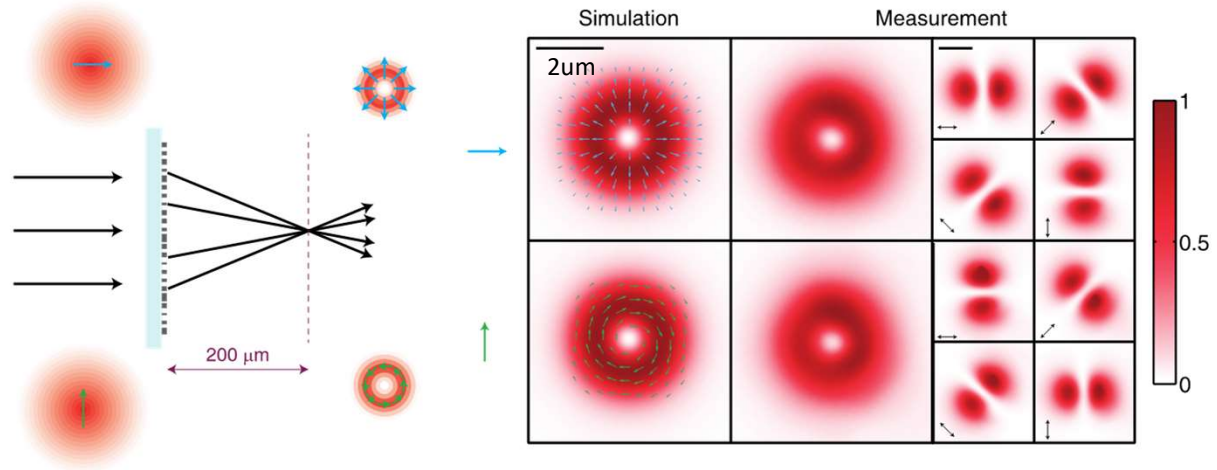
General Polarization Switchable Phase Hologram



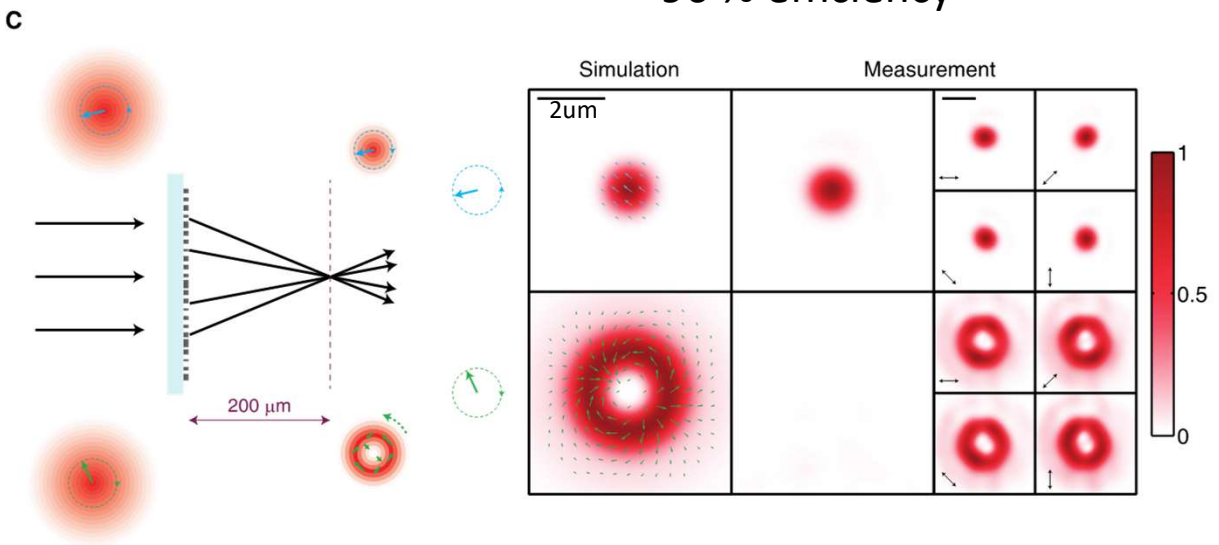
~87 % efficiency

Vector Beams

"Y-Phi" mask

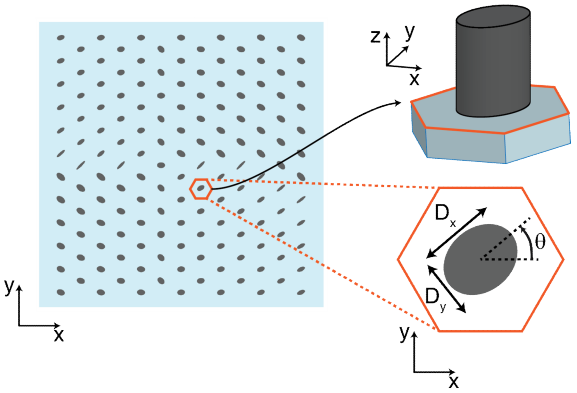


~96 % efficiency

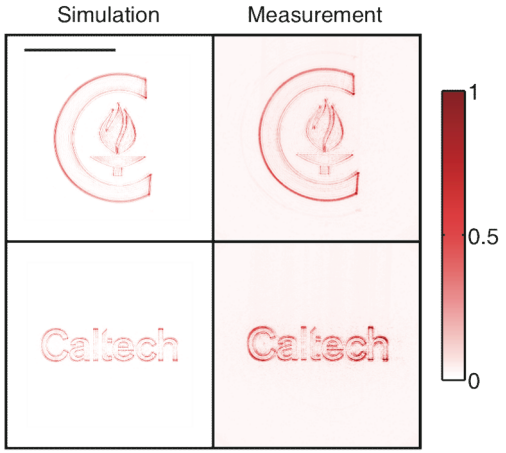


Outline

Metasurfaces for complete phase and polarization control



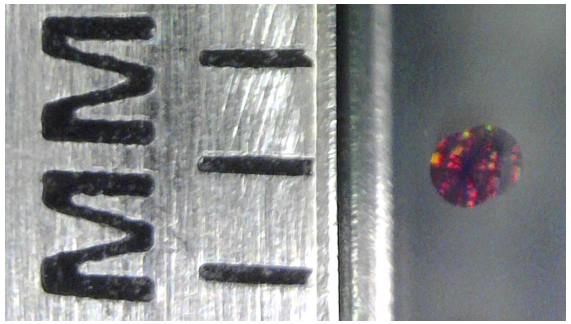
Arbitrary polarization/phase plates



APPLICATIONS

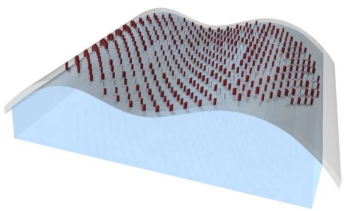
Microscopy

Ultra-Compact Camera Lenses

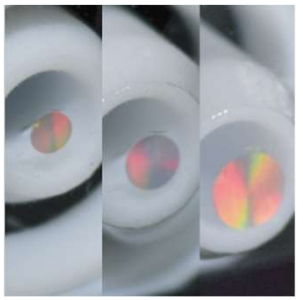


Retroreflector

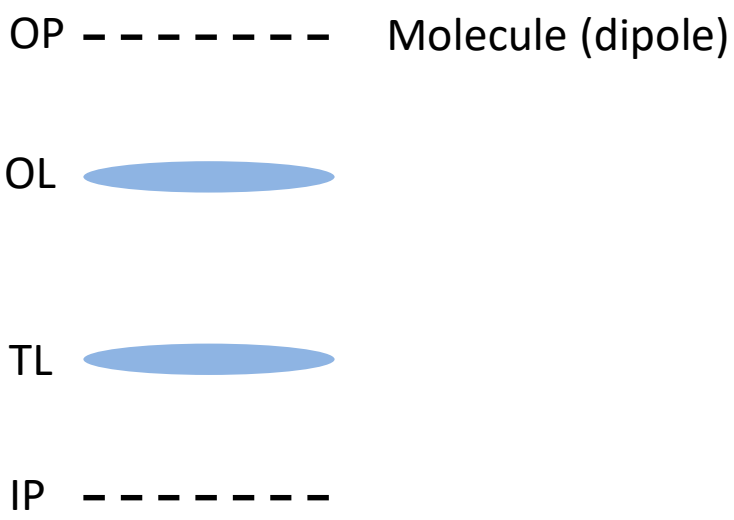
Conformal Optics



Tunable Lenses



Accurate single molecule localization using a y-ϕ mask

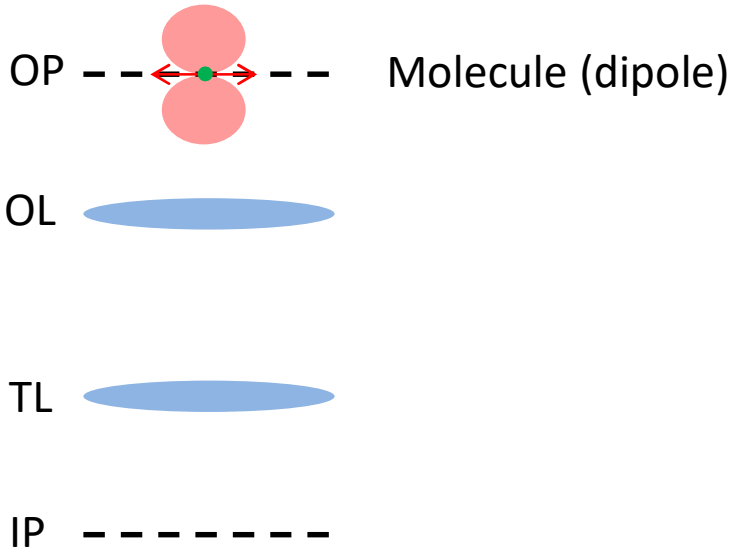


- Molecules emit like electric dipole profiles
- Out of focus dipoles with nonzero angle create localization biases

Caltech

Collaboration with Prof. W. E. Moerner 's group at Stanford

Accurate single molecule localization using a y-ϕ mask



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Caltech

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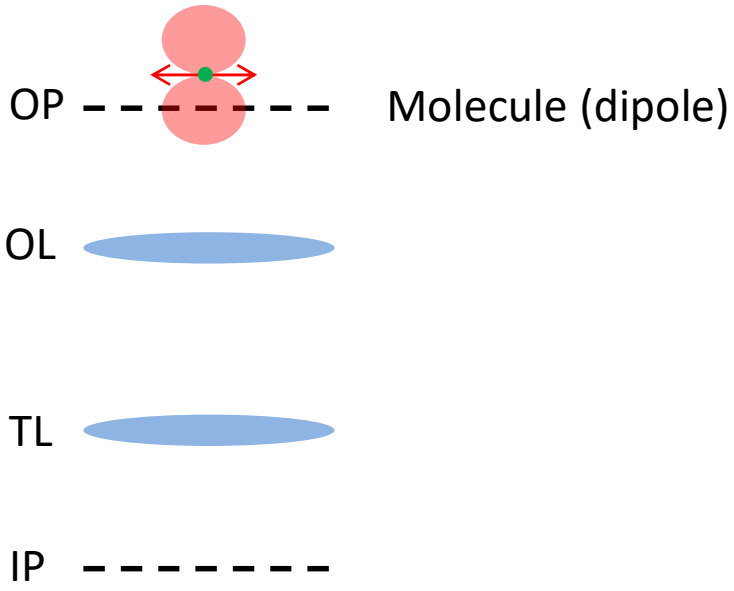
Accurate single molecule localization using a y-ϕ mask



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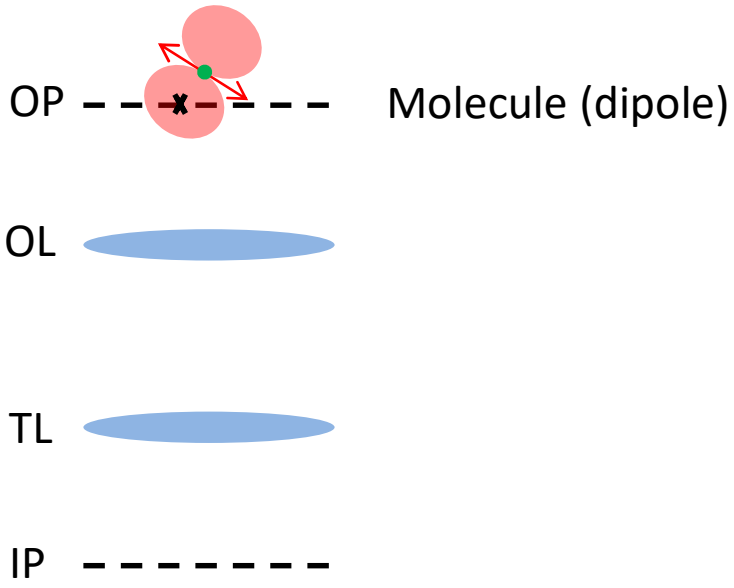

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Caltech

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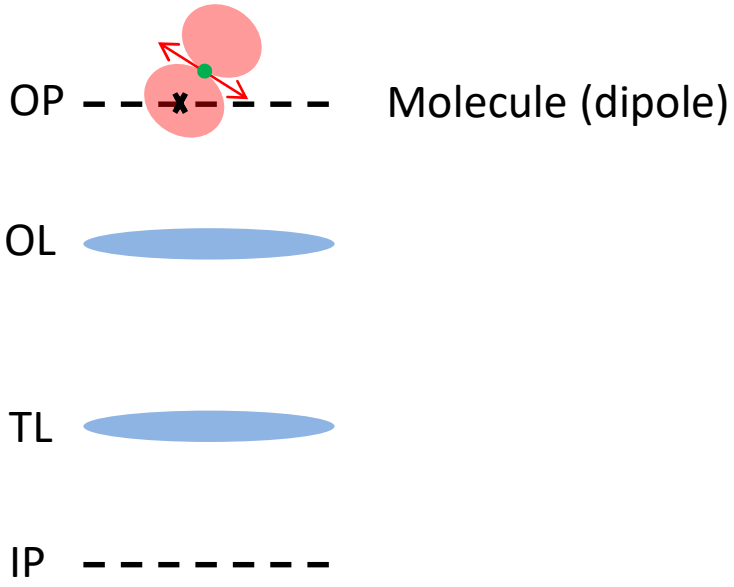


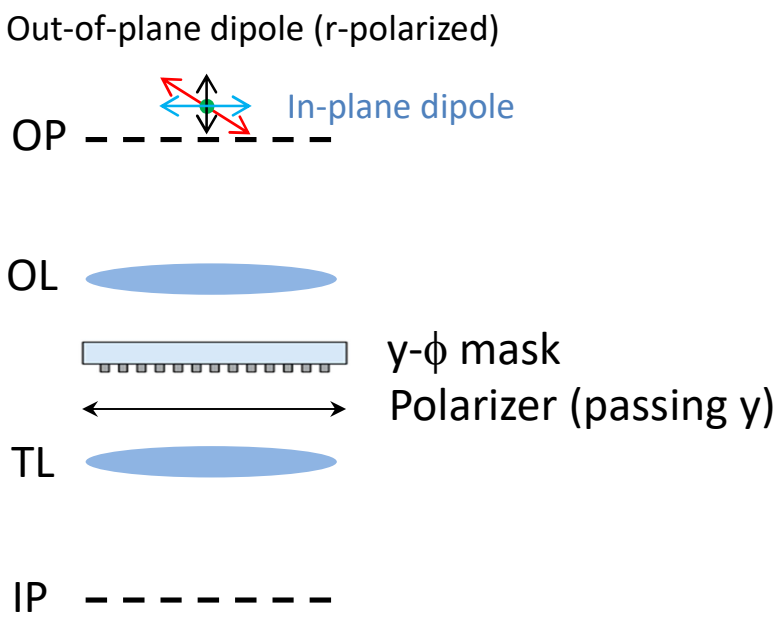
- Molecule appears to move laterally when scanning the objective z-axis

- Molecules emit like electric dipole profiles
- Out of focus dipoles with nonzero angle create localization biases

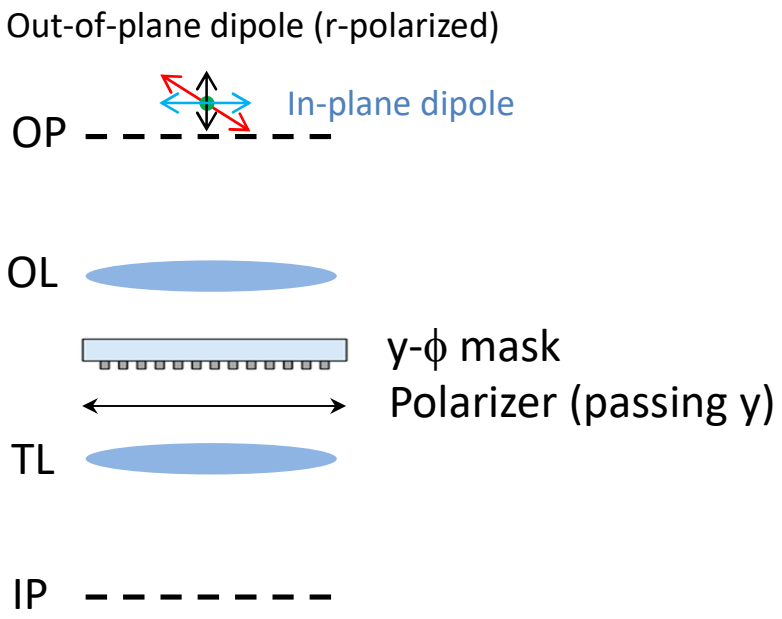
Caltech

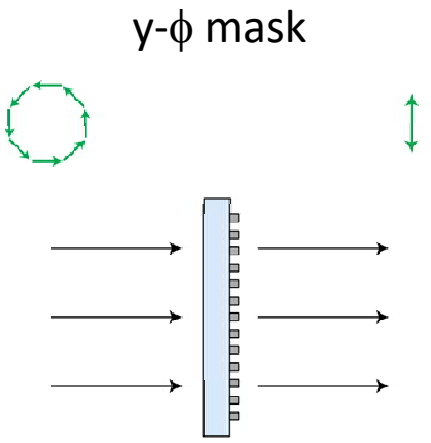
Collaboration with Prof. W. E. Moerner 's group at Stanford

Removing the bias using a y-ϕ mask



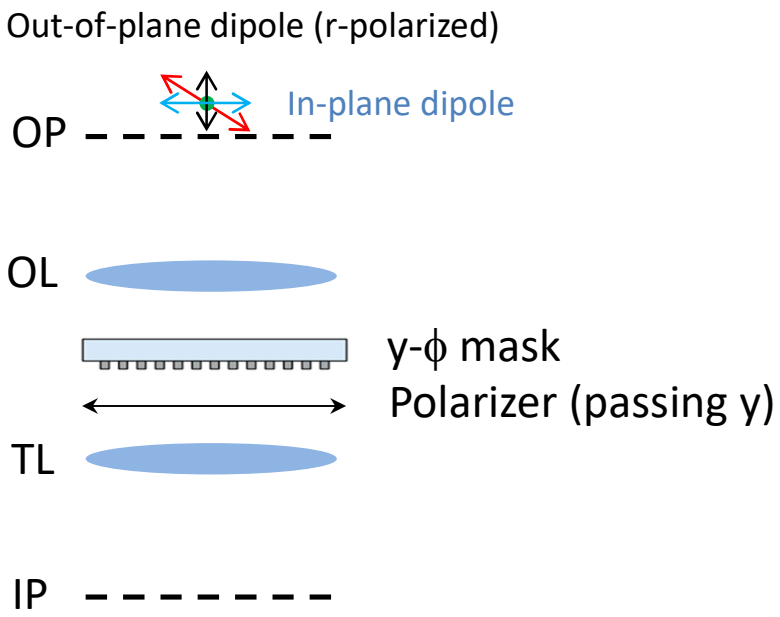
Removing the bias using a y-ϕ mask

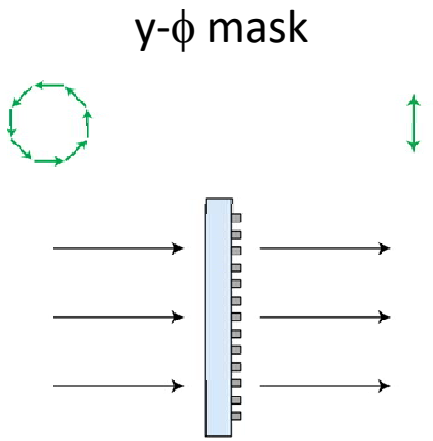




- Out-of-plane dipole emits radially polarized light
- Filter r-polarized light with polarization mask converting azimuthal to y polarization (radial to x-polarization) followed by a polarizer to block x-polarized
- Only in-plane dipole radiation reaches camera which does not have the localization bias

Removing the bias using a y-ϕ mask





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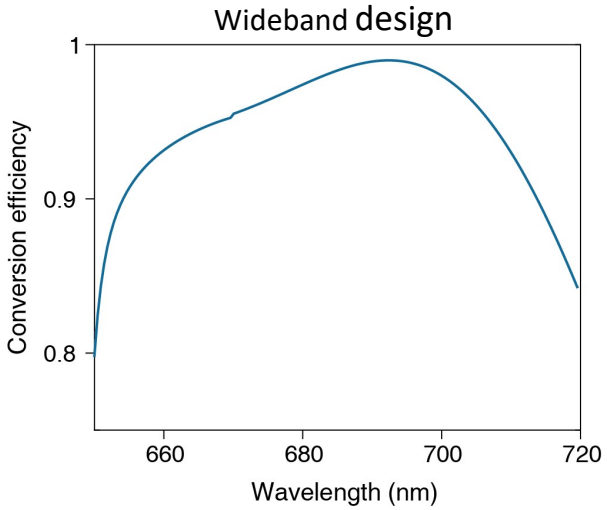
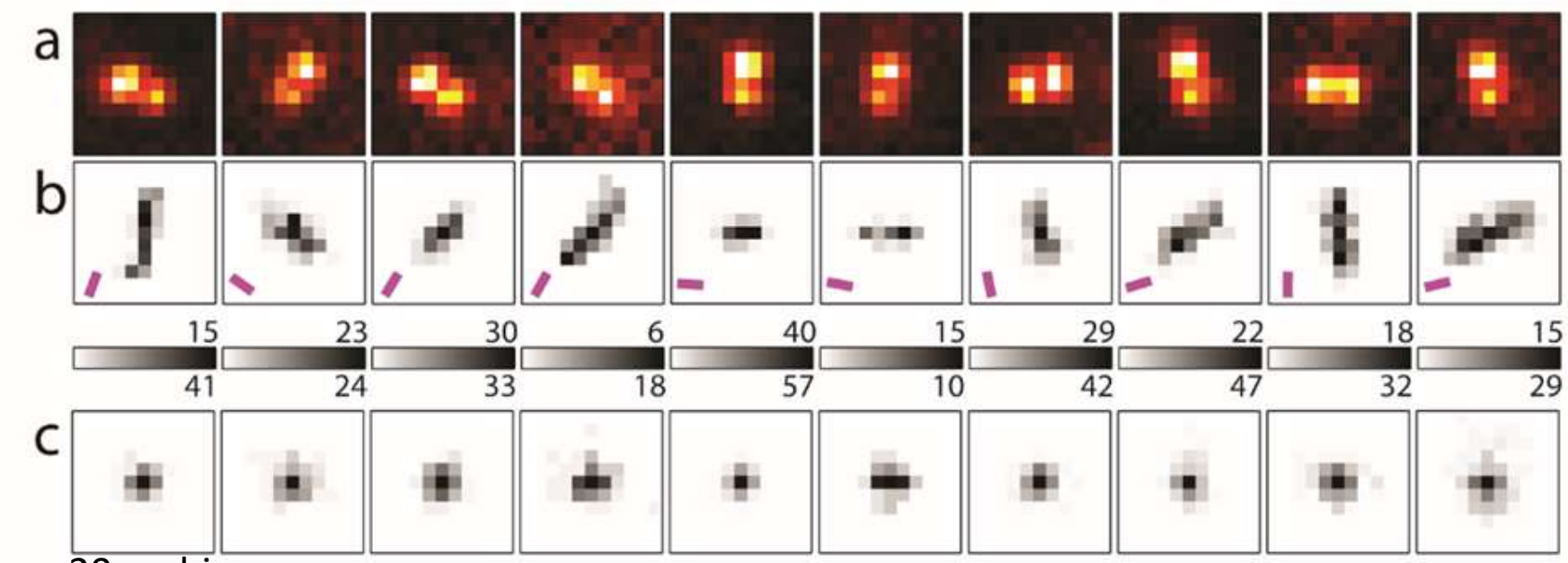


Nano-scale localization results



20nm bins

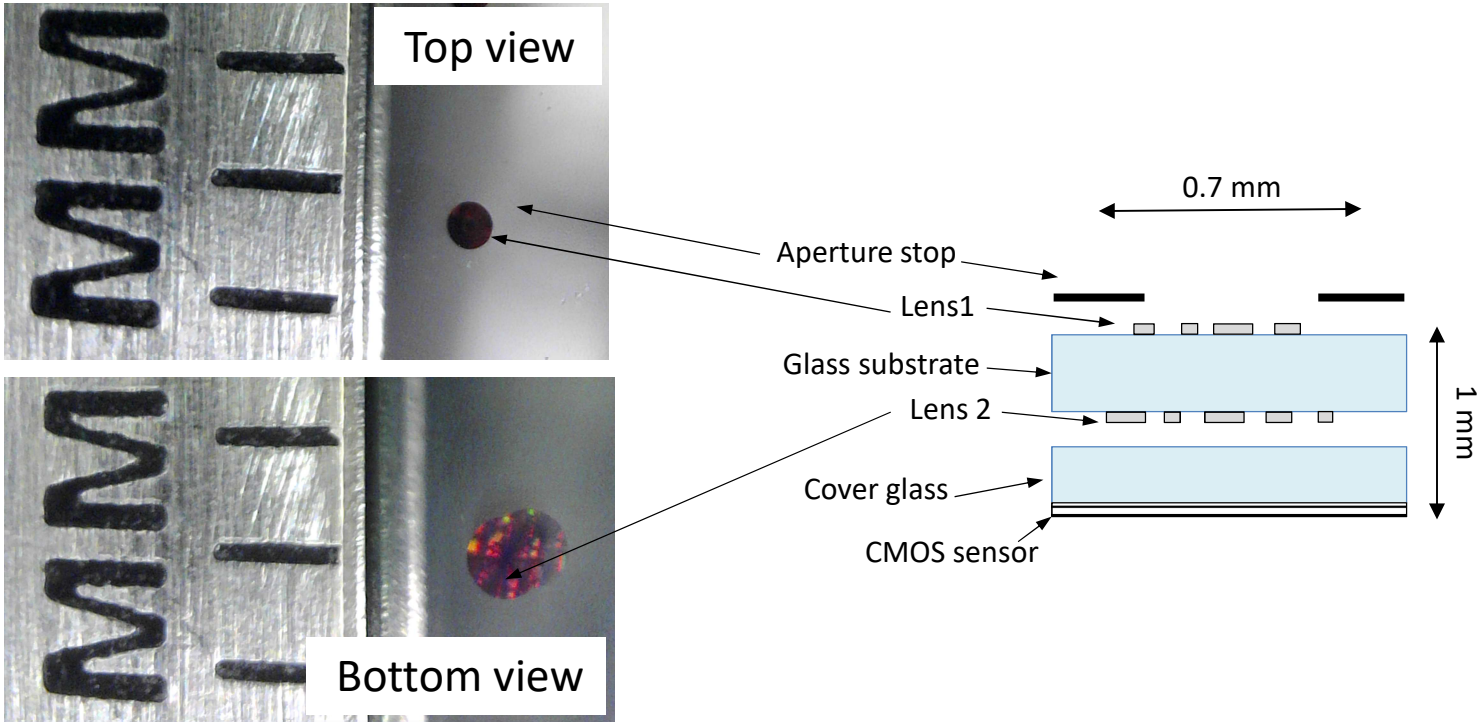
a) Images of 10 molecules (with y-ϕ mask and y-pol)
b) Position of molecules while z-scanning +-200nm (no y-ϕ mask and y-pol)
c) Position of molecules while z-scanning +-200nm (with y-ϕ mask and y-pol)

Caltech

M. Backlund, A. Arbabi *et al.*, **Nature Photonics**, 10, 459–462 (2016)

Ultra-compact camera lens

A camera with total volume ~ 0.5 mm^3 (including the image sensor)

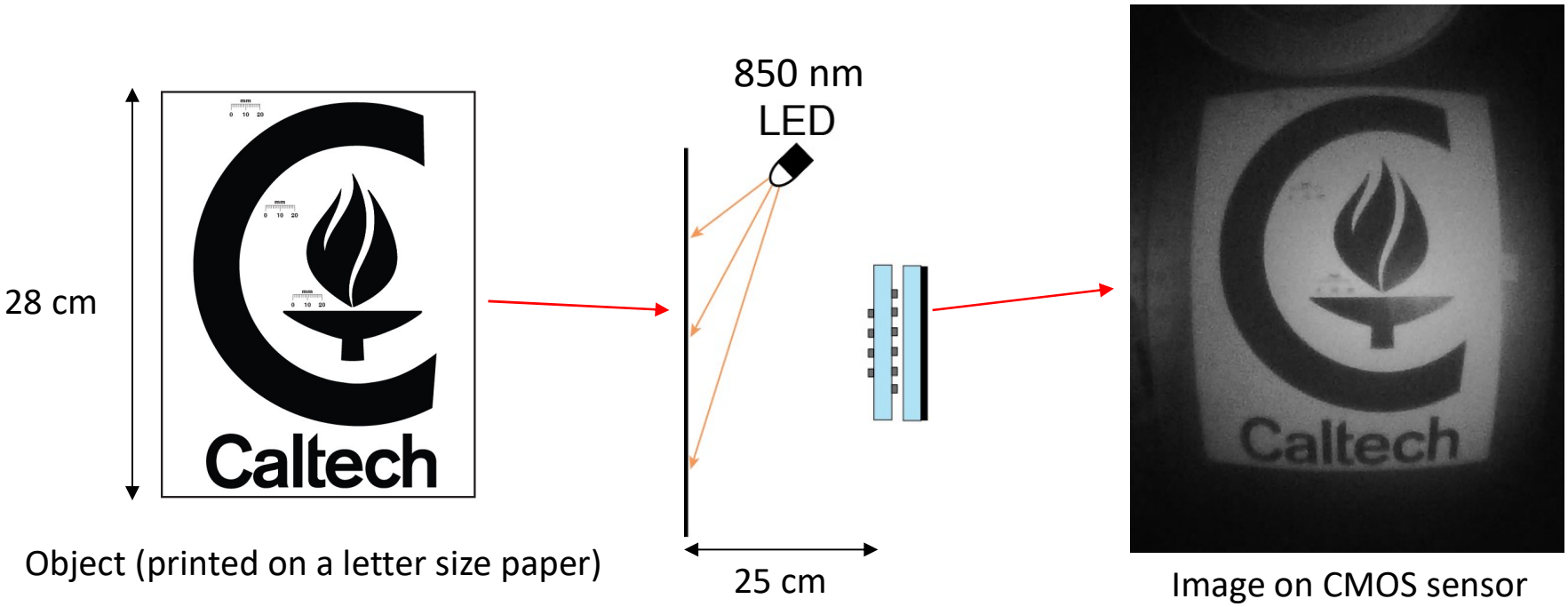


- Camera lens formed of two dielectric metasurfaces lenses (each 600 nm thick)
- Geometrical aberrations are corrected (fisheye lens)
- Works with 850nm LED illumination

Caltech

A. Arbabi *et al.*, arXiv:1604.06160, ***Nature Communications***, accepted

Imaging results with a CMOS image sensor

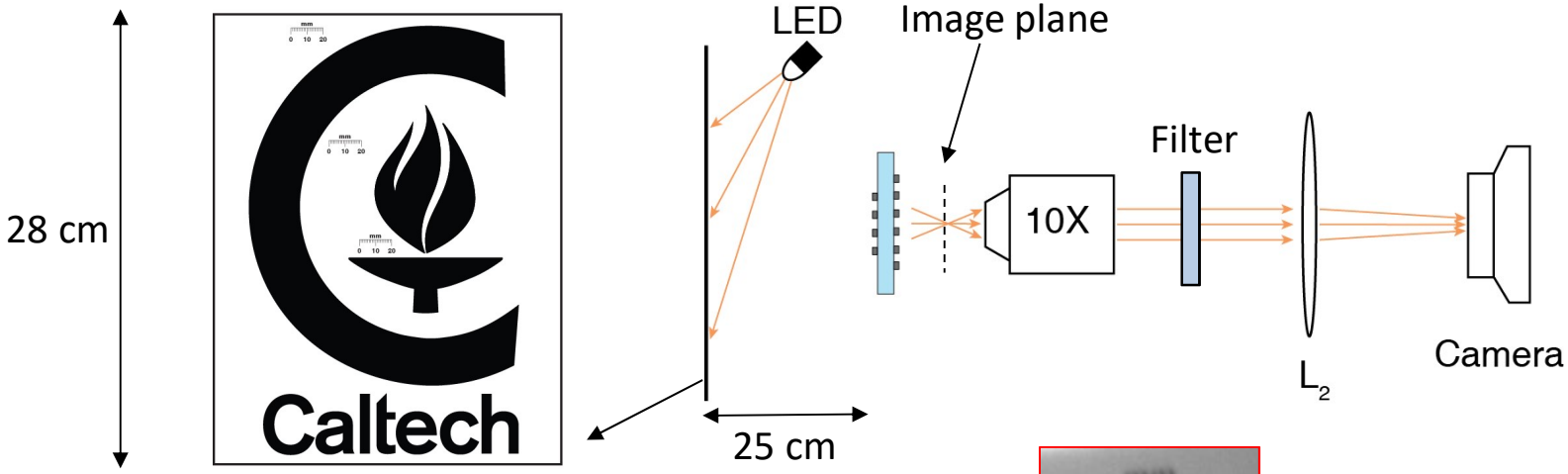


Object (printed on a letter size paper)

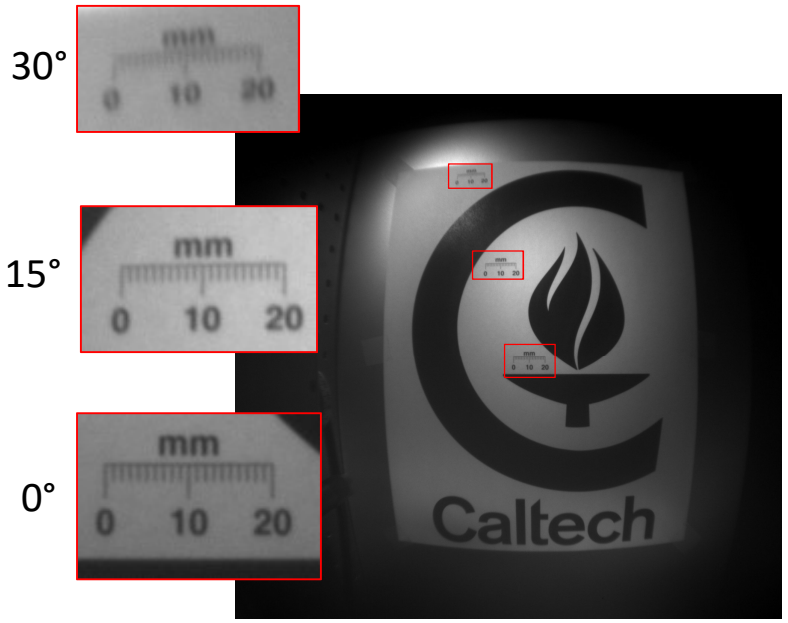
Image on CMOS sensor

f-number: 0.9
Field of view: ±40°

Image quality/ potential applications

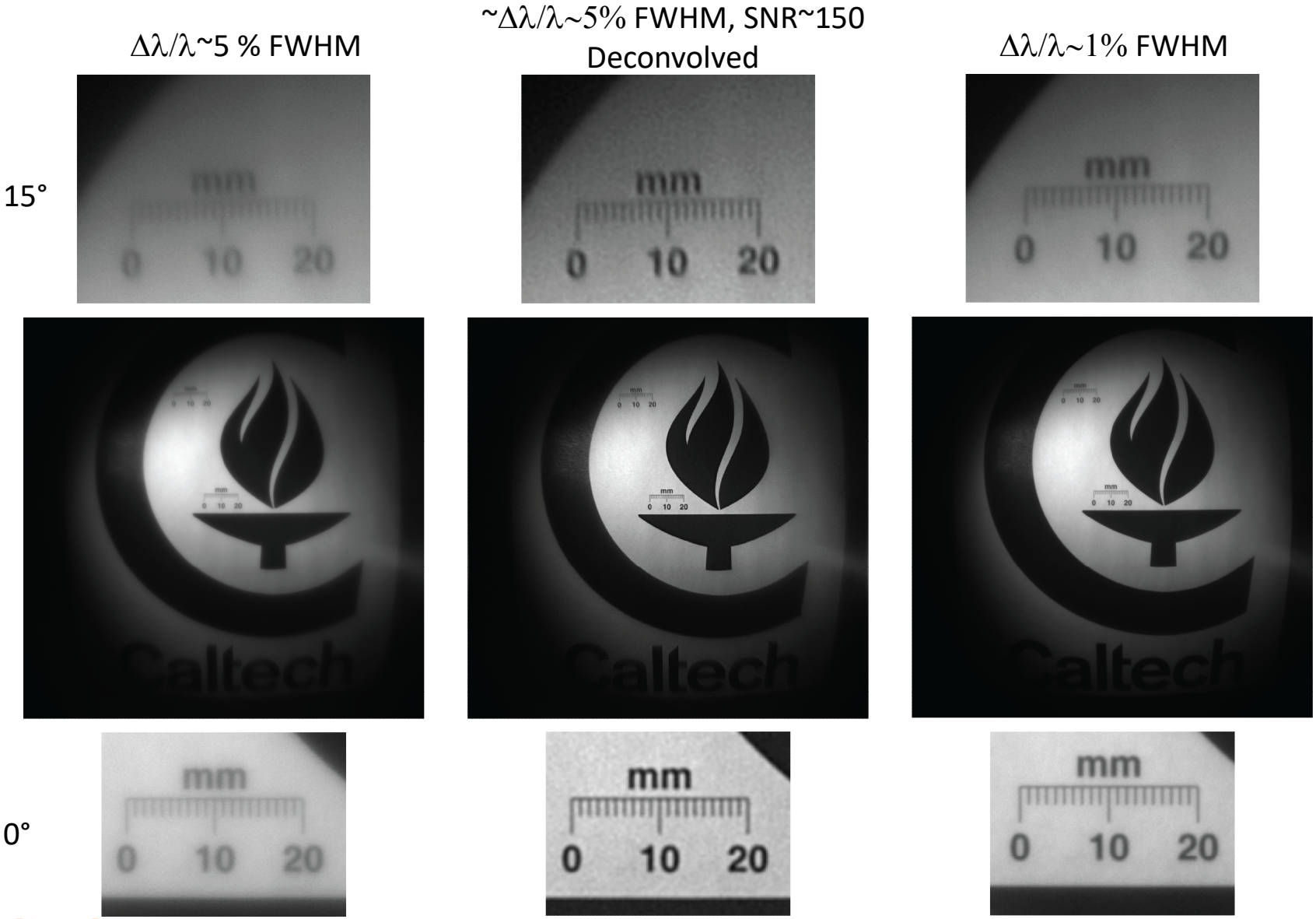


- Advantages:
  - Can be easily fabricated on top of image sensor using lithographic techniques
  - High image quality under LED illumination
- Possible applications
  - Ultra-compact imaging systems – drones, surveillance, endoscopes, internet of things

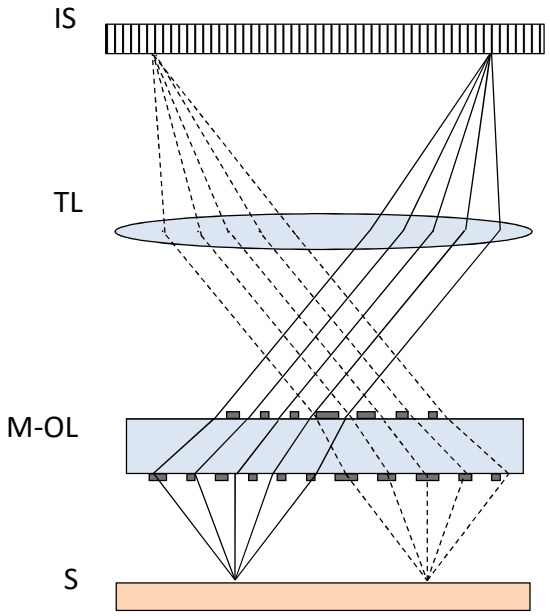


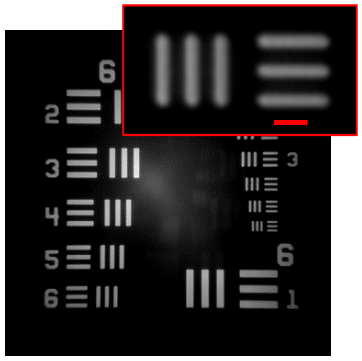
70% efficiency on the axis

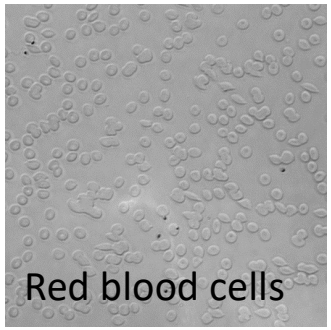
Image processing for chromatic aberration



Lens doublet used as a microscope objective





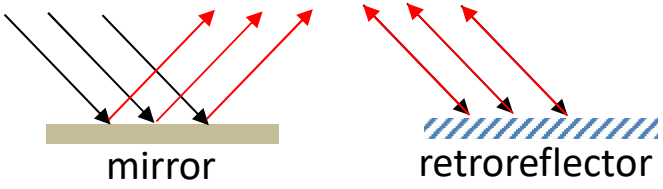


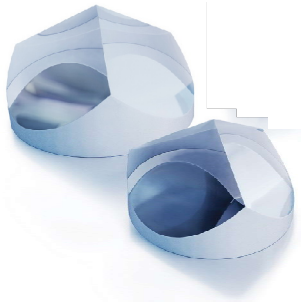
Pictures of people

Dr. Amir Arbabi | Yu Horie | Ehsan Arbabi | Mahsa Kamali | Dr. Andrei Faraon

Planar Retroreflectors

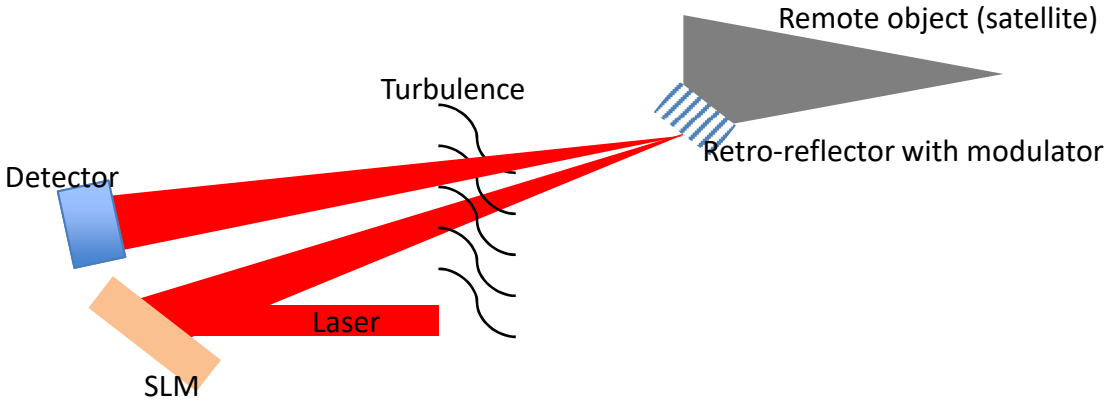
Retroreflectors reflect the light back along the incident angle

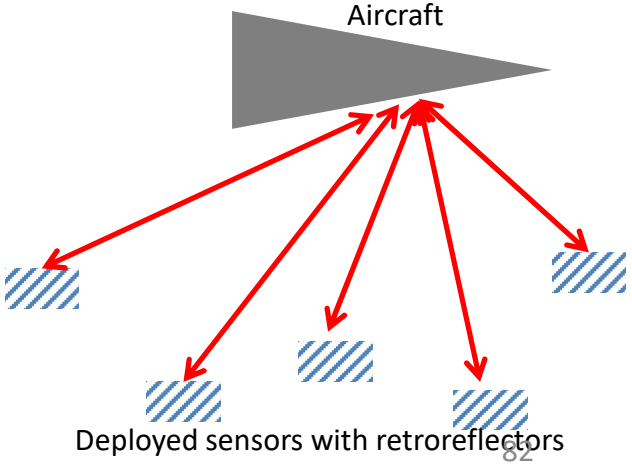




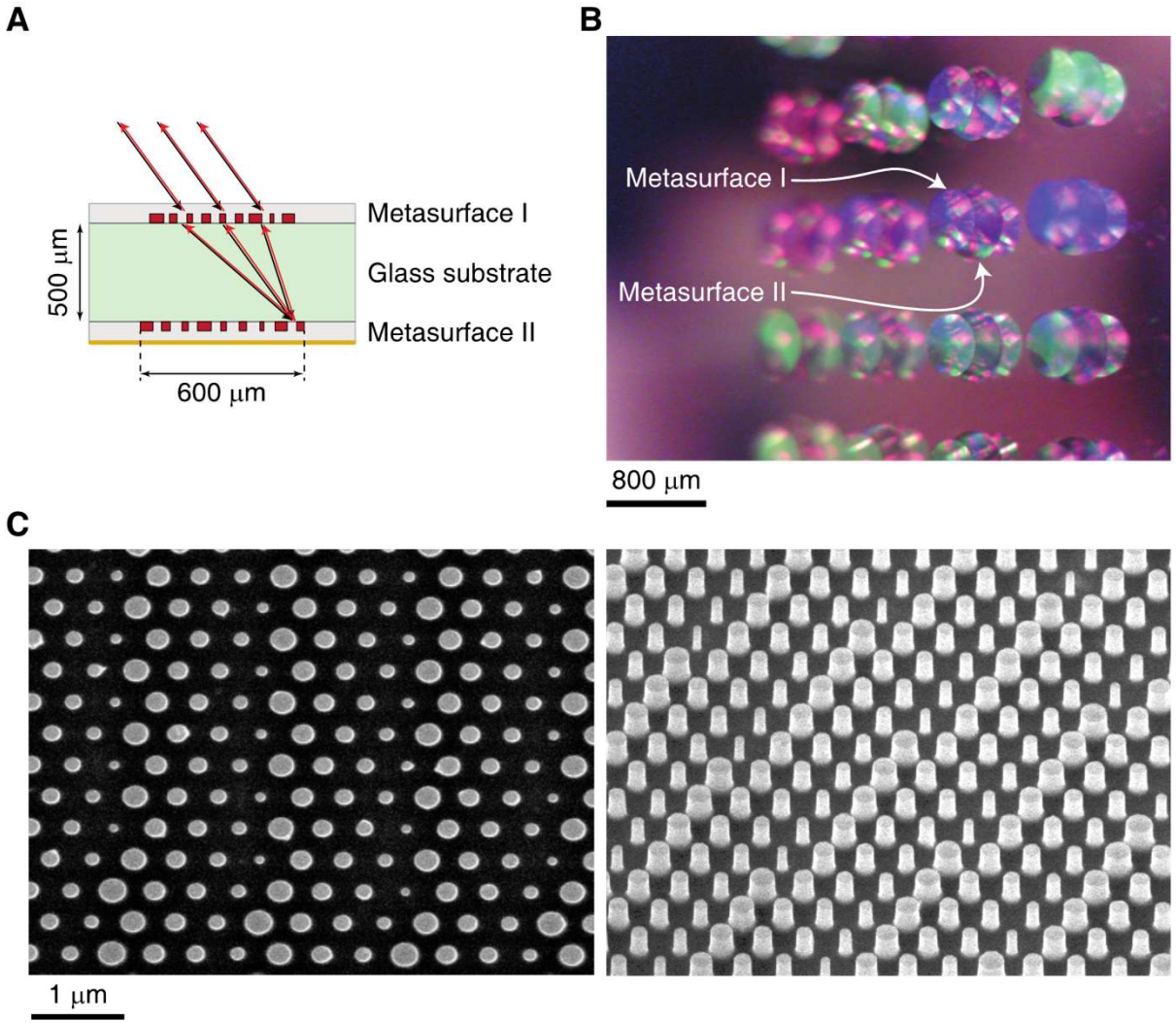
Applications in free space optical communications, length measurement, and optical remote sensing

- Small size and weight
- Integrability with an optical modulator





Metasurface Retroreflector Design



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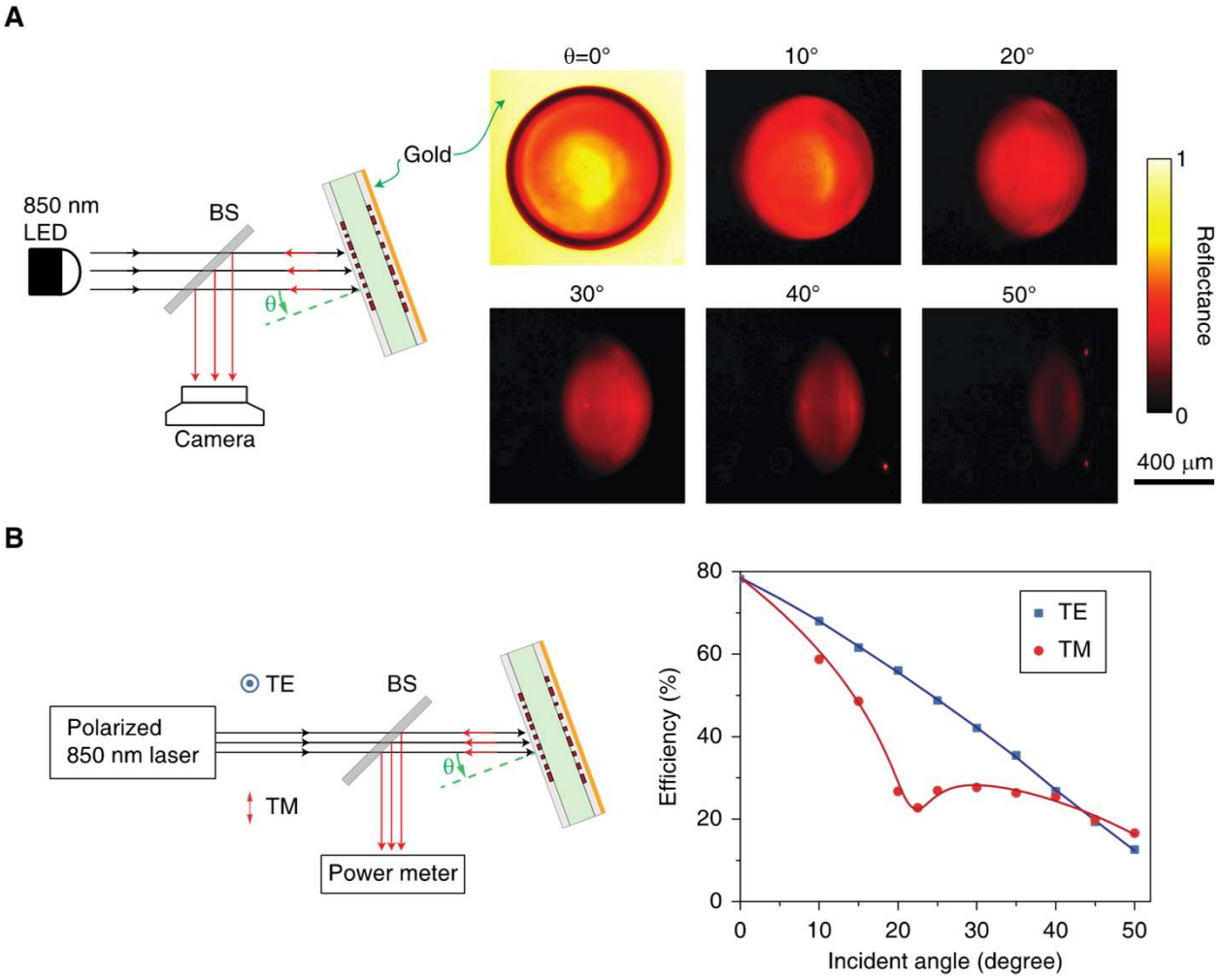
Retroreflector Measurements



A Arbabi et al, Submitted

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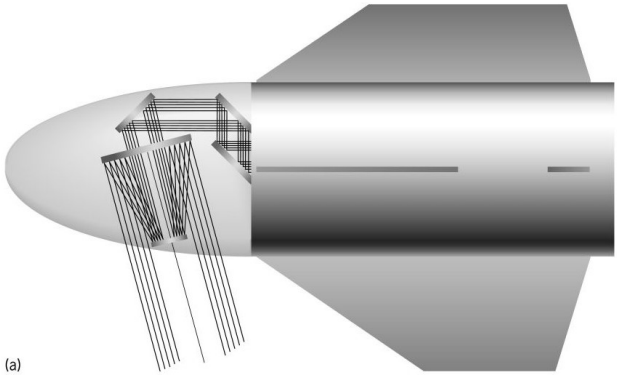
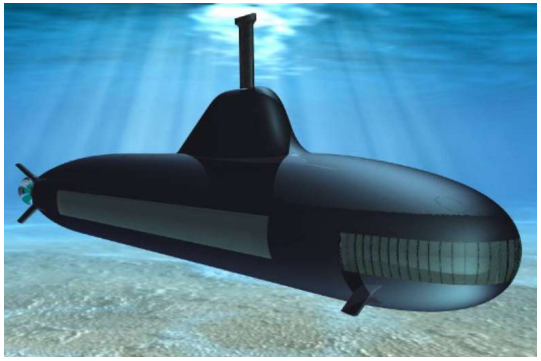
Conformal Optics - Motivation

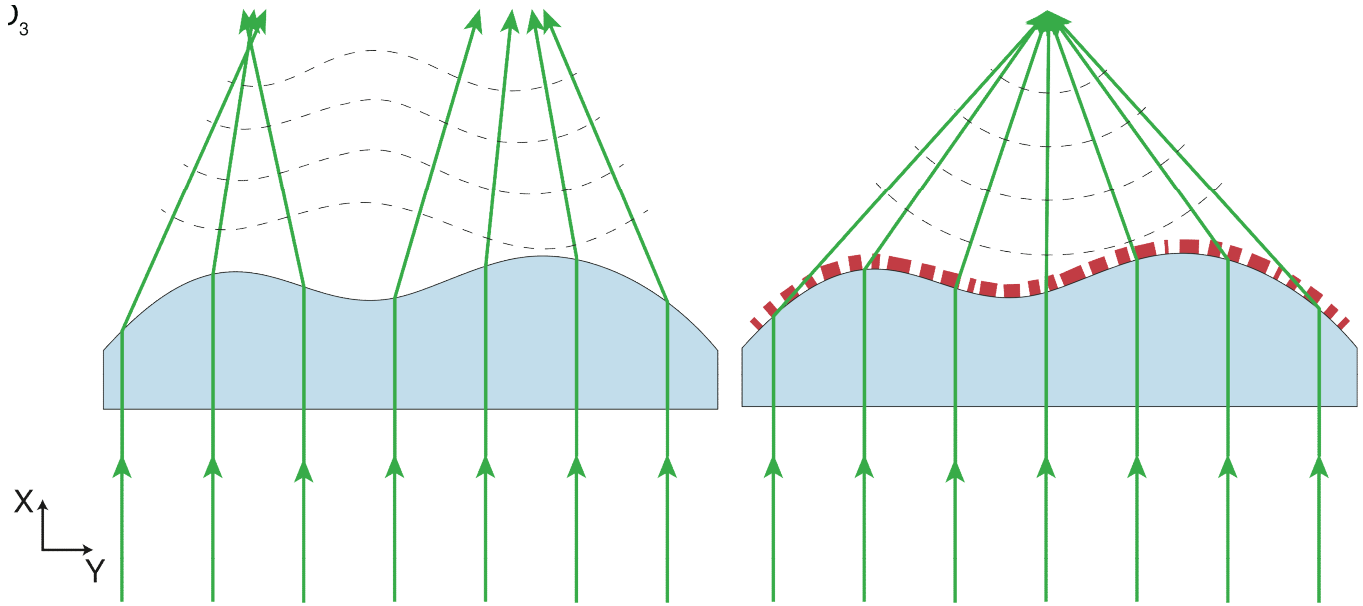
Conventional conformal optics



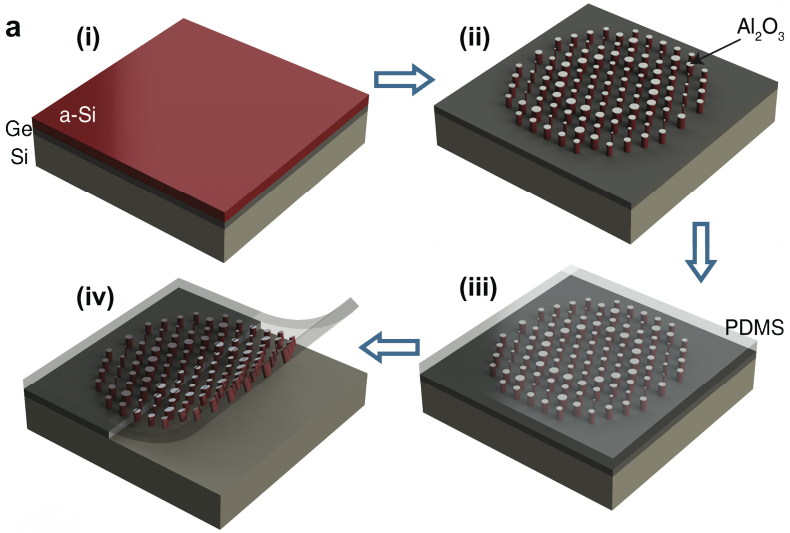


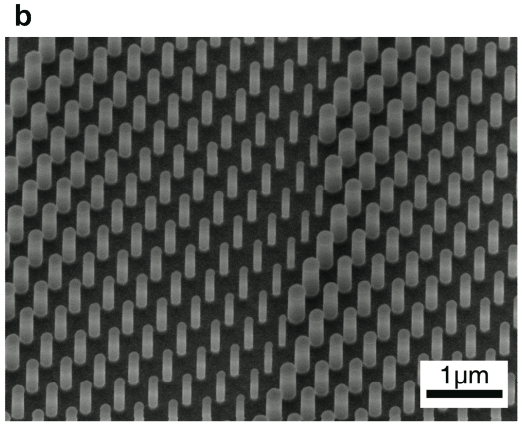
Integration with electronics and medical devices

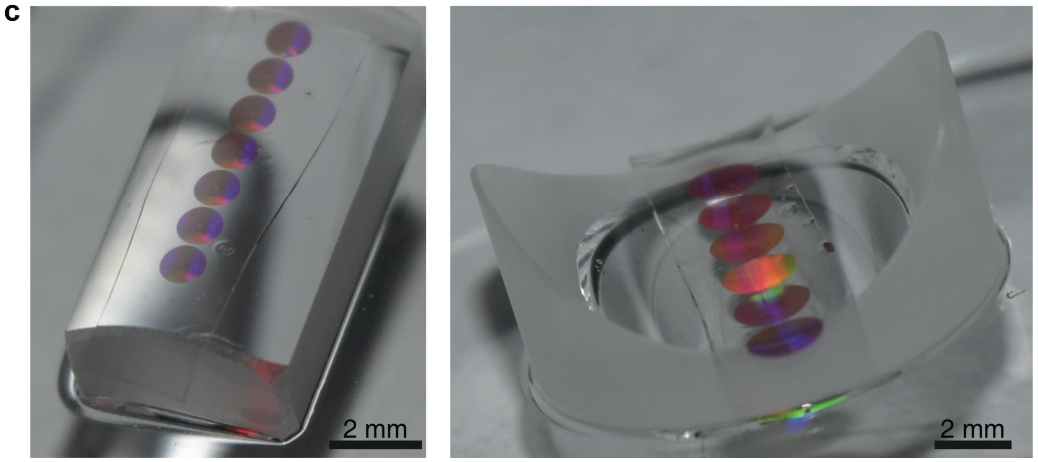
Conformal optics with phase compensation



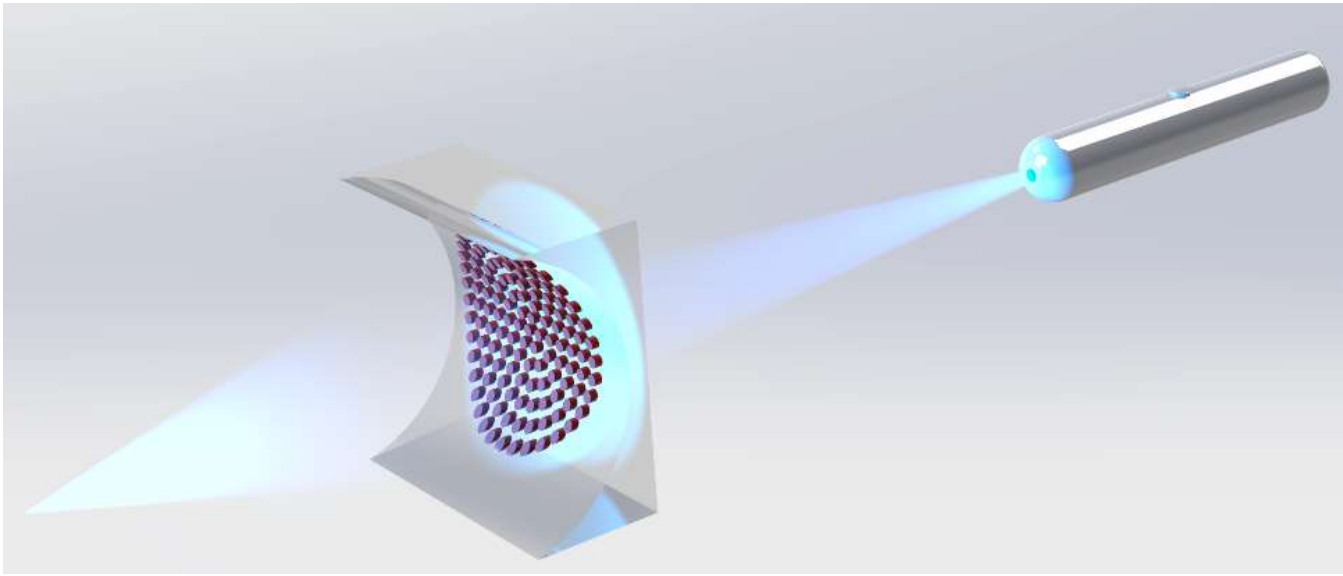
Flexible and Conformal Metasurfaces



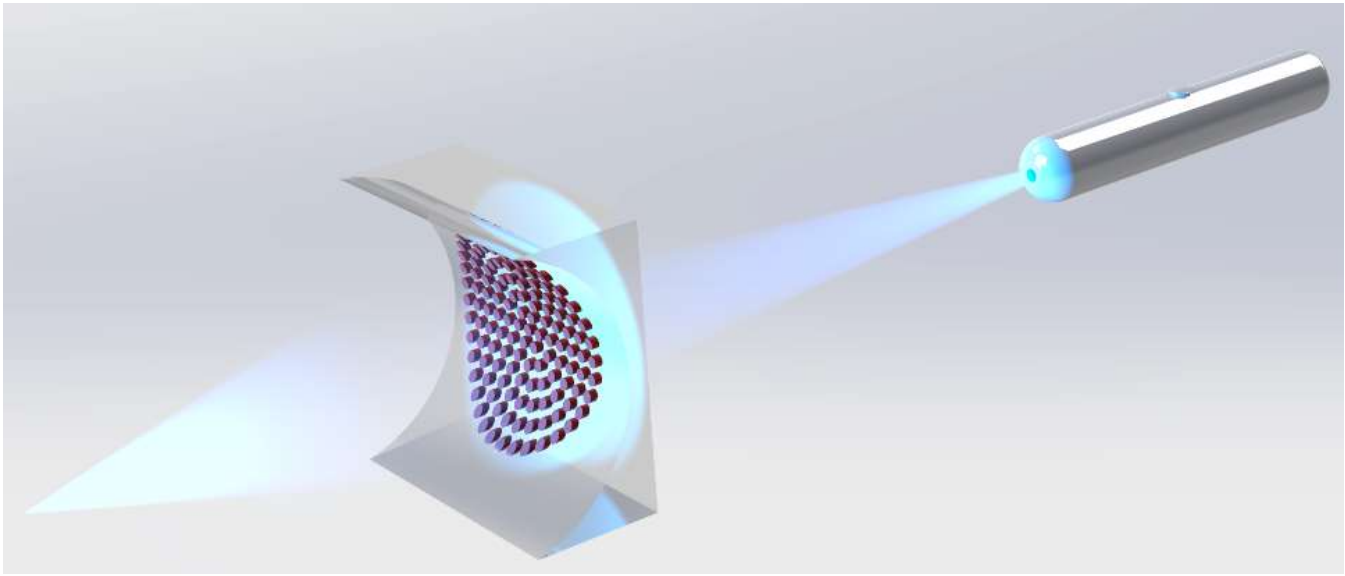


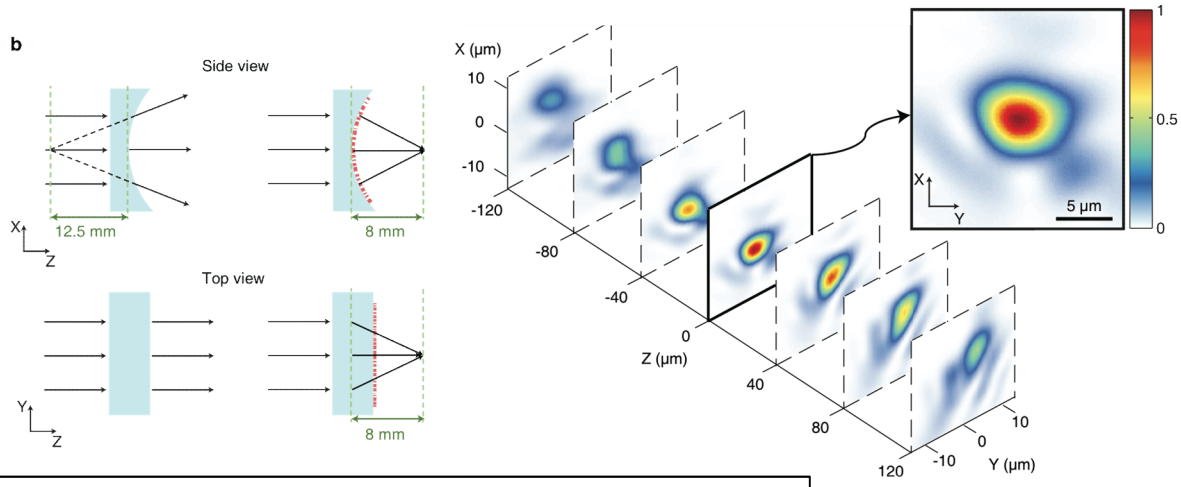


Concave cylinder focusing light to a point!



Concave cylinder focusing light to a point!



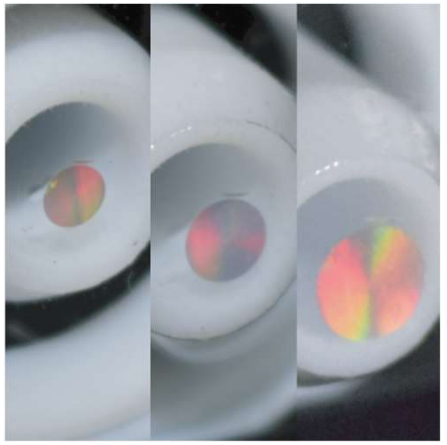


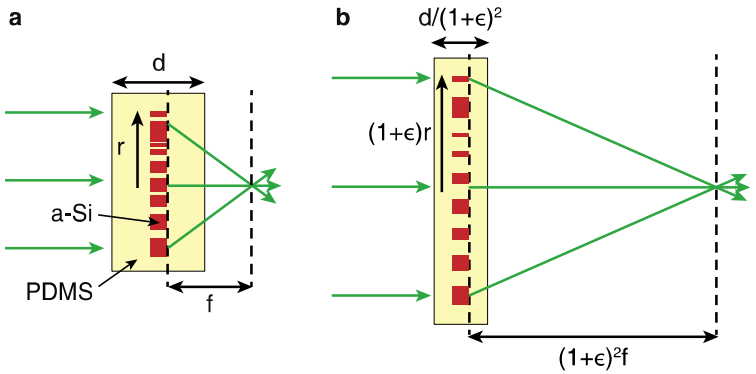
~55% efficiency (experiment)

Kamali et al, **Nature Communications** 7, Article number: 11618, 2016

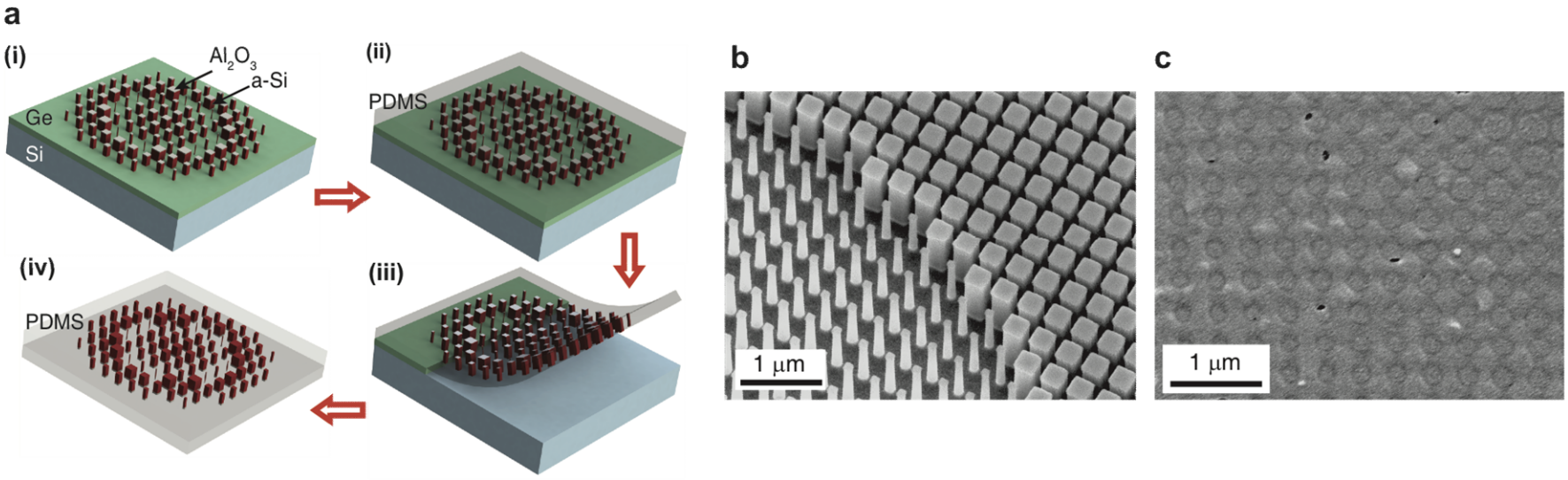
Flexible Tunable Lenses

Flexible Tunable Lenses

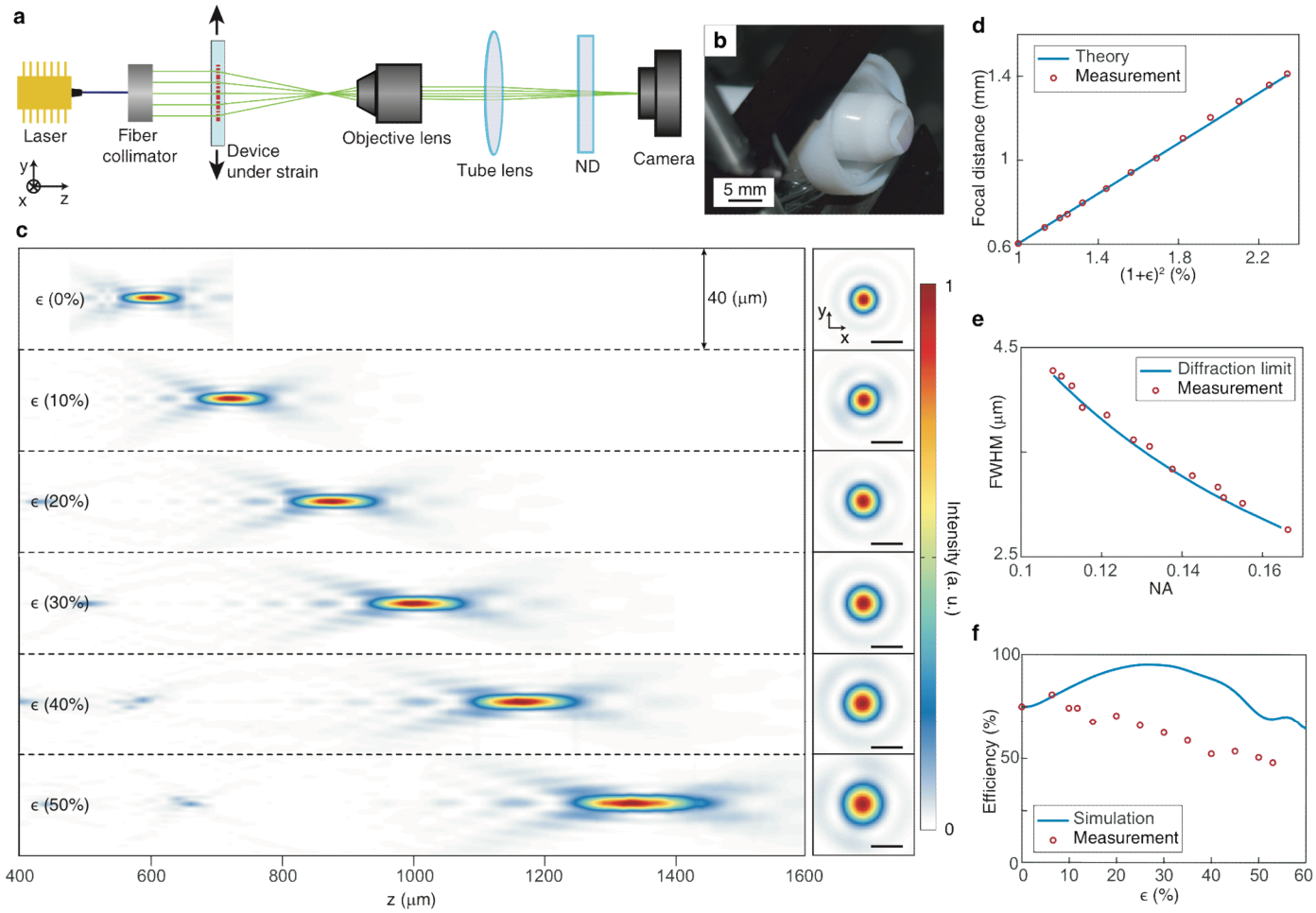




Fabrication of stretchable metasurfaces



Flexible tunable lens performance



Kamali et al, arXiv:1604.03597, (2016), accepted in **Lasers and Photonic Reviews**

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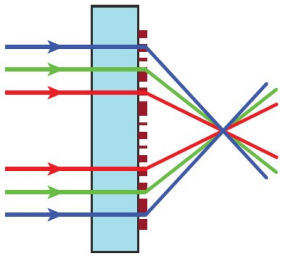
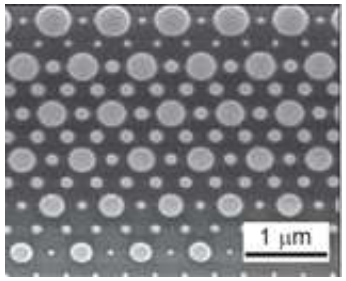
Other Applications

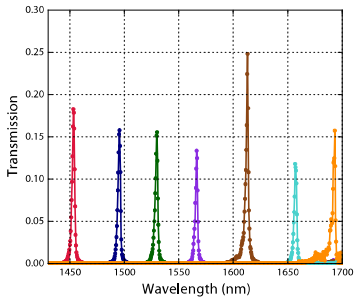
Multi-Wavelength Metasurface Lenses

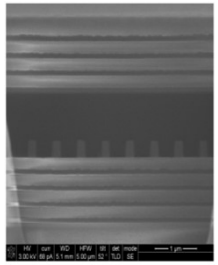




E Arbabi et al, **Optica** Vol. 3, Issue 6, pp. 628-633 (2016)
E Arbabi et al, **Optics Express** Vol. 24, Issue 16, pp. 18468-18477 (2016)
E Arbabi et al, **Scientific Reports**, DOI:10.1038/srep32803 (2016)

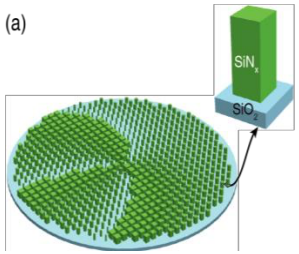
On-chip optical filter arrays

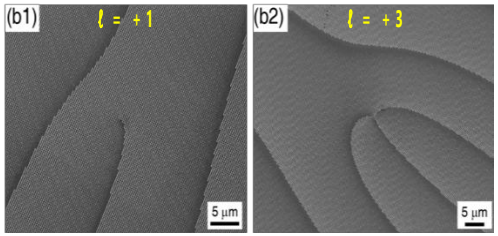




Y Horie et al, **Optics Express** Vol. 24, Issue 11, pp. 11677-11682 (2016)
Y Horie et al, **Optics Express** Vol. 23, Issue 23, pp. 29848-29854 (2015)

Phase masks for OAM under-water communications





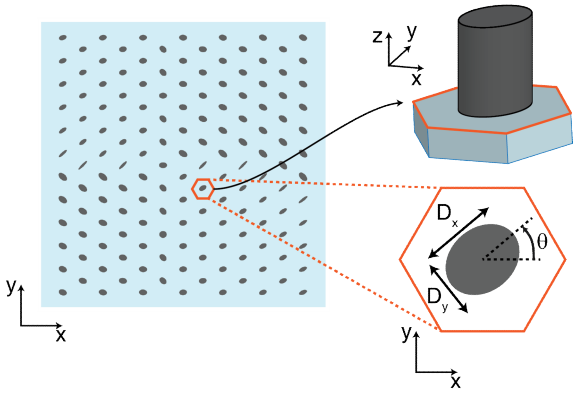
Ren et al, **Scientific Reports** 6, Article number: 33306 (2016)

Outlook

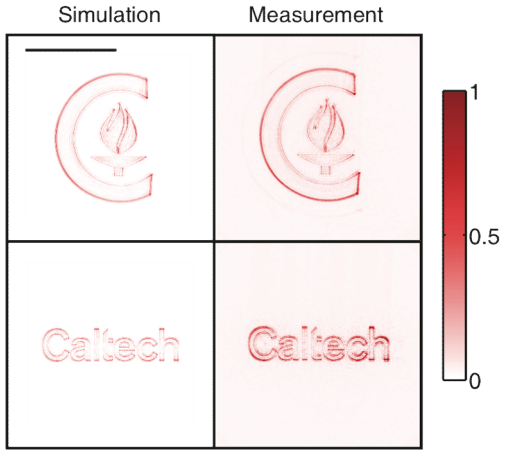
- Ultra-compact microscopy systems
- Holographic microscopy based on bi-refringent elements
- Optical phased arrays

Summary

Metasurfaces for complete phase and polarization control

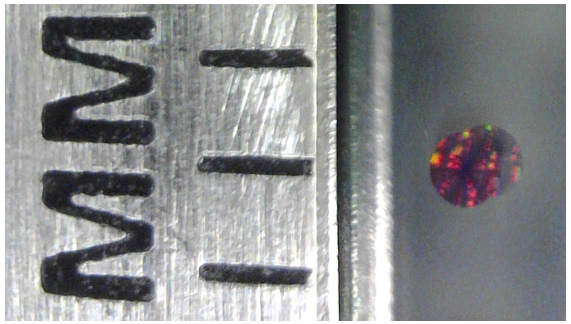


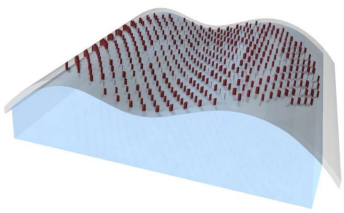
Arbitrary polarization/phase plates

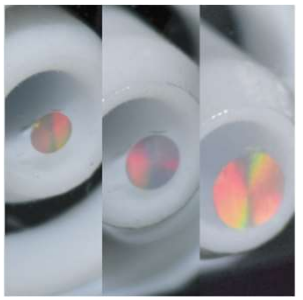


APPLICATIONS

Microscopy Ultra-Compact Camera Lenses Retroreflector Conformal Optics Tunable Lenses







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