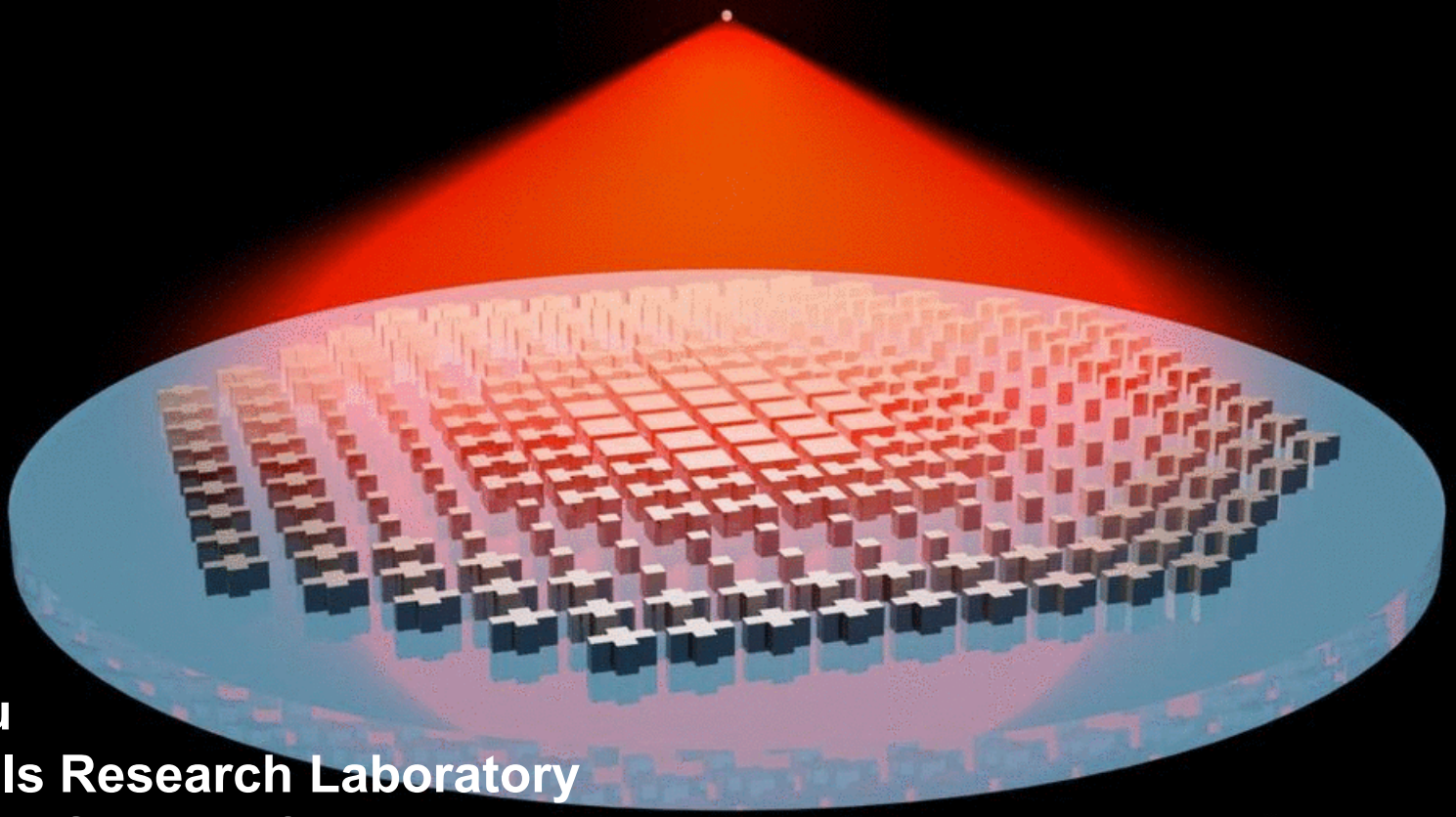
Reconfigurable metasurface optics for dynamic light shaping



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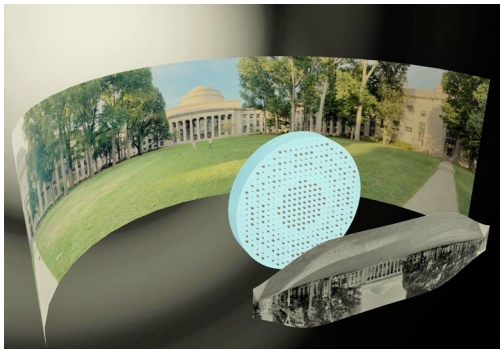
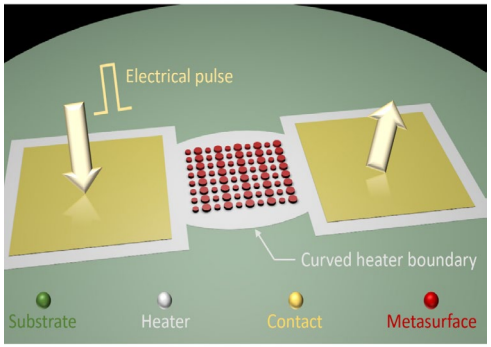
Massachusetts Institute of Technology

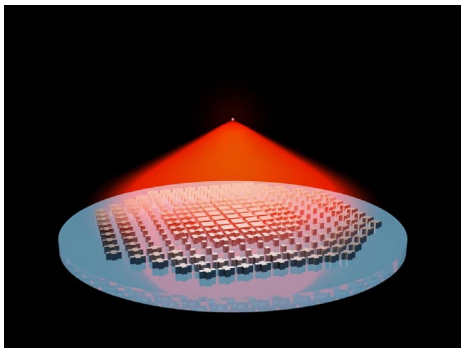
OPTICA
Formerly OSA



Ultra-compact metasurface flat opics



Active optics & photonics platform



Reconfigurable meta-optics

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Traditional lens

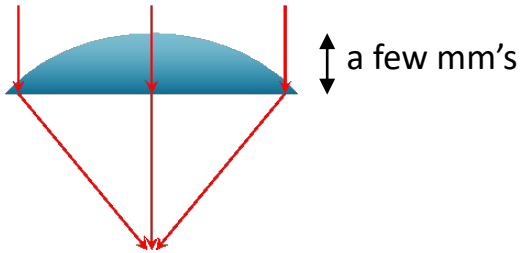


Image plane

$\Delta x \ll \lambda$

Metasurface flat lens

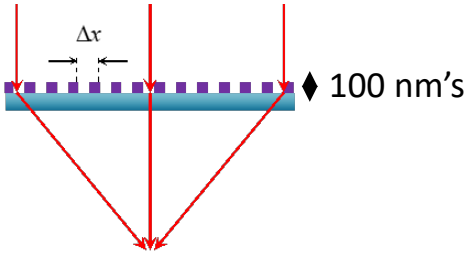


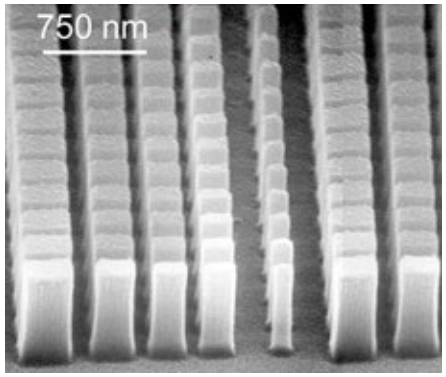
Image plane

Traditional optical systems are bulky, complicated, costly, and difficult to scale.

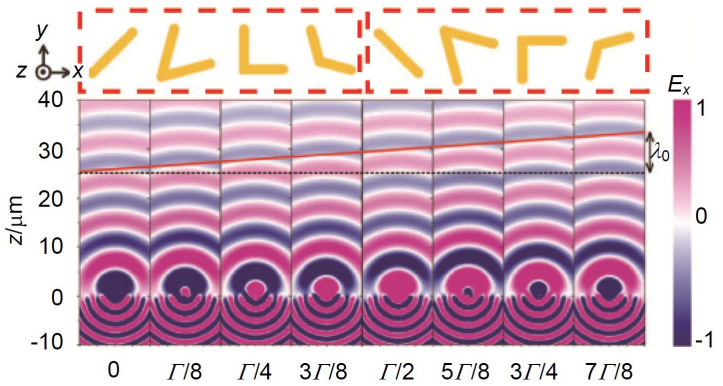
Novel flat optics solutions significantly improve performance, compactness, and scalability.

Metasurface optics

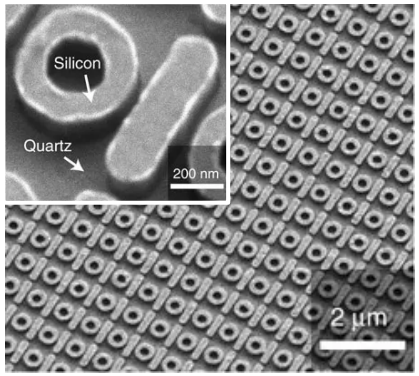
and many others …



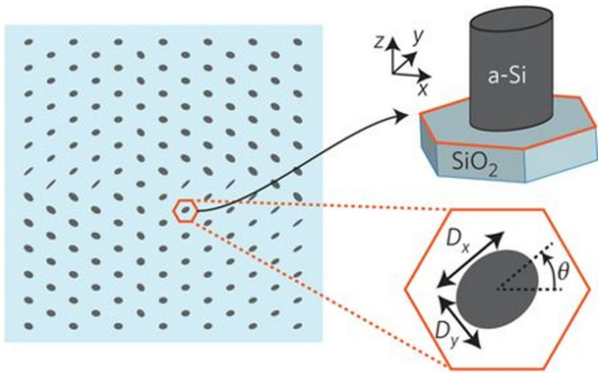
Opt. Lett. **23**, 1081 (1998)



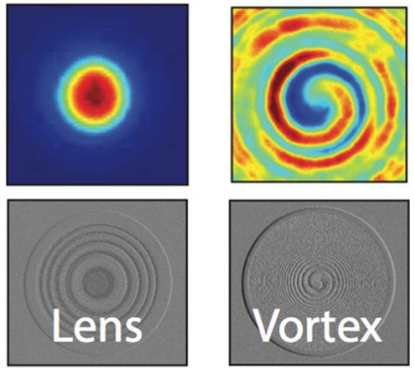
Science, **334**, 333 (2011)



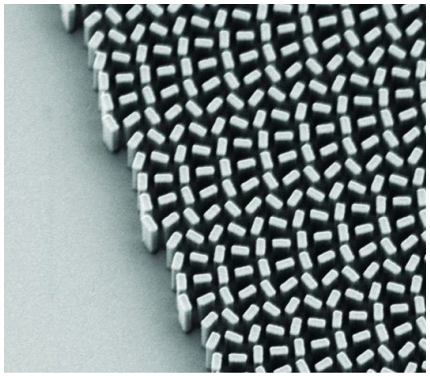
Nat. Commun. **5**, 5753 (2014)



Nat. Nanotechnol. **10**, 937 (2015)



ACS Photonics **3**, 209 (2016)



Science **352**, 1190 (2016)

PMAT

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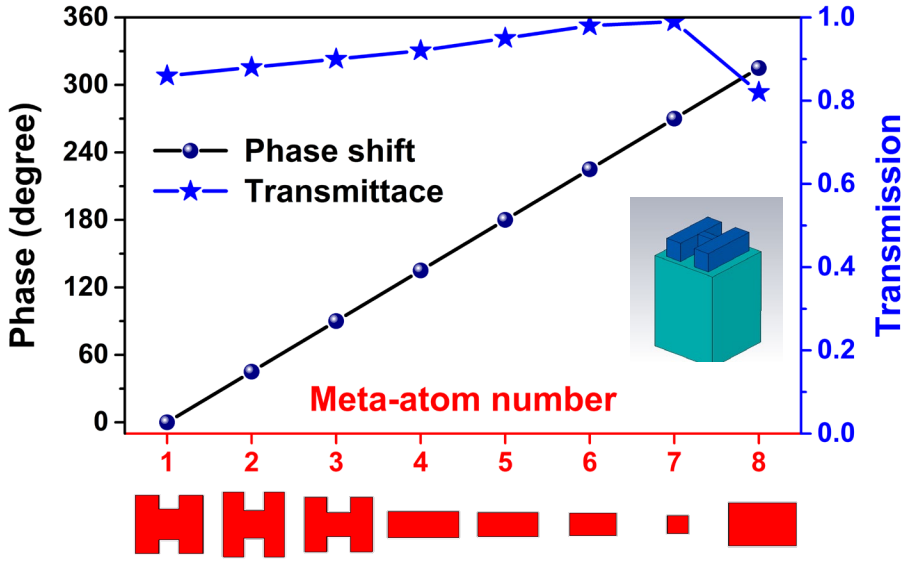
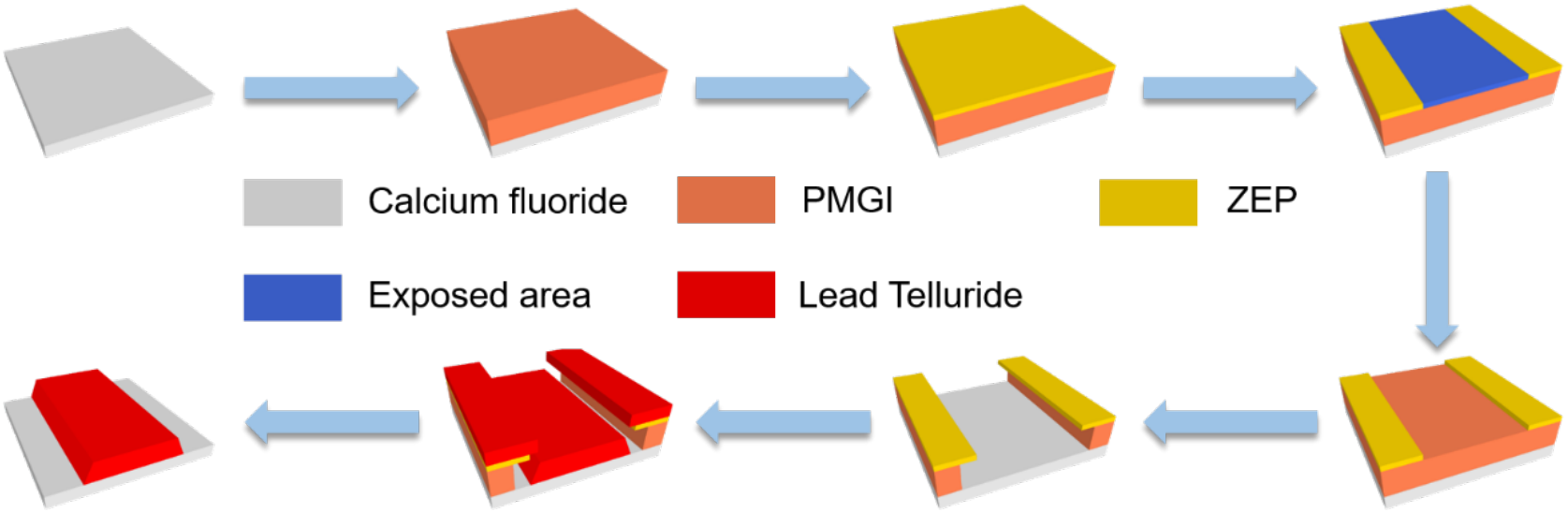
Photonic MATerials

Ultra-thin dielectric Huygens meta-atom design



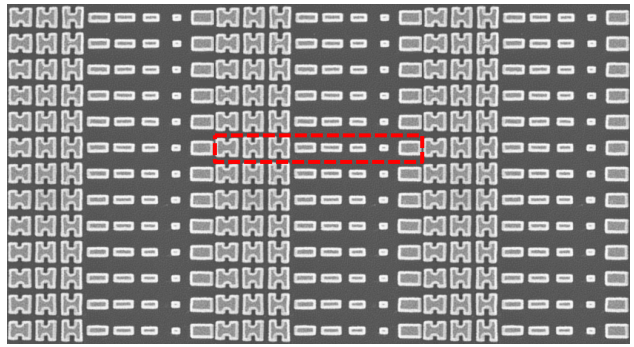
- Novel two-component Huygens meta-atom design (λ_0 = 5.2 μm)
  - High-index (n= 5) PbTe on IR-transparent CaF2 (n= 1.4) substrates
  - Support both electric dipole and magnetic dipole resonances
  - Full 2π phase coverage; near-unity optical transmission
  - Low-profile: thickness = 650 nm ($\lambda_0 / 8$), aspect ratio < 1.25

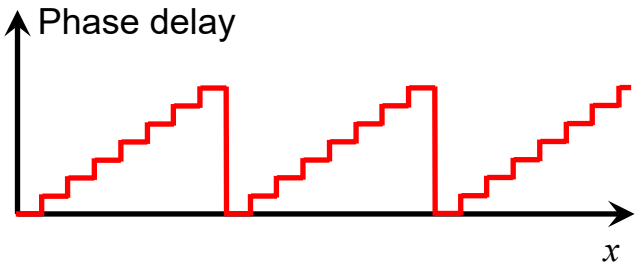
High-index PbTe meta-atom processing

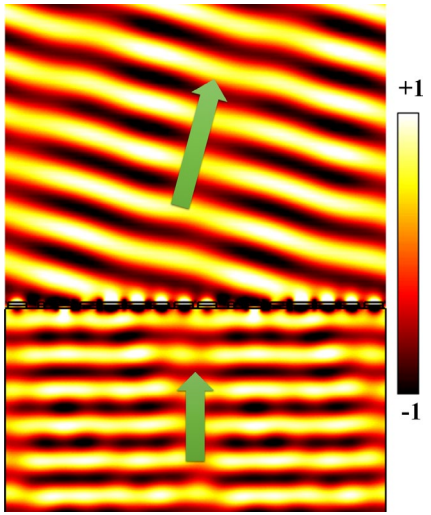


High-index (n = 5) PbTe on IR-transparent CaF_2 (n = 1.4) substrates: high-efficiency & ultrathin profile ($\lambda_0 / 8$)

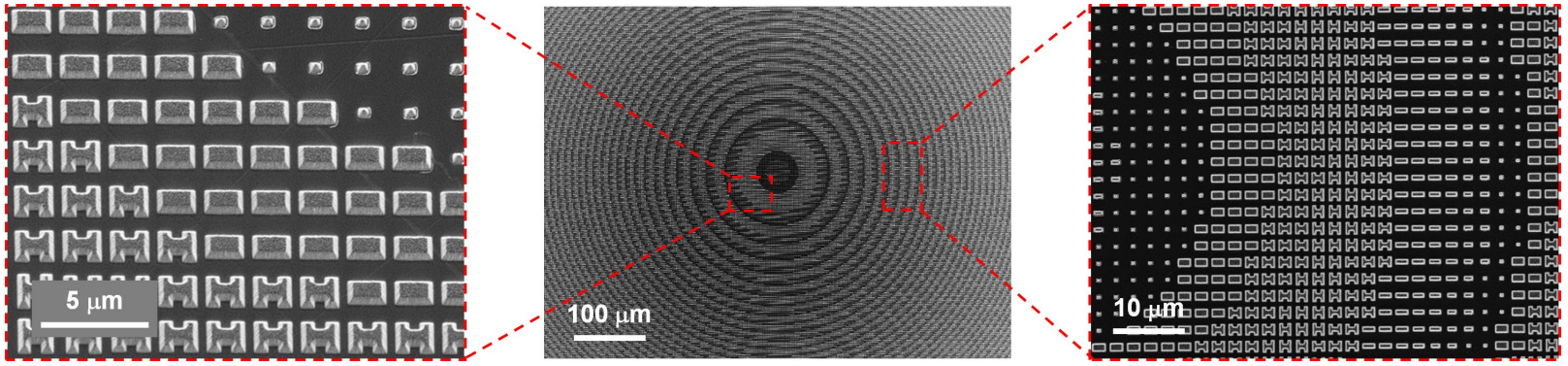
Wavefront shaping using metasurface

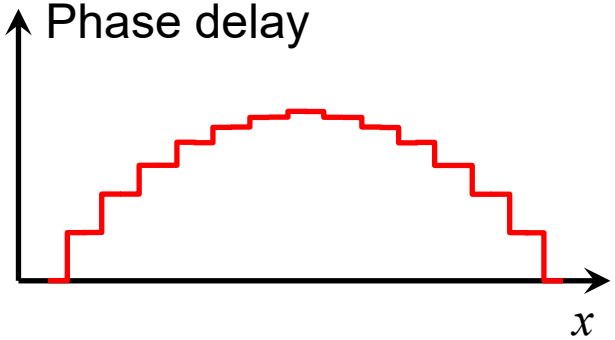




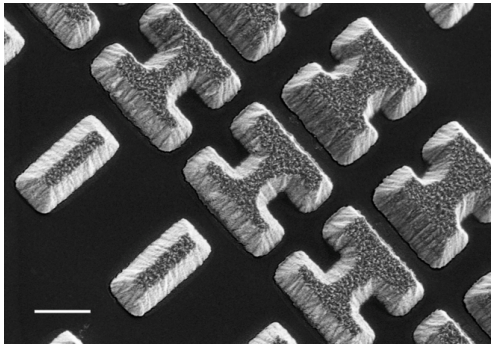


Aspheric Huygens metalens



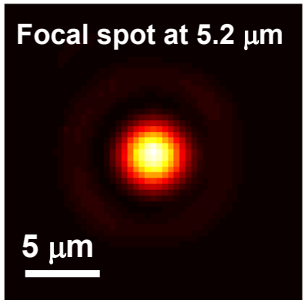


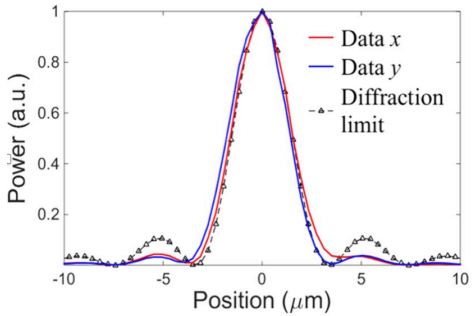
$$\phi_{ideal} = -\frac{2\pi}{\lambda}\left(\sqrt{f^2 + x^2 + y^2} - f\right)$$



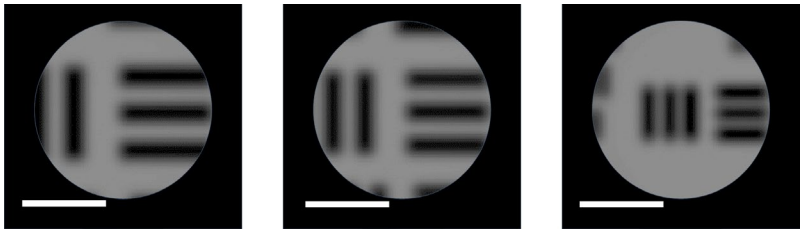
1 x 1 mm^2, NA = 0.71

Diffraction-limited aspheric meta-lens

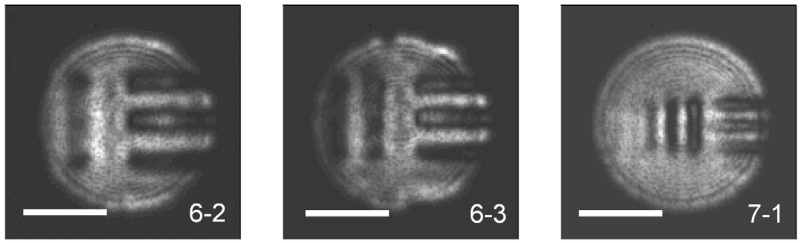




Perfect lens (theory)



Meta-lens (experiment)



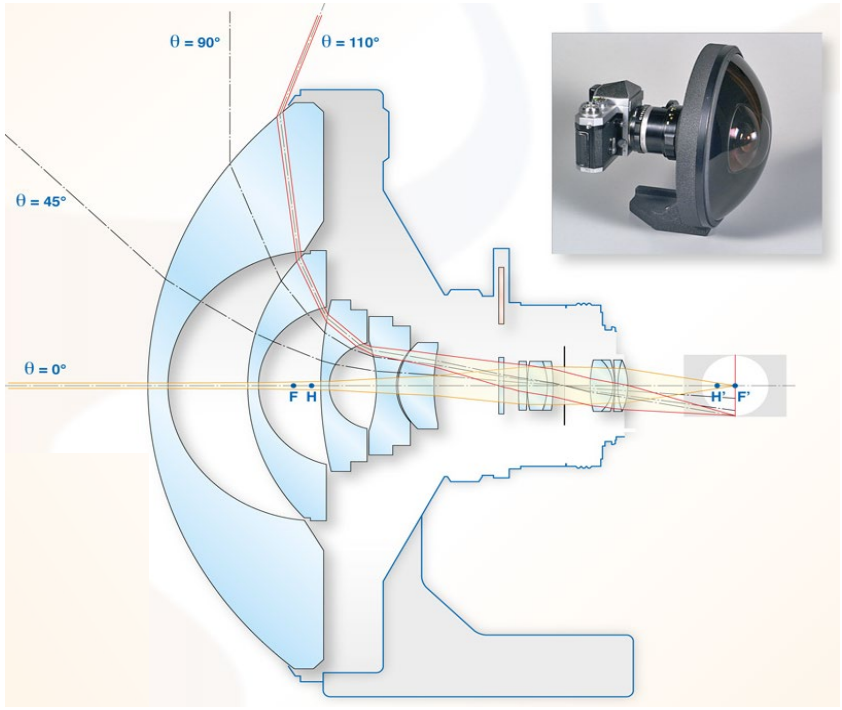
Scale bar: 30 μm

Resolution: 3.9 μm at λ_0 = 5.2 μm

- Focusing efficiency: **75%** (w/o anti-reflection coating)
- Diffraction-limited focusing 5.1 – 5.4 μm
- Sub-wavelength diffraction-limited imaging in mid-IR

Nat. Commun. **9**, 1481 (2018)

Compact, wide field-of-view optics: a critical need



Fisheye-Nikkor 6 mm f/2.8 simplified section:
www.pierretoscani.com/fisheyes-(in-english).html

- Wide field-of-view optical systems are vital for imaging, sensing, and display.
- Conventional wide-angle optical systems are bulky and complicated.

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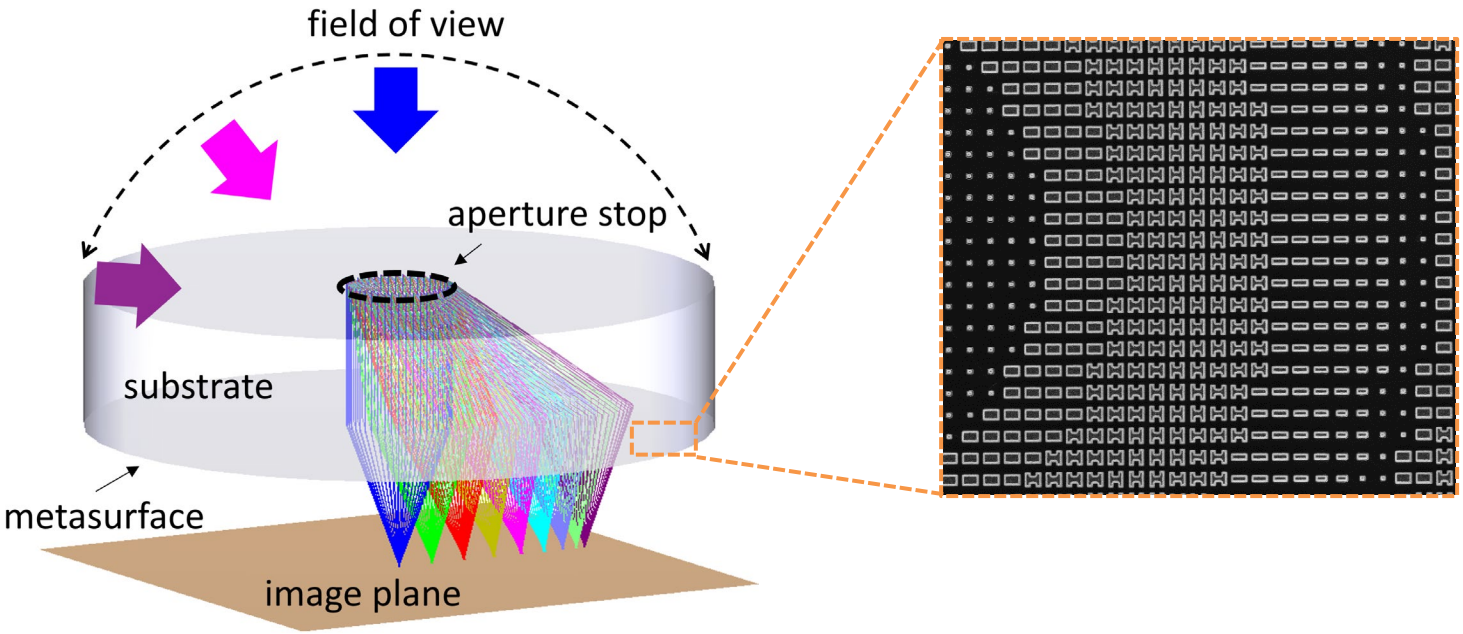
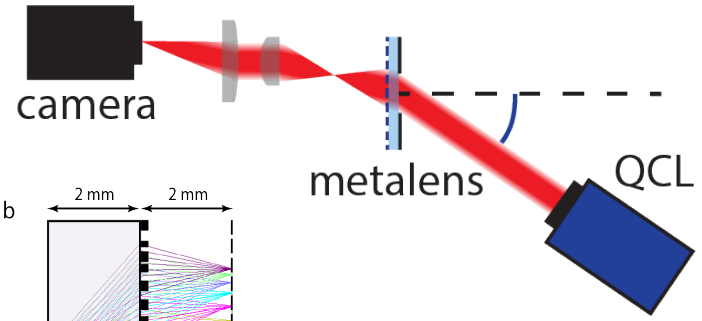
A single-element, flat fisheye metalens

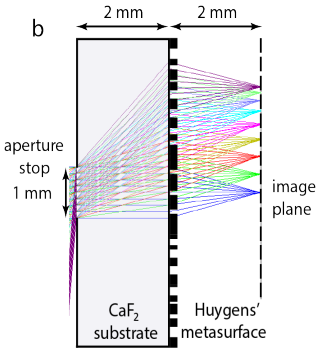


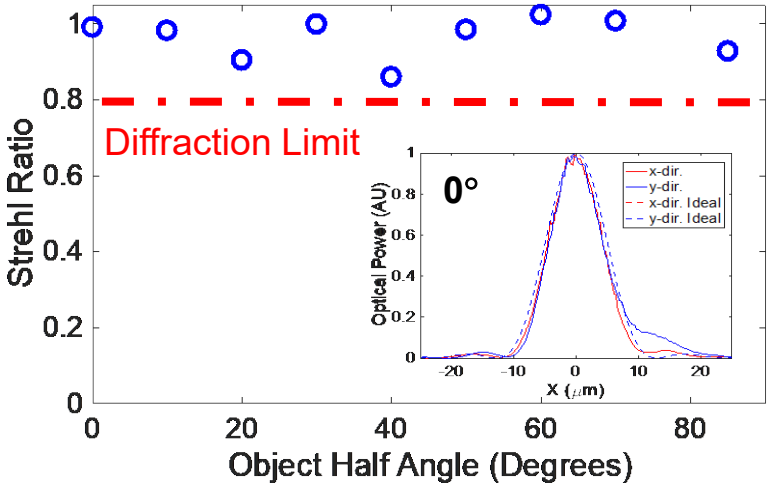
- ✓ **Ultra-wide FOV:** record near-180° FOV
- ✓ **High resolution:** aberration-free performance across the entire FOV
- ✓ **Compact, single-element, light-weight** optical architecture
- ✓ **Generic**, versatile meta-optic platform
- ✓ **Low cost**: compatible with large volume foundry manufacturing

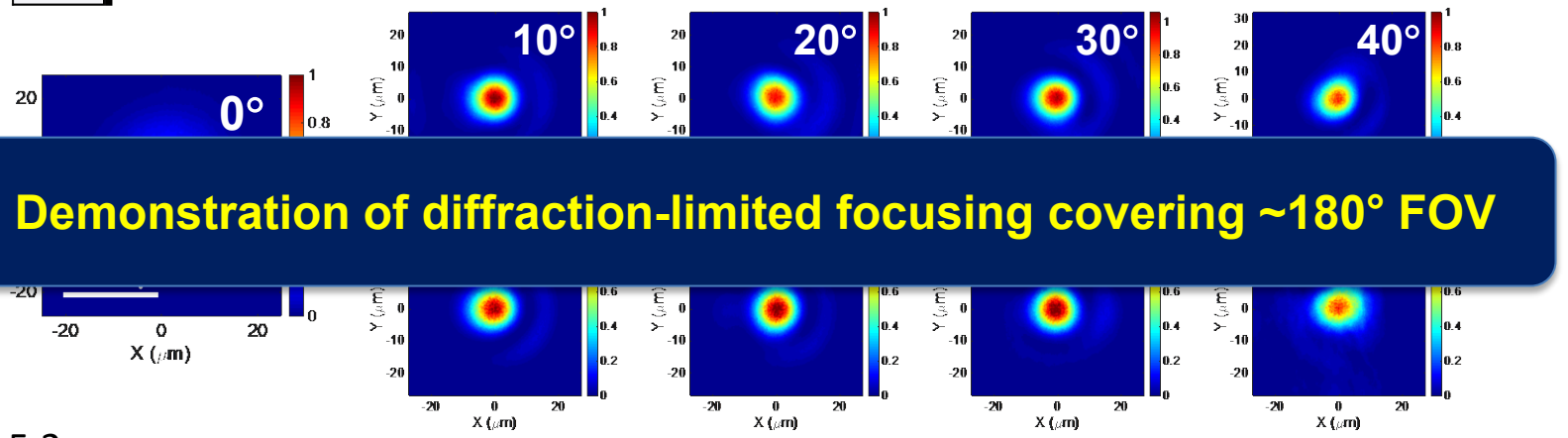
Nano Lett. **20**, 7429-7437 (2020)

Wide-FOV metalens in mid-IR







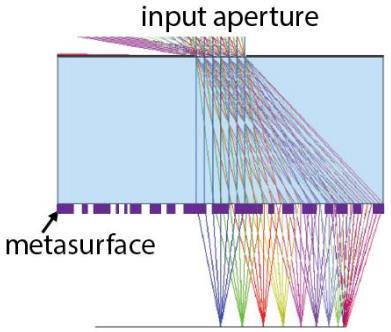


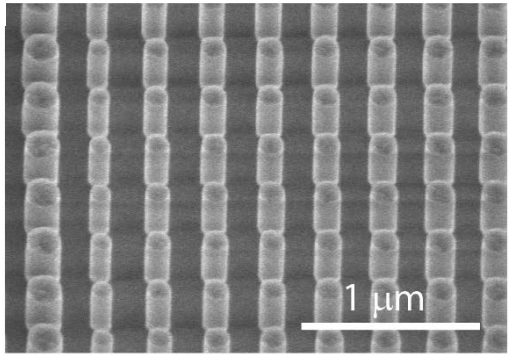
Demonstration of diffraction-limited focusing covering ~180° FOV

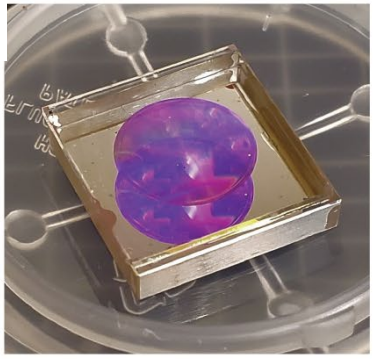
λ_0 = 5.2 μm

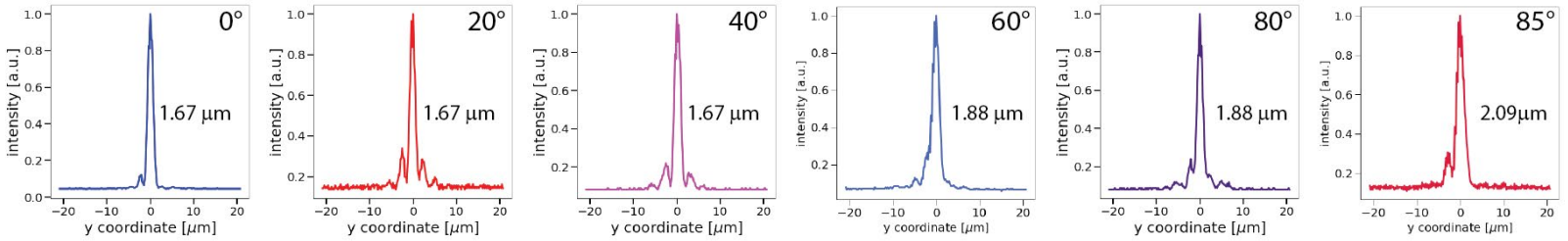
Nano Lett. **20**, 7429-7437 (2020)

Wide-FOV metalens in visible





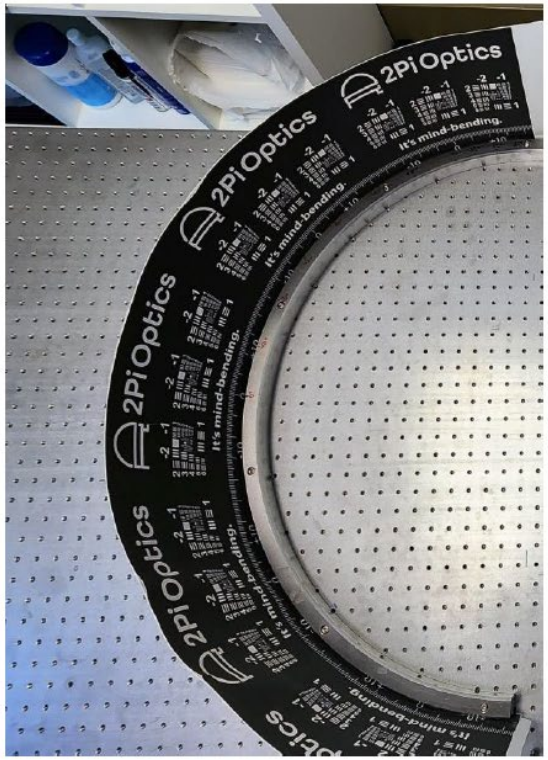




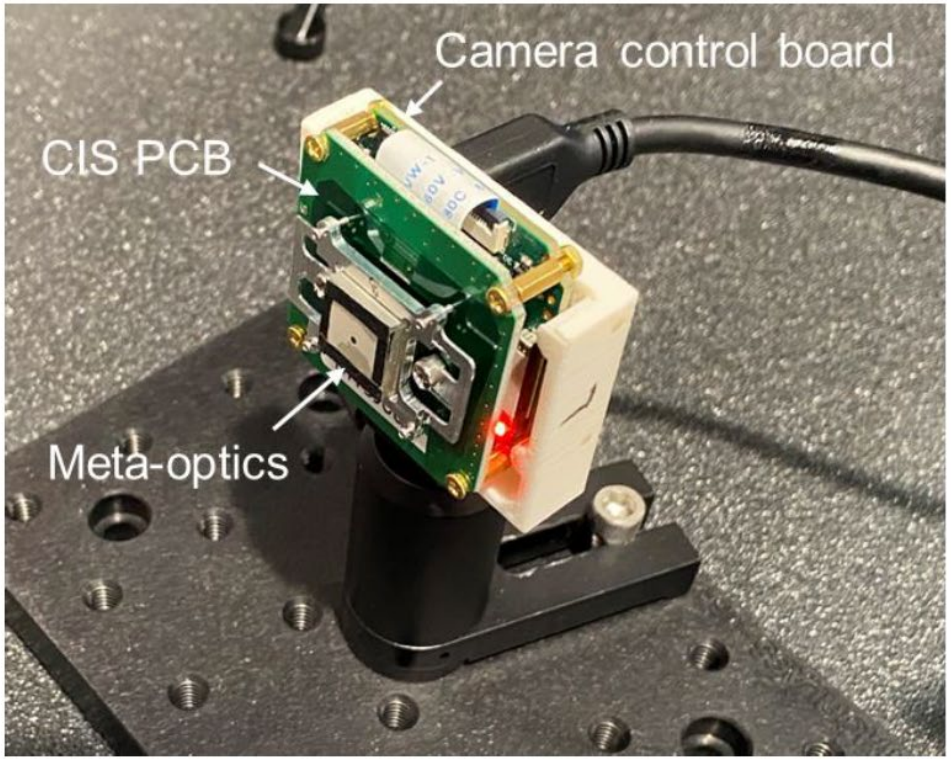
Near diffraction limit imaging over ~180° FOV

λ_0 = 670 nm

Fisheye meta-camera in near-NIR



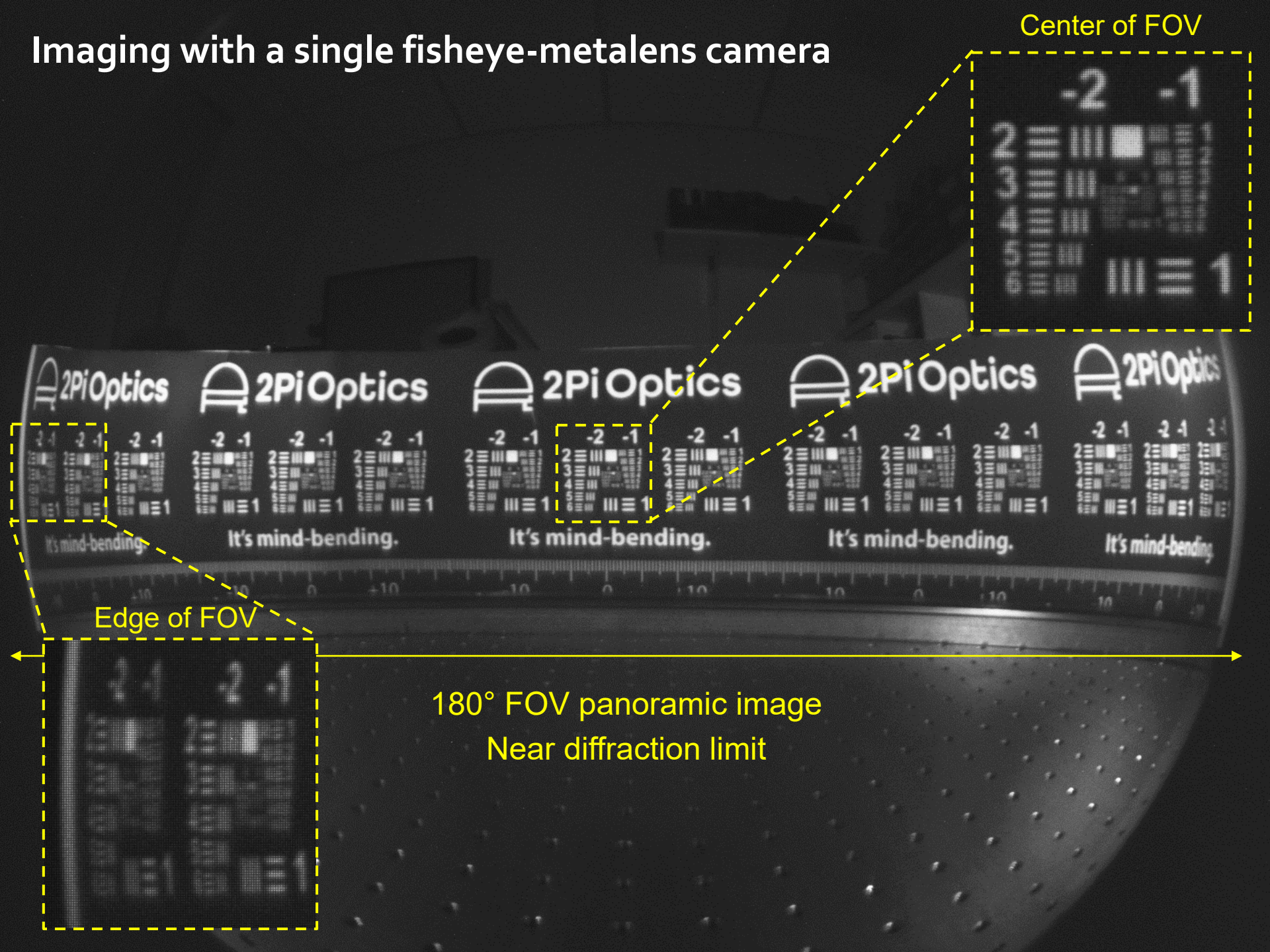
Circular 180° target

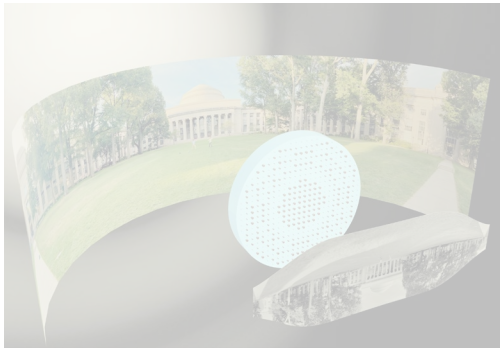


Metalens + image sensor assembly

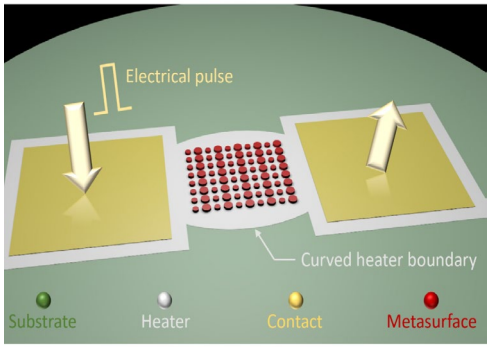
λ_0 = 940 nm

Imaging with a single fisheye-metalens camera

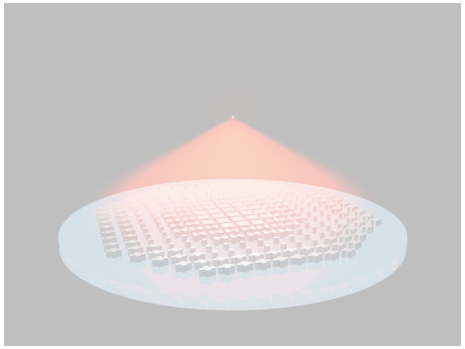




Ultra-compact metasurface flat opics



Active optics & photonics platform



Reconfigurable meta-optics

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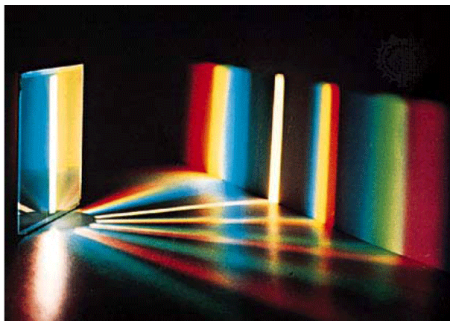
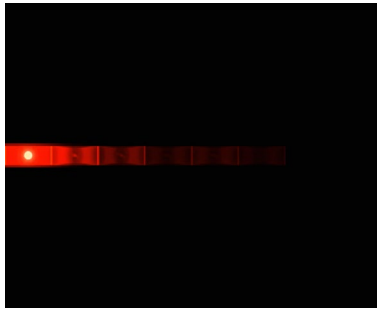
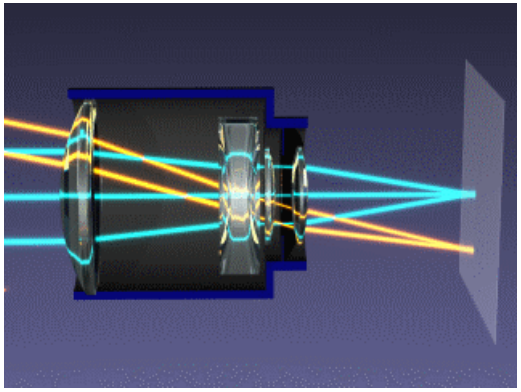
Reconfigurable optics and photonics



Tunable grating



Variable Lens

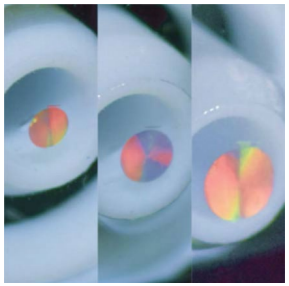


...

Nat. Photon. **17**, 48 (2023)

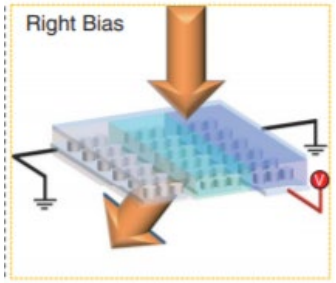
Active metasurfaces: tuning mechanisms

Mechanical

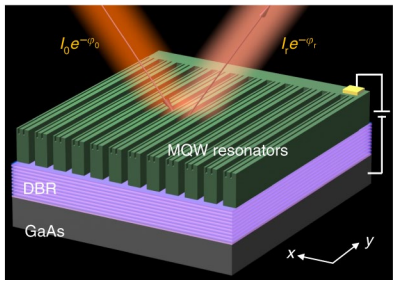


Laser Photon. Rev. **10**, (2016)

Electro-optic

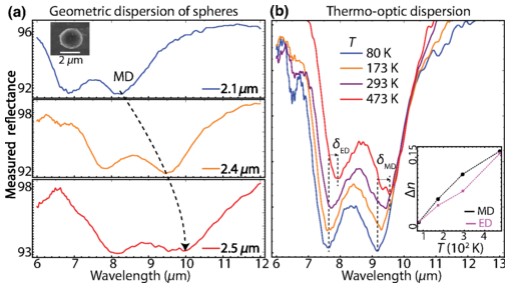


Science **364**, 1087 (2019)



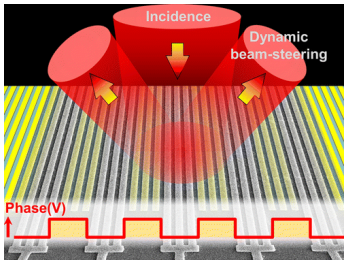
Nat. Commun. **10**, 3654 (2019)

Thermo-optic

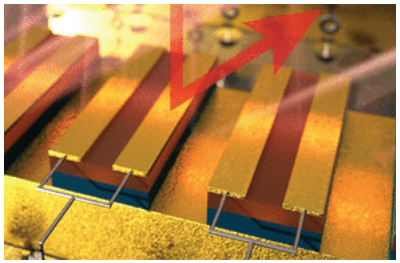


Phys. Rev. Appl. **10**, 044029 (2018)

Free-carrier injection

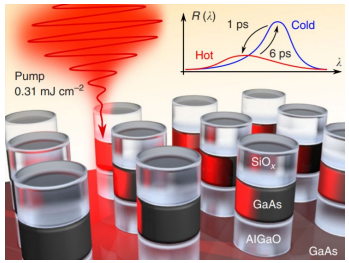


Nano Lett. **16**, 5319 (2016)



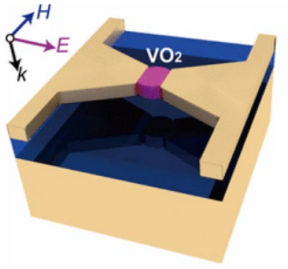
ACS Photonics **6**, 1345 (2019)

All-optical



Nat. Commun. **8**, 17 (2017)

Phase transition

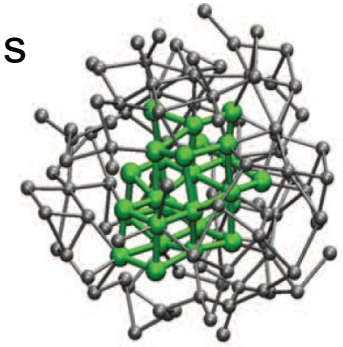


Nano Lett. **17**, 4881 (2017)

…magneto-optical, electrochemical, hydrogenation, and others…

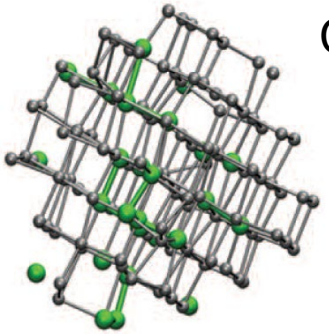
Phase change materials (PCMs)

Amorphous



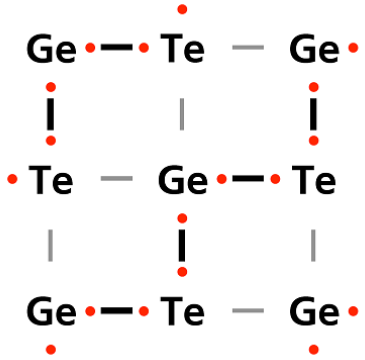
Quench

Anneal

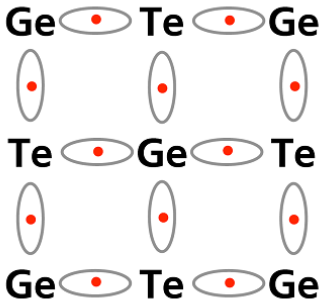


Crystalline

Covalent bonding



Large electrical & optical contrasts

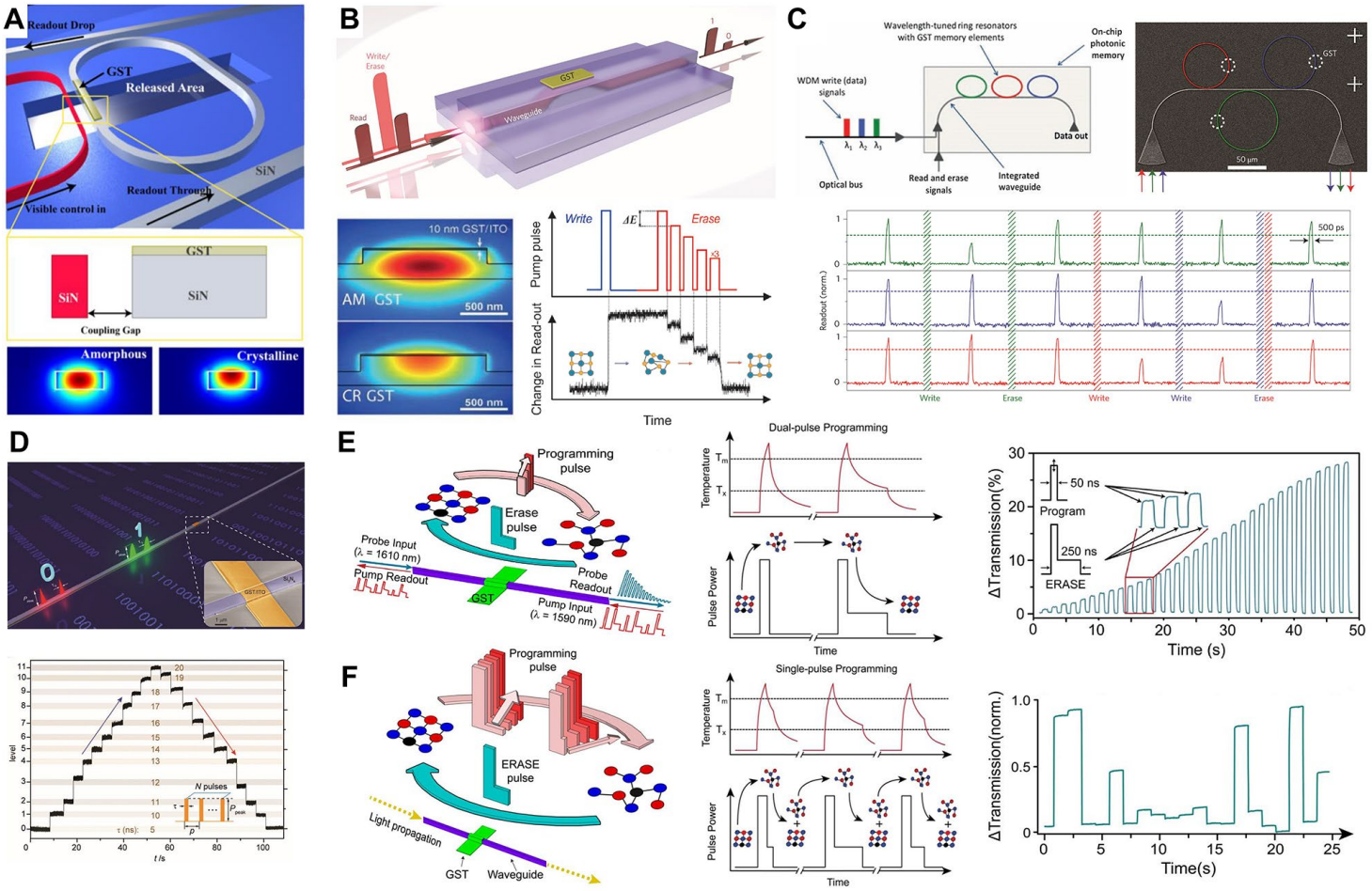


Resonant (metavalent) bonding

Adv. Mater. **31**, 1806280 (2019)

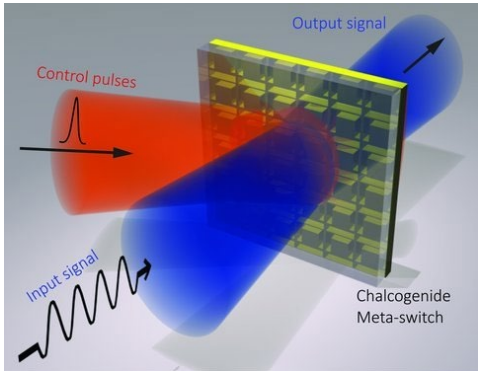
Non-volatile photonic reconfiguration

PCM-based reconfigurable integrated photonics

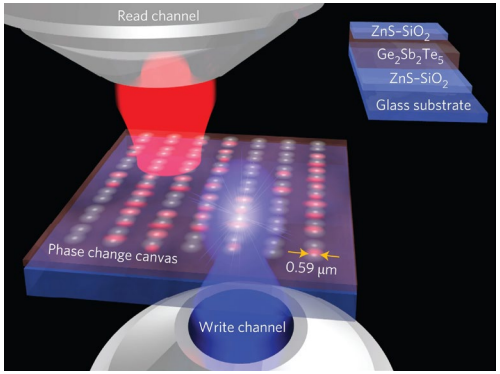


Nanophotonics **9**, 1189 (2020)

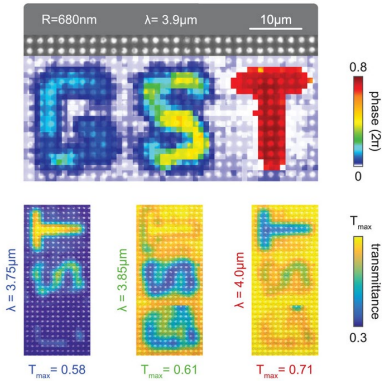
PCM-based active metasurface devices



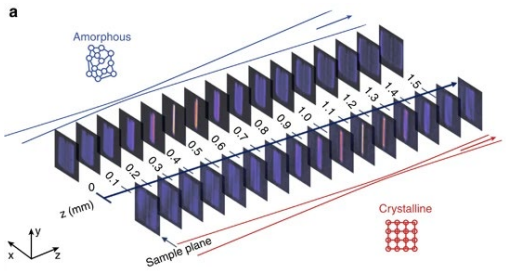
Adv. Mater. **25**, 3050 (2013)



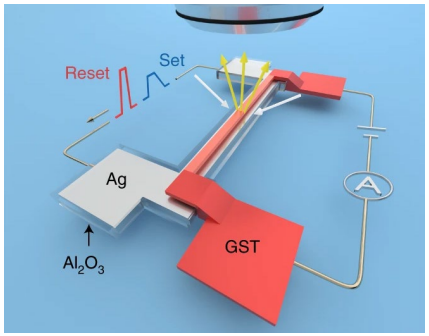
Nat. Photonics **10**, 60 (2016)



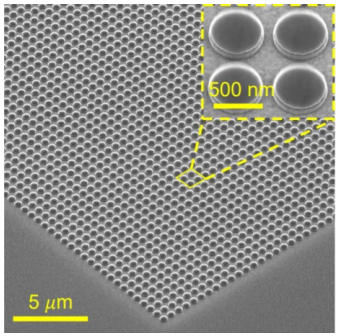
Adv. Funct. Mater. **30**, 1910259 (2020)



Light Sci. Appl. **6**, e17016 (2017)



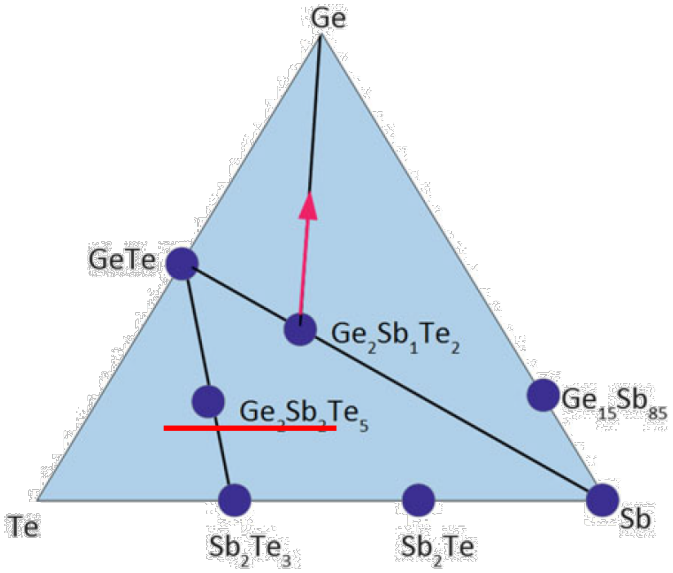
Nat. Nanotechnol. **16**, 667 (2021)

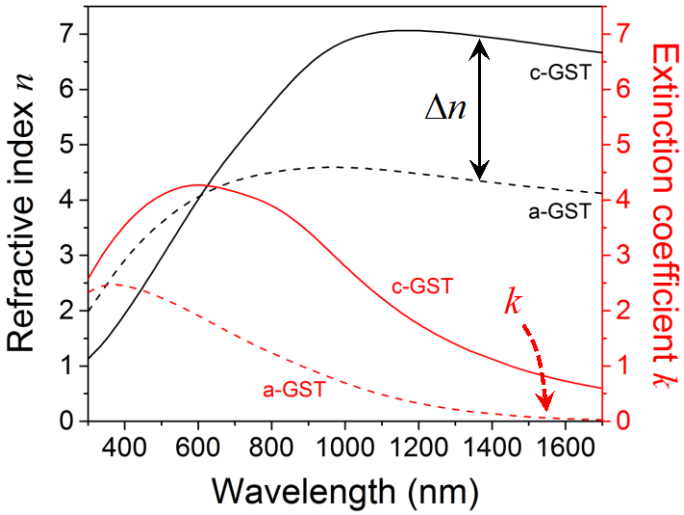


Nano Lett. **21**, 1238 (2021)

and many others…

The classical Ge-Sb-Te-225 alloy is optically lossy





$$\text{FOM} = \frac{\Delta n}{k}$$

Δn → Index change: the desired modulation effect

k → Optical absorption: the unwanted loss penalty

- ✓ Index change: Δn = 2.6
- × Loss: k = 0.06 (a) / 1.1 (c) @ 1550 nm (**2.2 dB/μm (a) / 40 dB/μm (c)**)

PMAT

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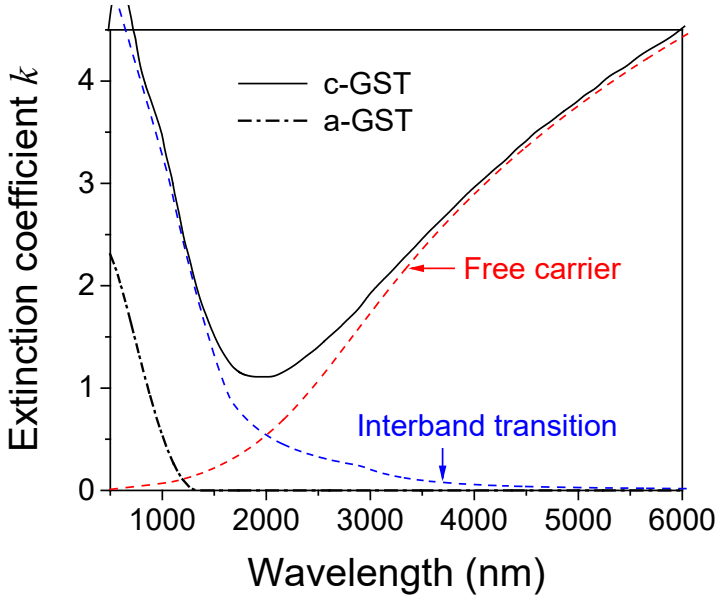
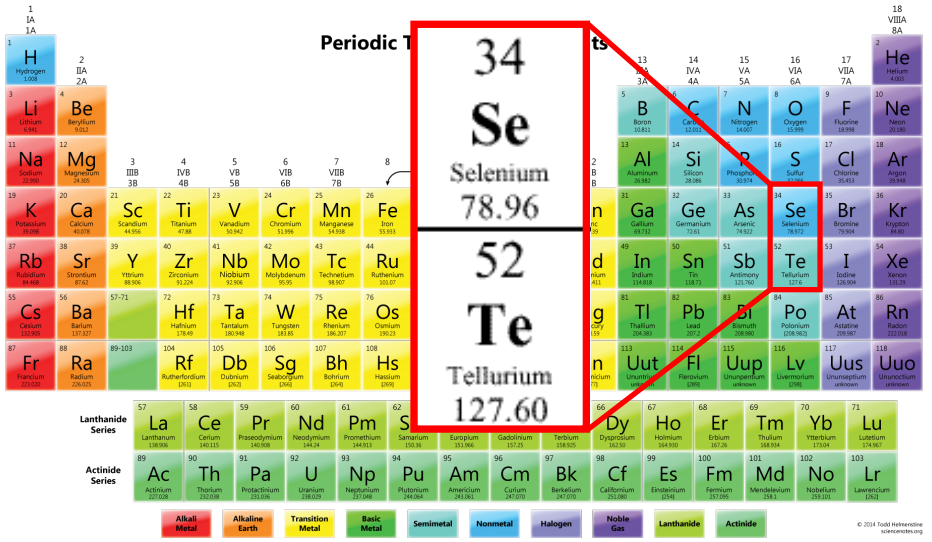
Photonic MATerials

Mitigating optical losses in O-PCM



Ge-Sb-Se-Te (GSST)



Se substitution of Te leads to:

- ✓ Bandgap increase: low loss operation in 1310 nm and 1550 nm
- ✓ Free carrier mobility decrease: suppress FCA in IR
- ✓ Improved glass stability from increased crystallization temperature

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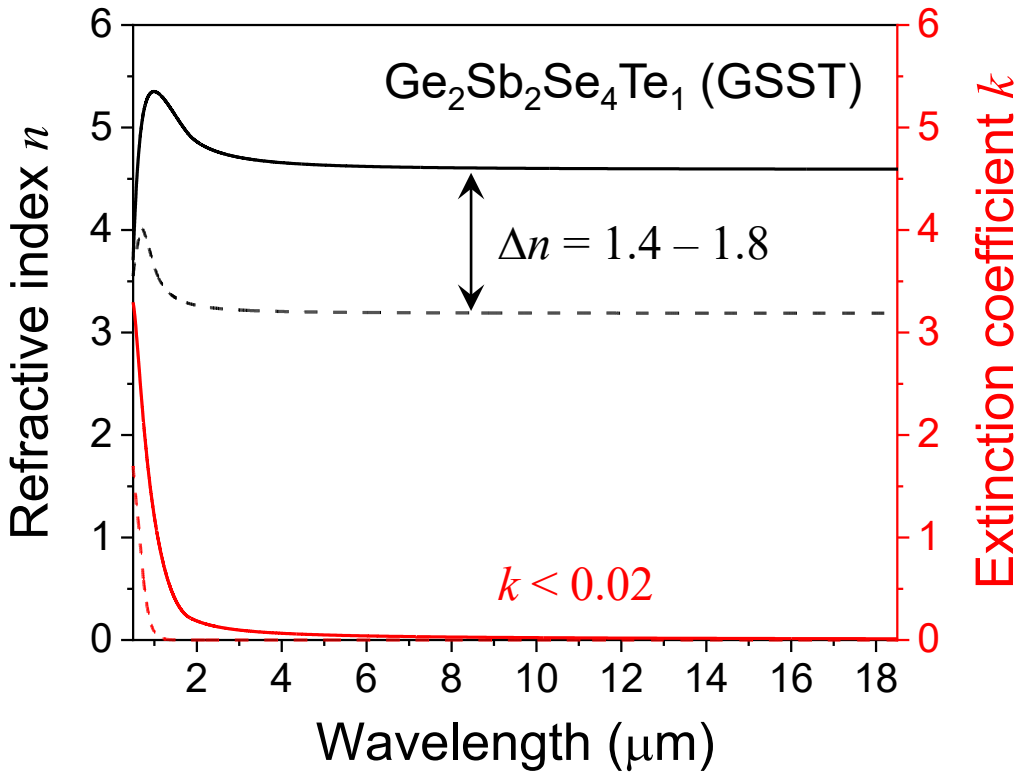
GSST: an extreme broadband transparent phase change alloy



- ✓ Index change: Δn = 1.4 – 1.8
- ✓ Loss: k < 0.02

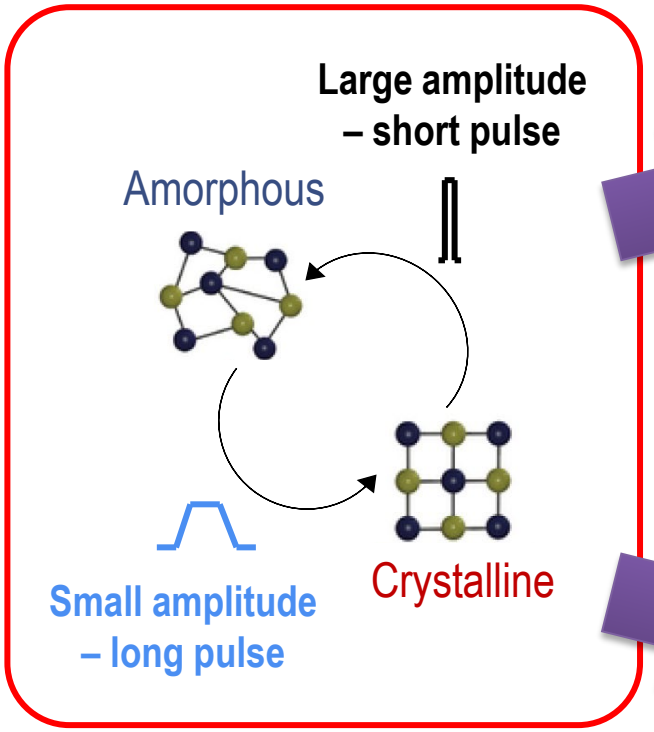
1 – 18.5 μm (a)
5 – 18.5 μm (c)

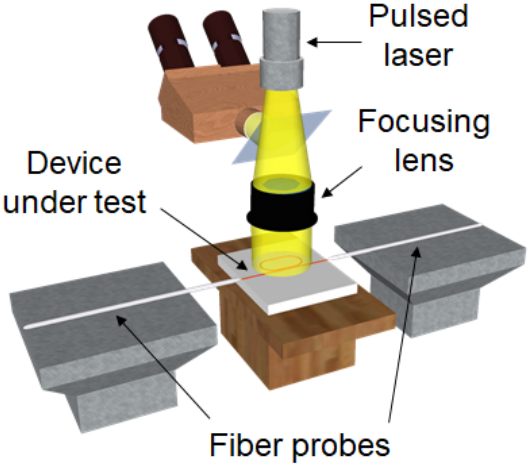
$$\text{FOM} = \frac{\Delta n}{\quad}$$

FOM **100x** higher than GST-225

Broadband transparency covering 1 micron to LWIR.

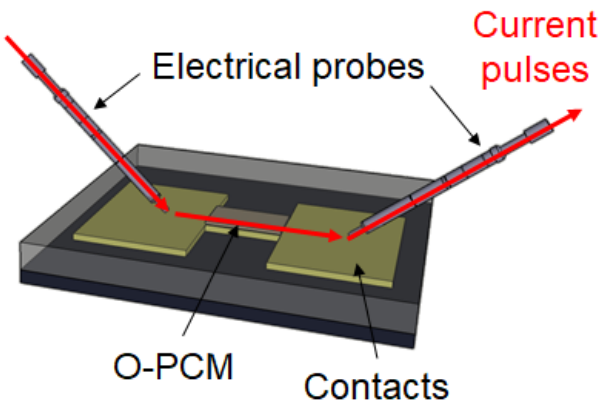
Optical and electrical switching of GSST





Optical
(laser) switch

Electrical
switch



- ✓ Bi-directional, complete switching
- ✓ Scalable to large-area arrays

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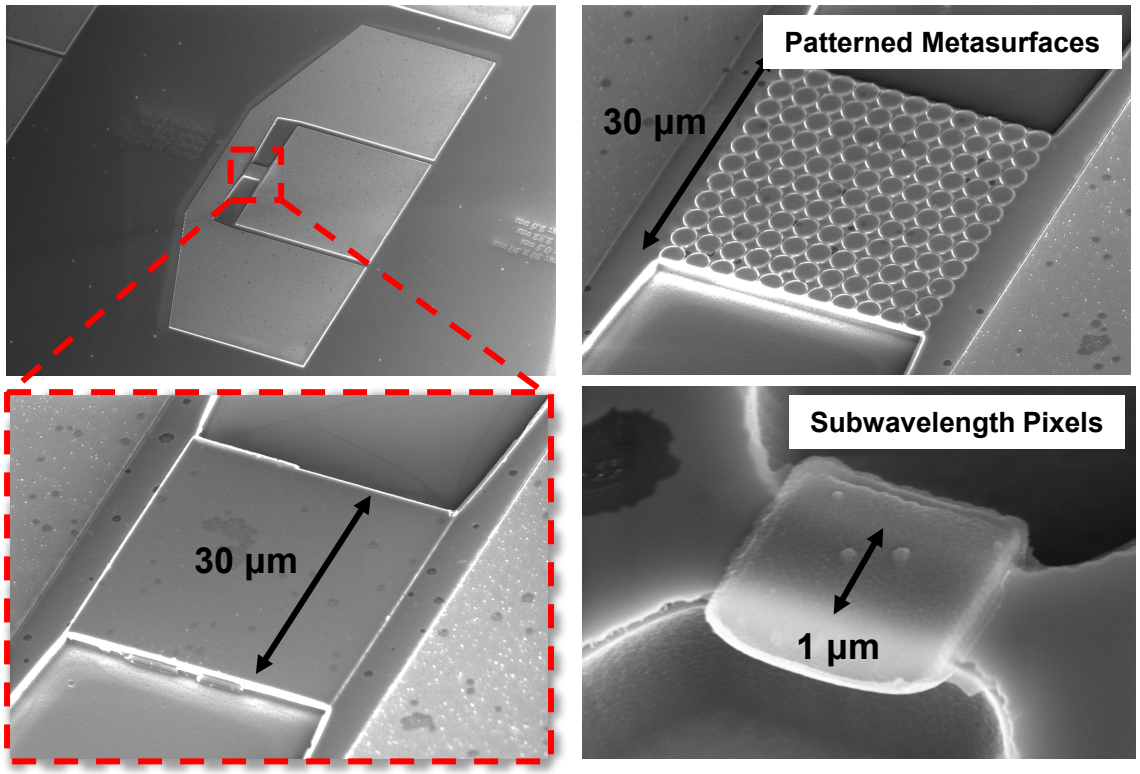
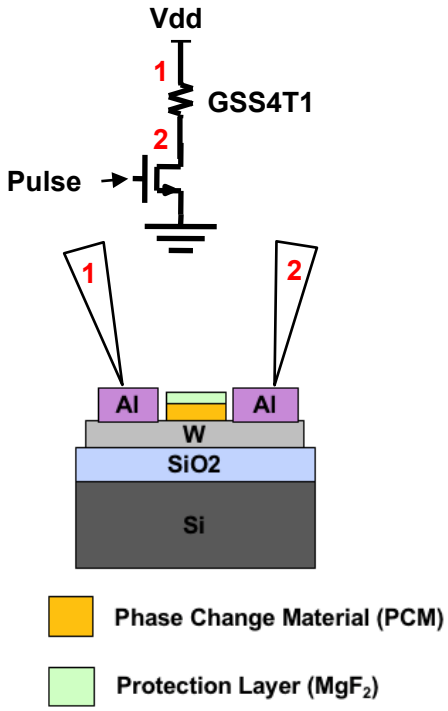
Photonic MATerials

Free-space reflective light modulator pixel





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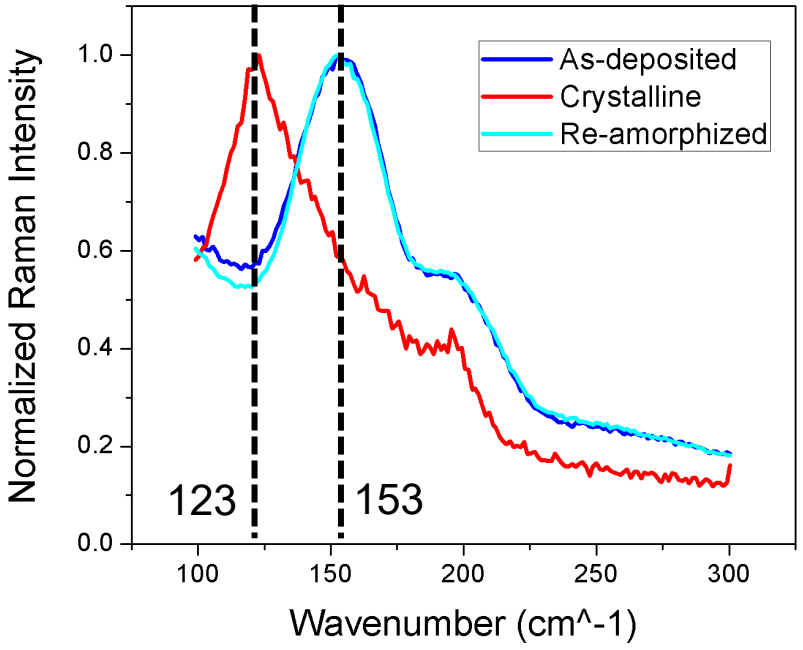
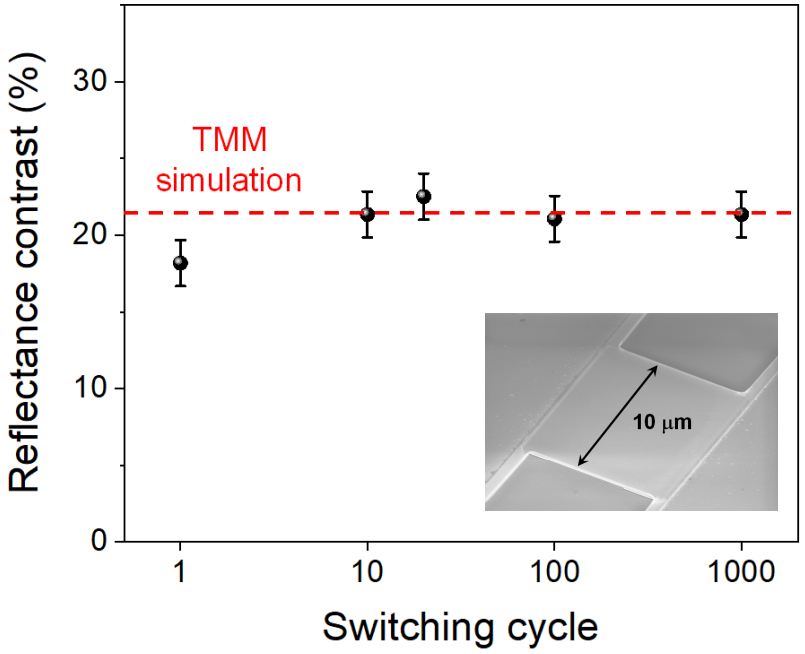
GSST switching characterization

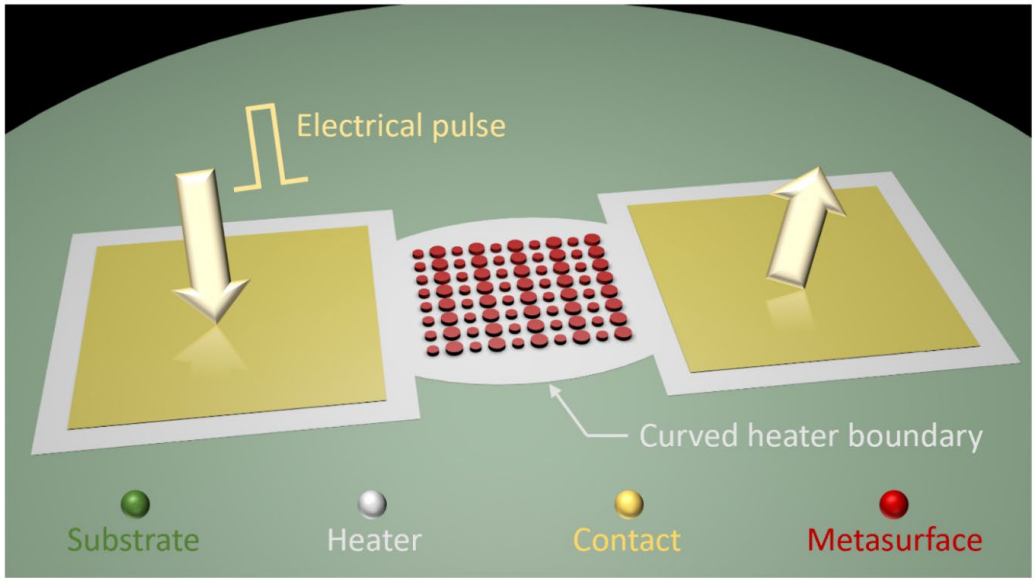


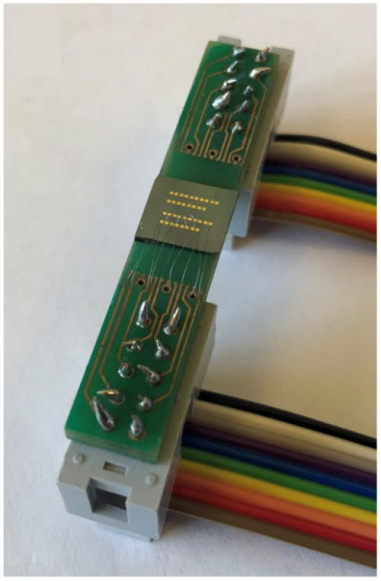


Raman spectroscopy confirms structural transition

1000-cycle switching with 21% absolute reflectance contrast

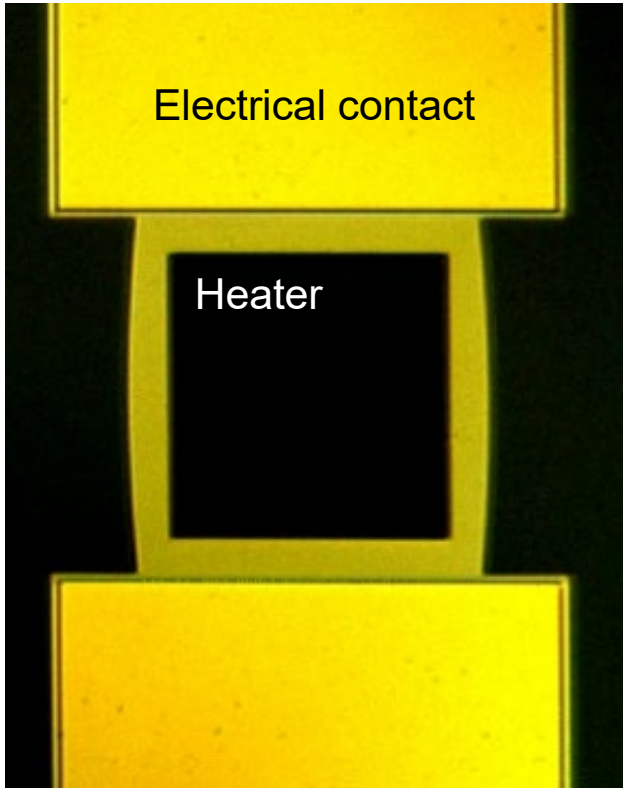
Electrically tuned metasurface using metal heaters



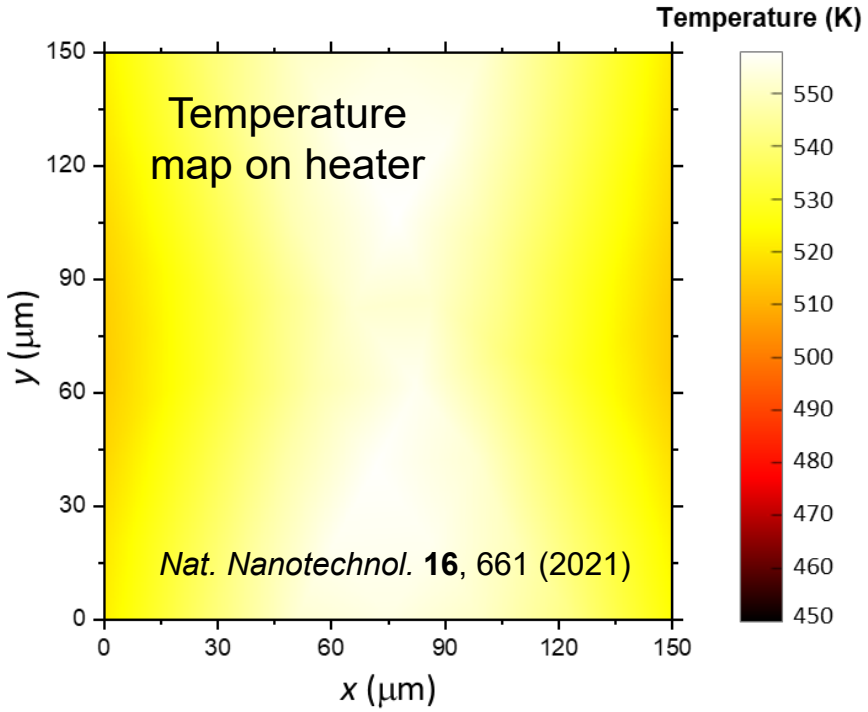


First electrically switched PCM metasurface

Heater geometry optimization

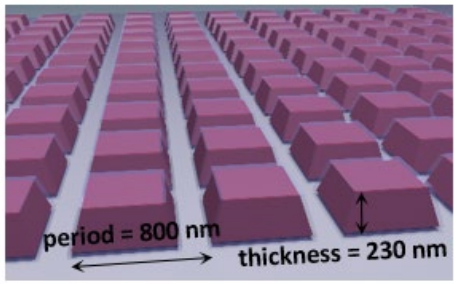


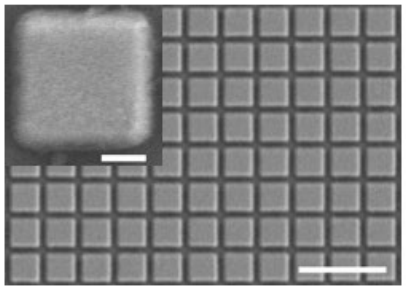
Optimized heater design
with **curved** boundaries



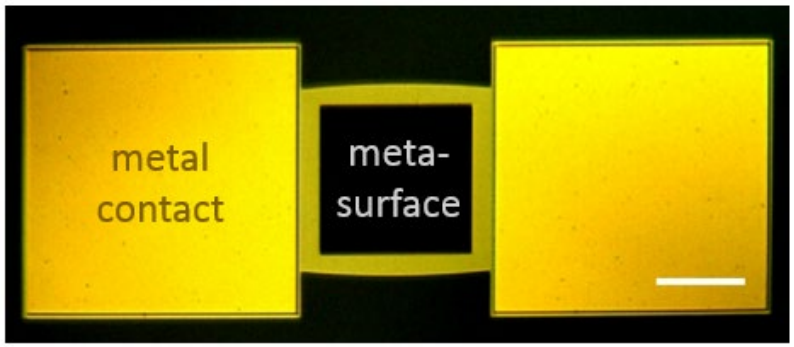
Enhanced thermal uniformity allows large optical aperture

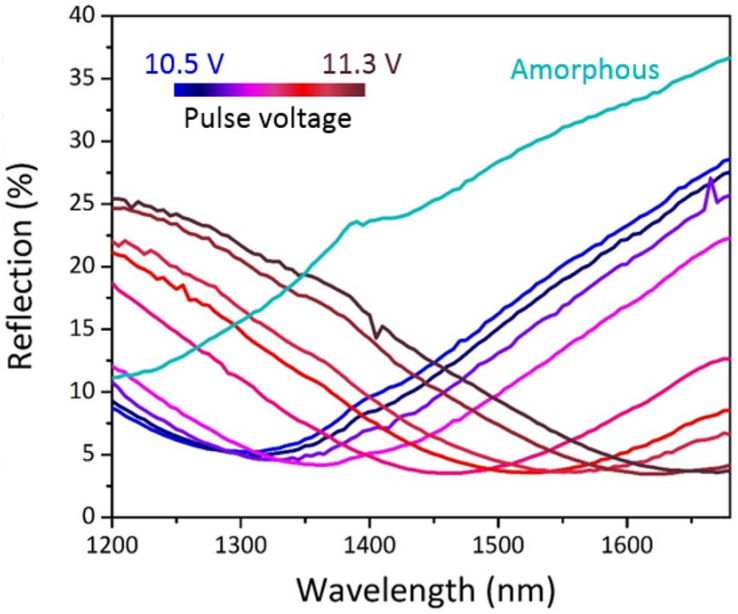
Electrically tuned metasurface using metal heaters





dipole-like resonant mode (A); quadrupole-like mode (c)

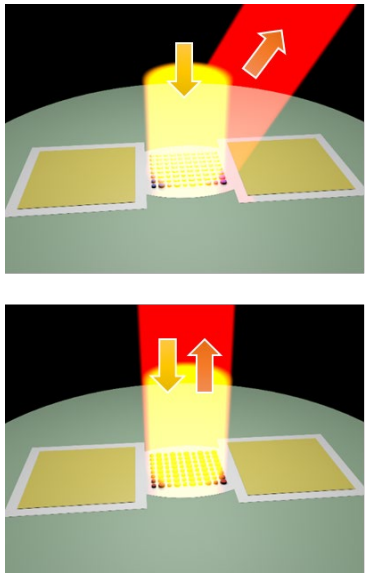


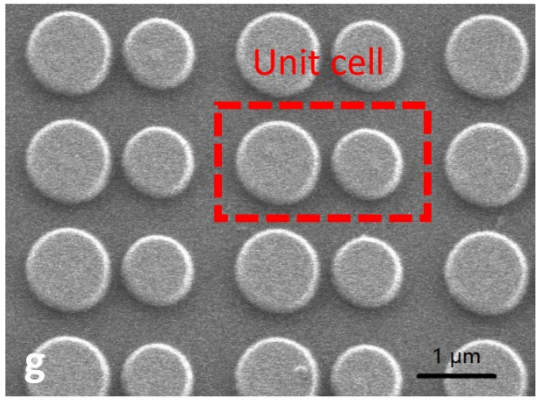


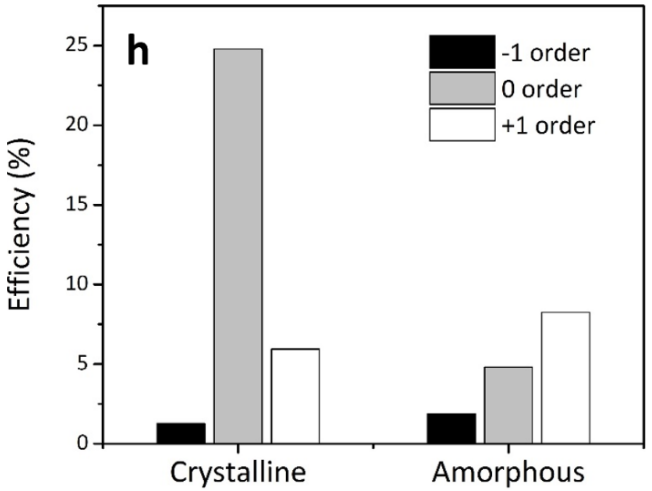
Half-octave (480 nm) spectral tuning

First electrically switched PCM metasurface

Electrically tuned metasurface beam reflector



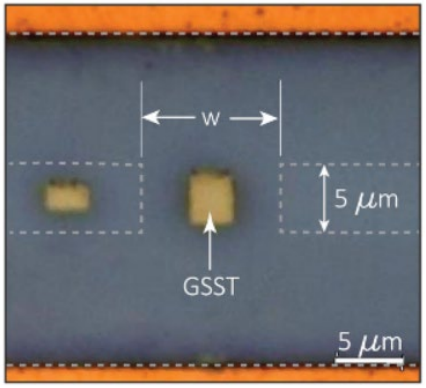


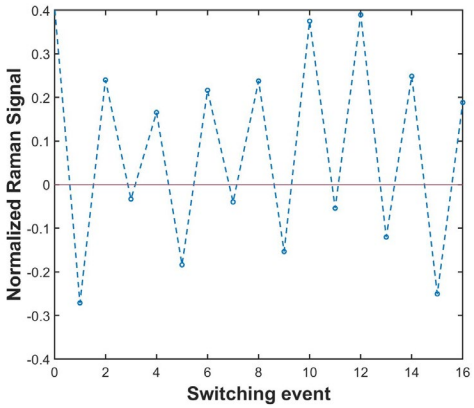


Polarization-insensitive wavefront control using a reconfigurable metasurface.
Deflection angle: 32˚

Nat. Nanotechnol. **16**, 661 (2021)

Integrated PCM micro-heater platforms

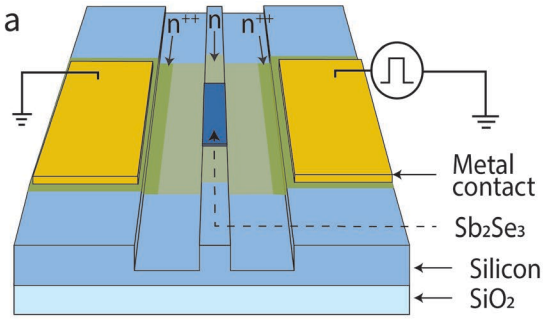


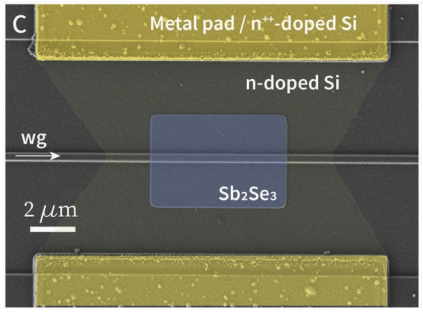


Crystallization: 20 ms, 6V, ~212 μJ
Amorphization: 13 μs, 7.5 V, 0.22 μJ

Electrothermal switching of PCM using a single-layer graphene microheater

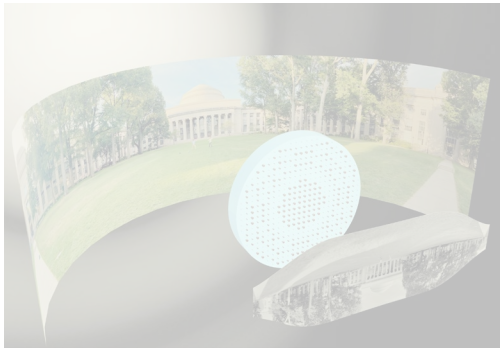
Adv. Photonics Res. 2000034 (2020)



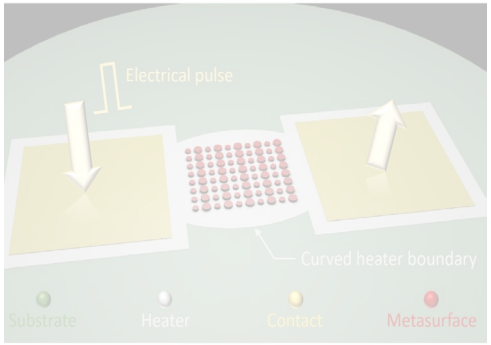


Nonvolatile phase shifter for Si photonics by electrothermal switching

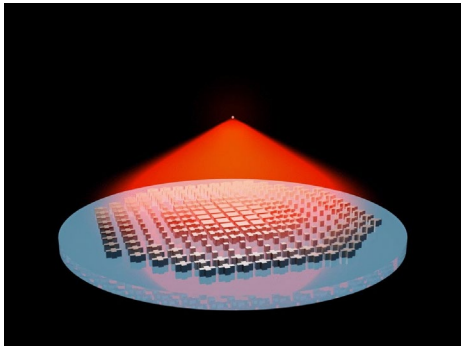
PhotoniX **3**, 26 (2022)



Ultra-compact metasurface flat opics



Active optics & photonics platform



Reconfigurable meta-optics

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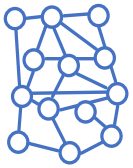
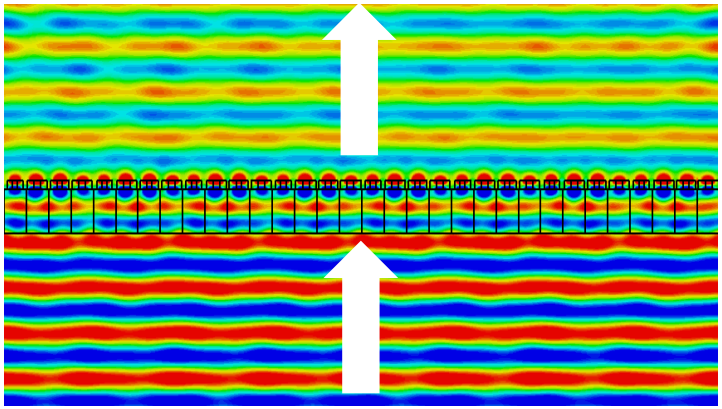
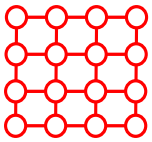
Reconfigurable metasurface

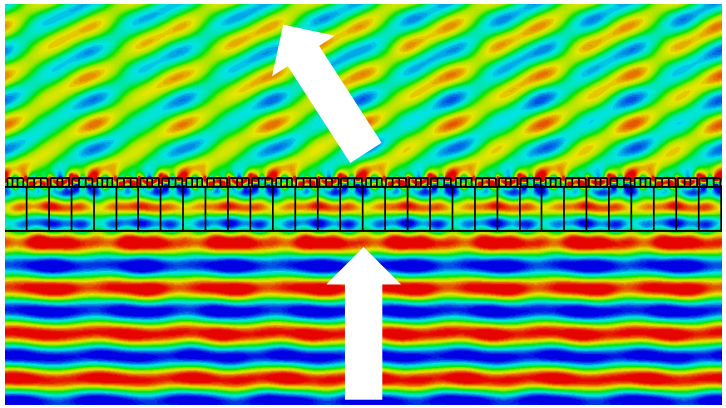
Amorphous



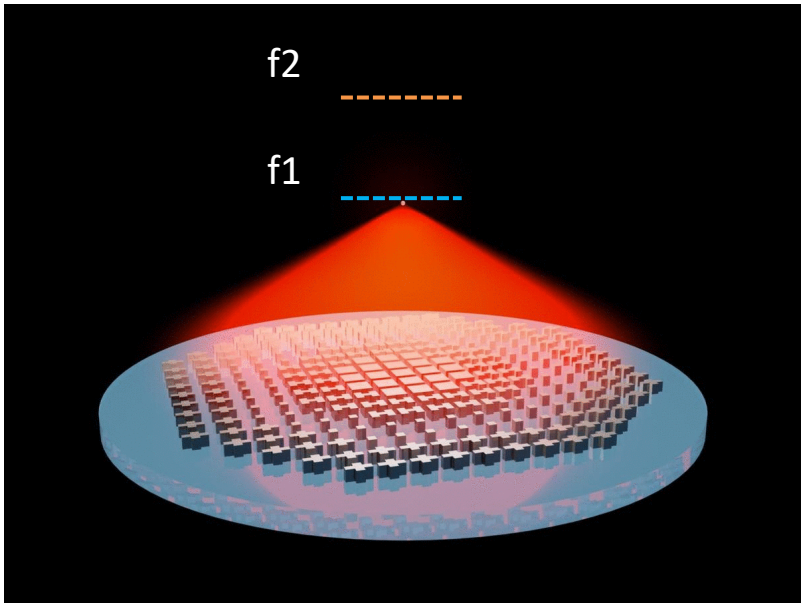


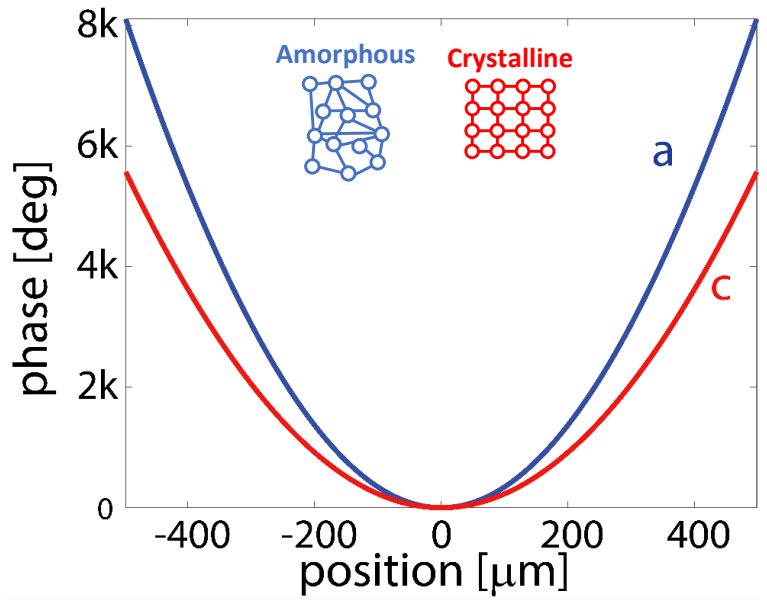
Crystalline





GSST varifocal metalens: concept





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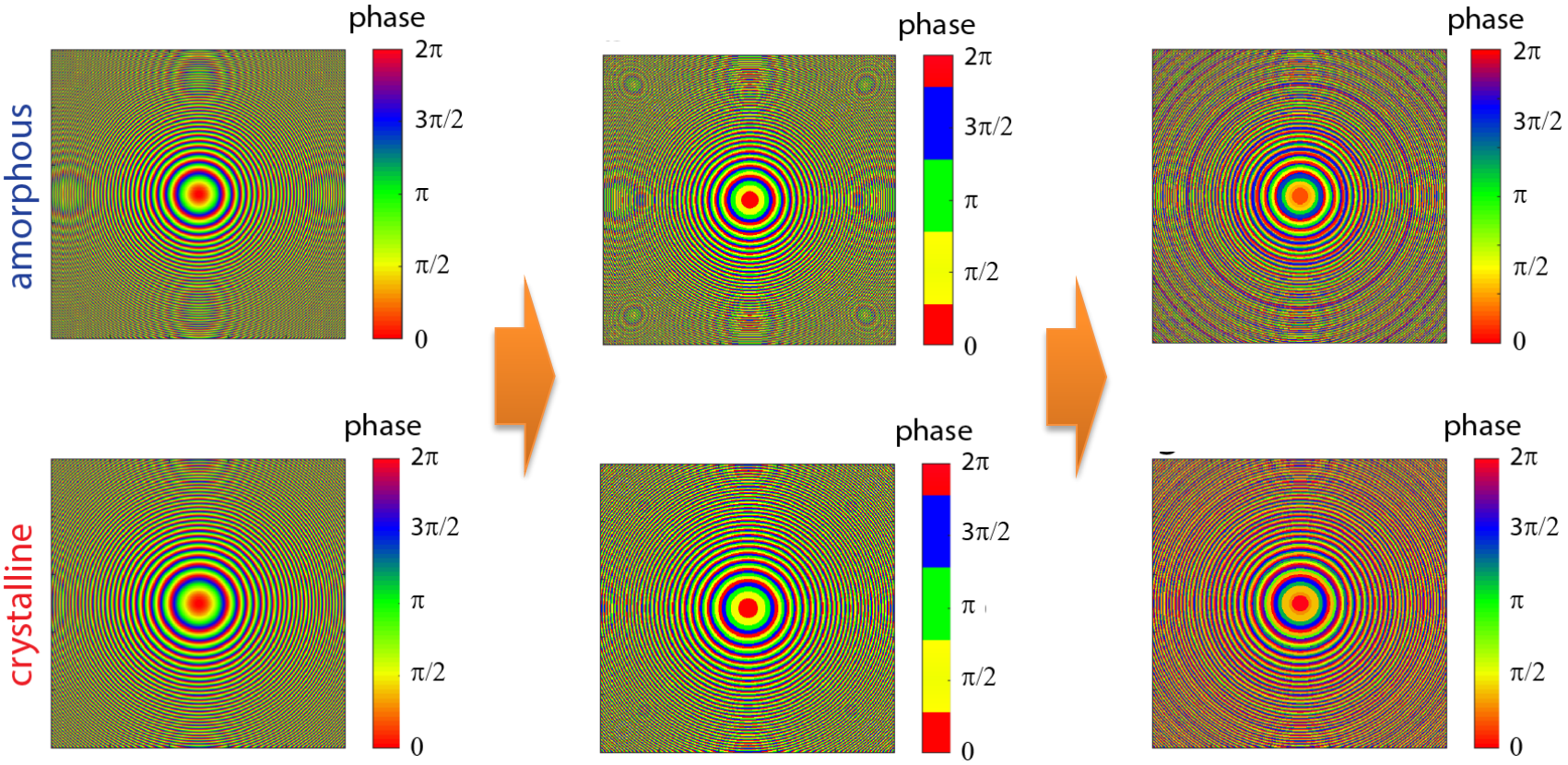
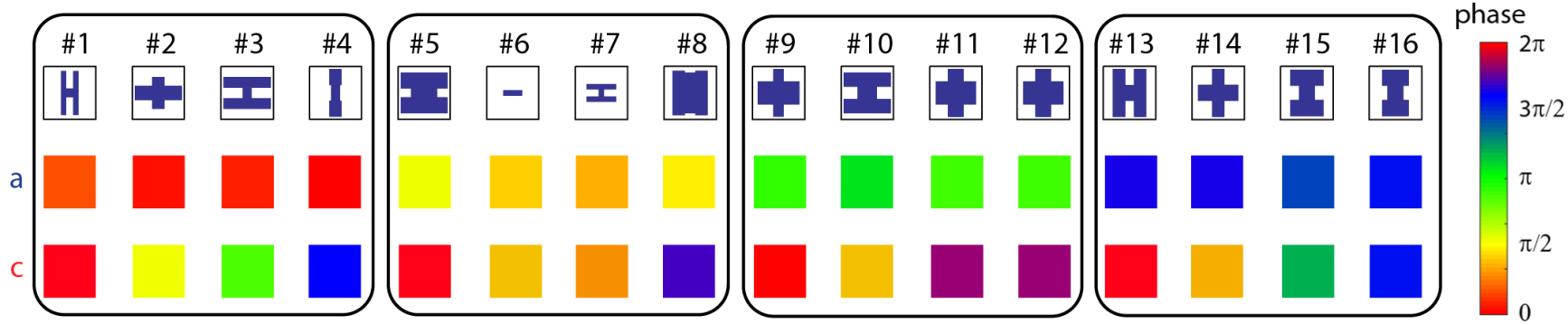
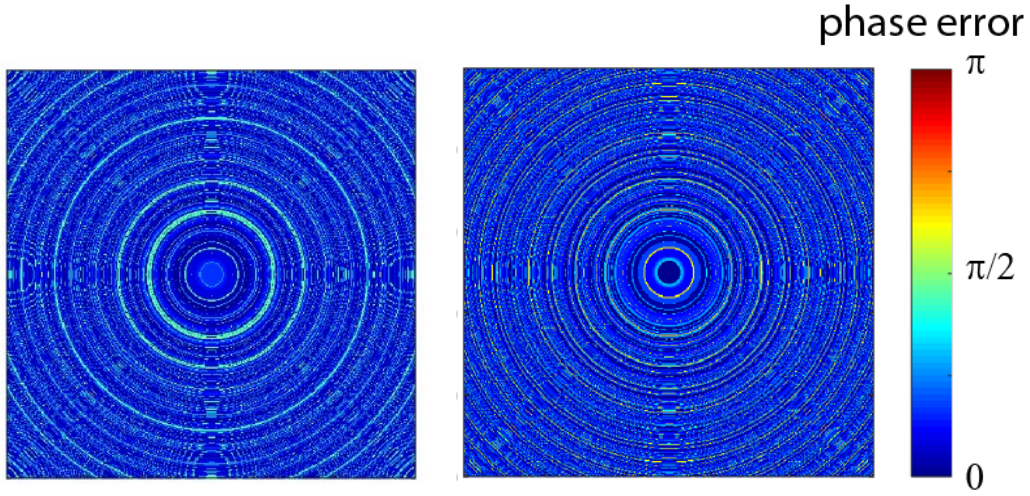
GSST varifocal metalens: design



GSST varifocal metalens: design

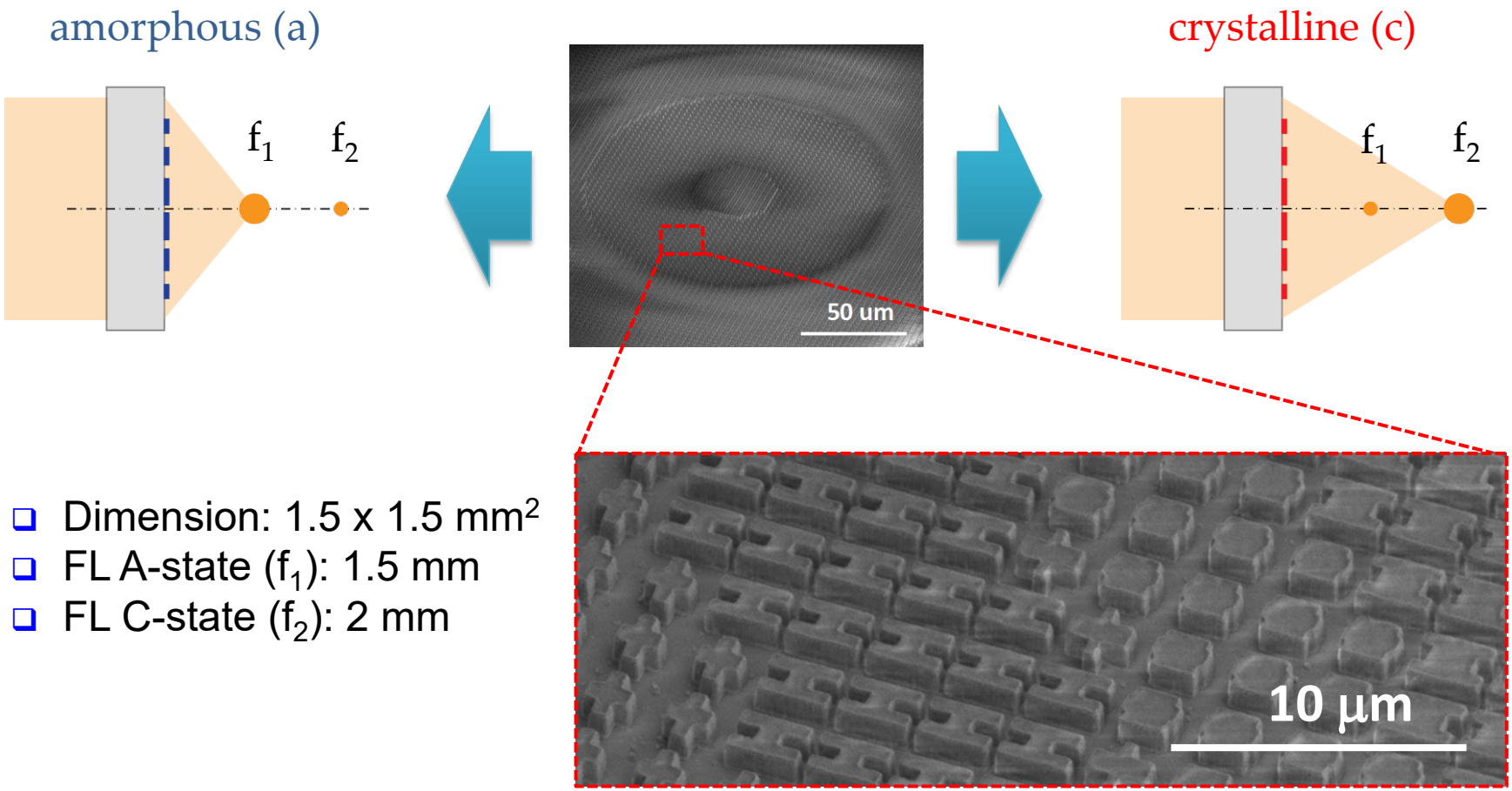




Switch a metasurface with **m** phase levels between **n** states requires $\mathbf{m}^{\mathbf{n}}$ meta-atoms

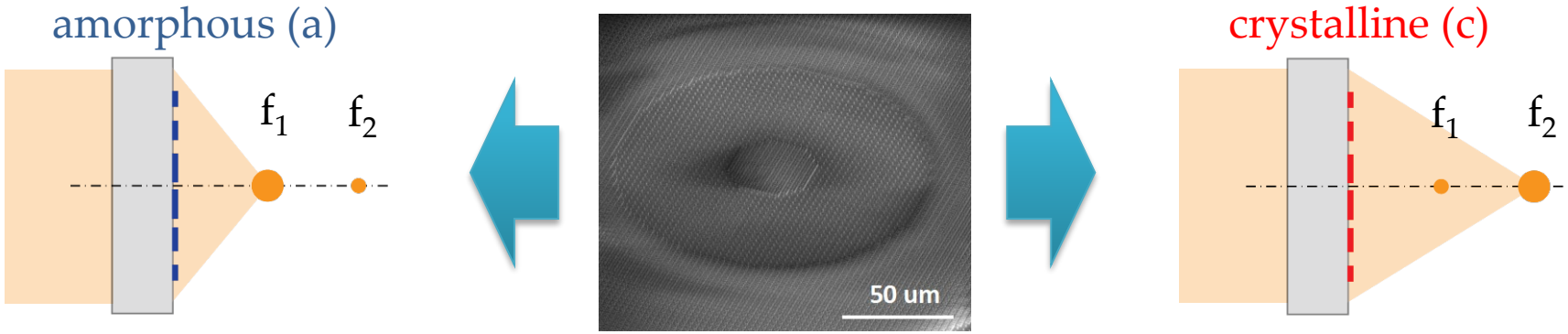
Nat. Commun. **12**, 1225 (2021)

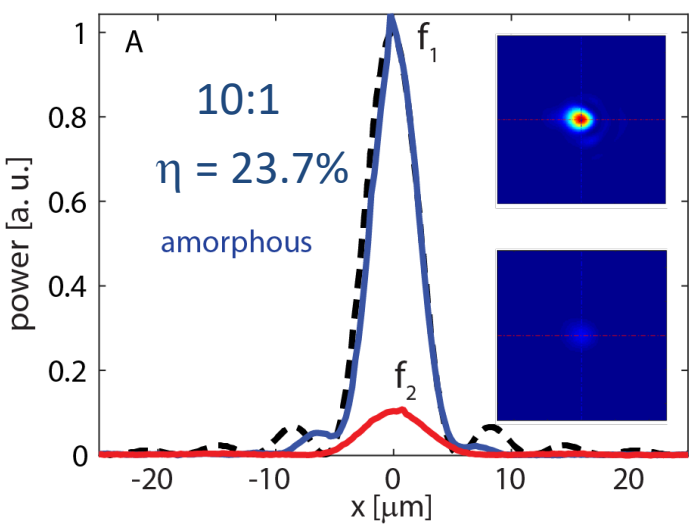
GSST varifocal metalens: fabrication

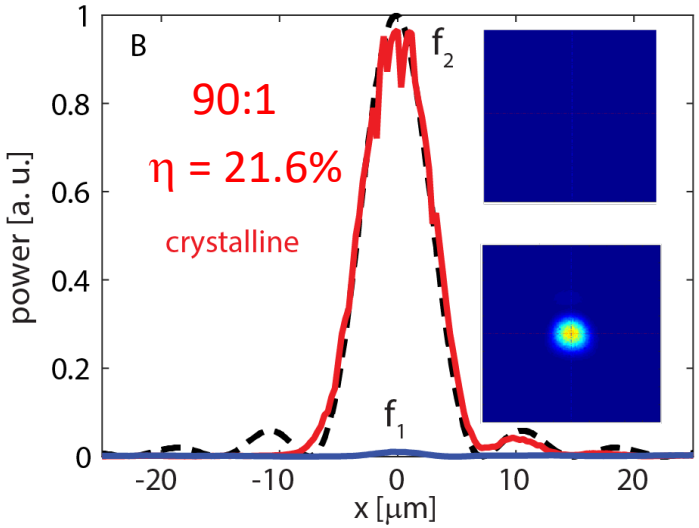


- Dimension: 1.5 x 1.5 mm^2
- FL A-state (f_1): 1.5 mm
- FL C-state (f_2): 2 mm

GSST varifocal metalens: demonstration



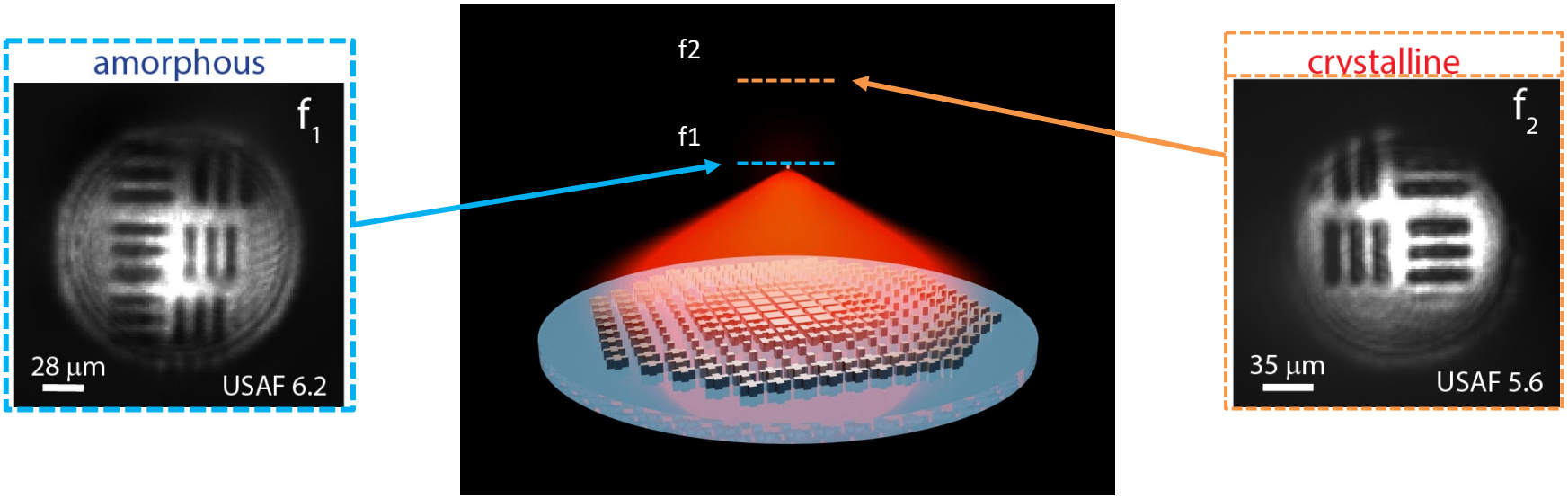




Diffraction-limited high-contrast focus switching between two states

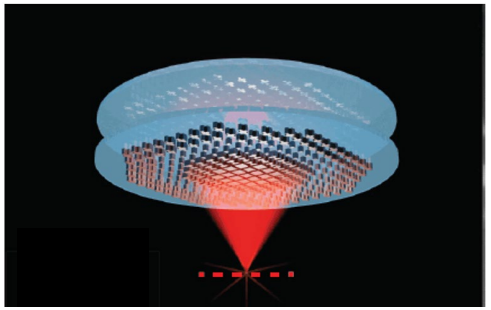
Nat. Commun. **12**, 1225 (2021)

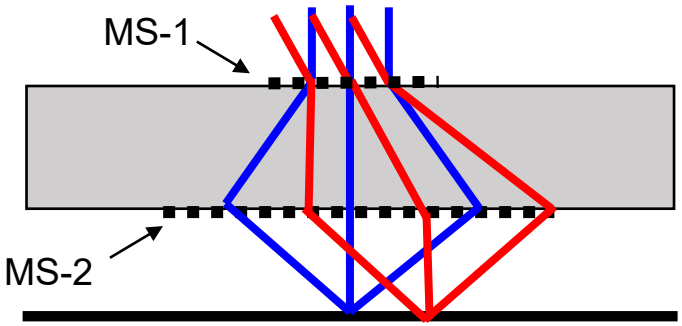
Varifocal metalens



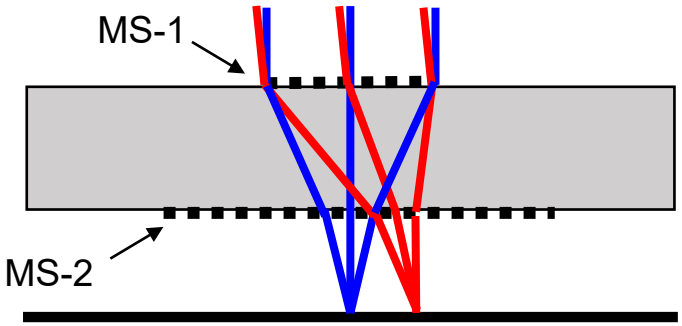
Diffraction-limited, crosstalk-free reconfigurable imaging

Reconfigurable Parfocal Zoom Metalens





wide-angle mode



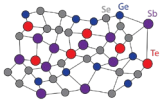
telephoto mode

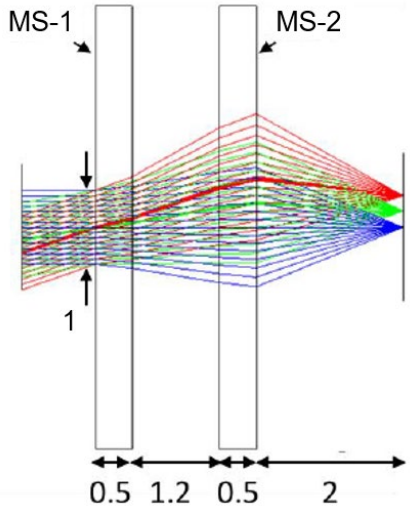
Multi-functional optical metasurfaces with large step zoom ratios and no mechanical moving parts.

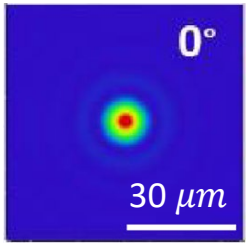
Reconfigurable Parfocal Zoom Metalens

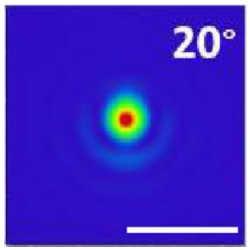
wide-angle mode

amorphous GSST







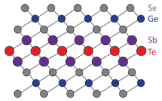


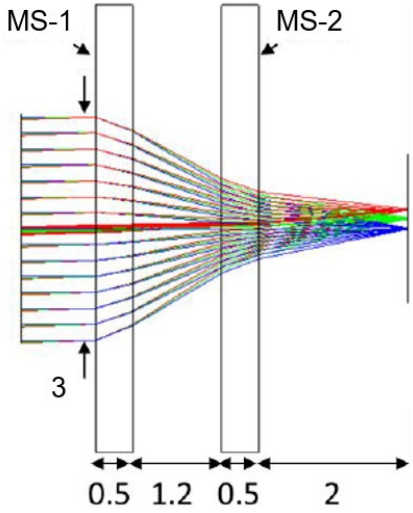
unit: mm

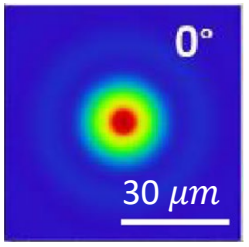
40° FOV, effective focal length 1.3 mm

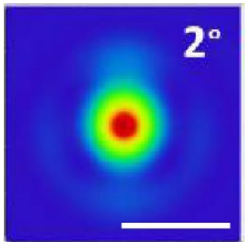
telephoto mode

crystalline GSST





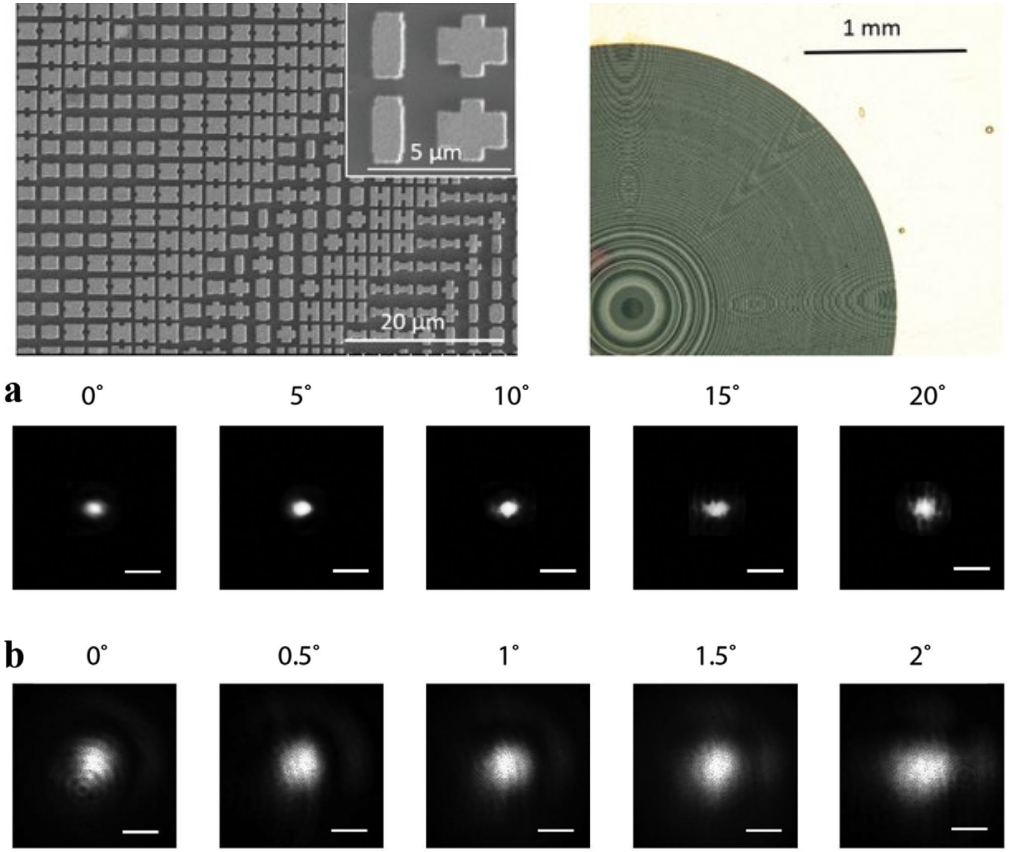




4° FOV, effective focal length 13 mm

10x parfocal zoom with diffraction limited imaging performance and minimum distortion

Parfocal zoom metalens



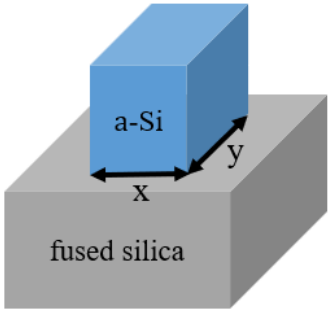
wide-angle mode

telephoto mode

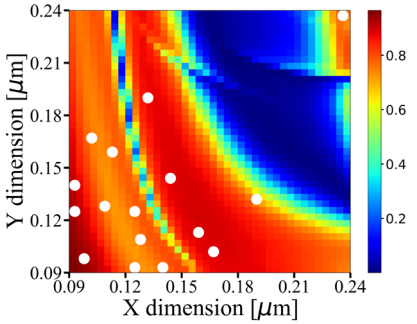
10X step optical zoom with no mechanical moving parts.

Polarization-multiplexed meta-atom design

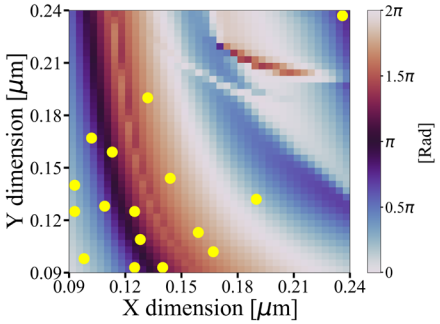
Meta-atom structure



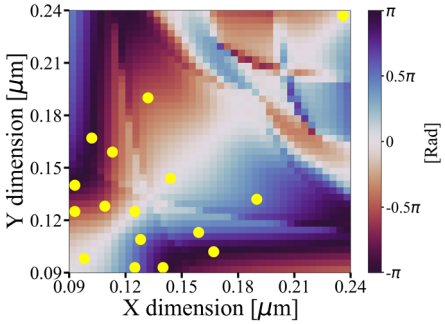
Amplitude

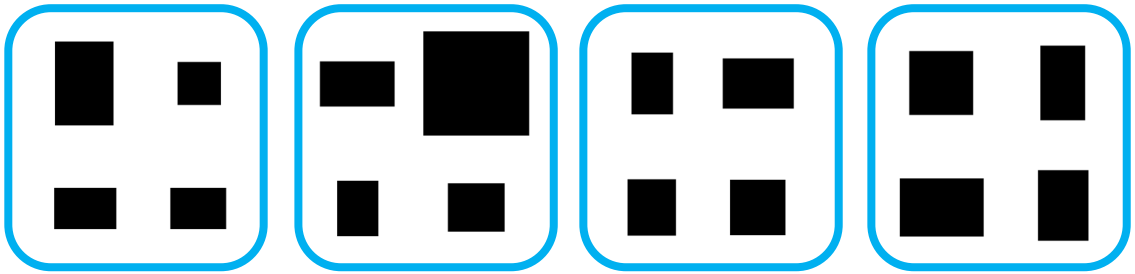


Phase delay



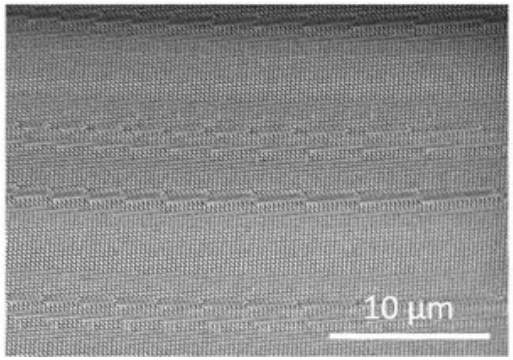
Phase delay difference

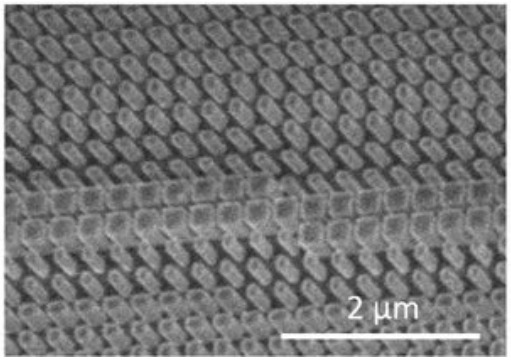


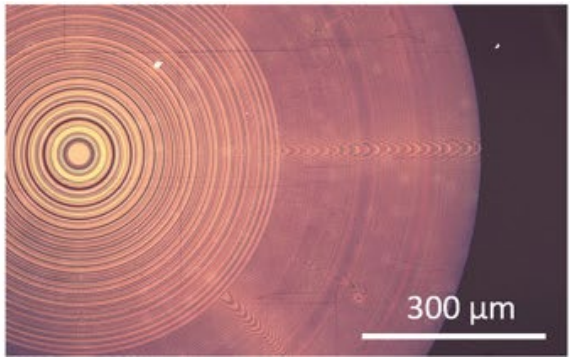


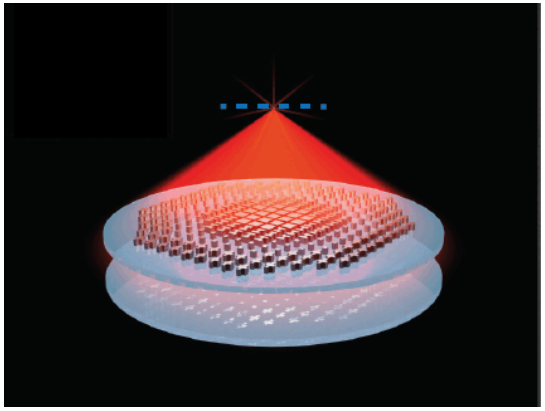
- 4-level design
- high amplitude
- 2π phase coverage for two polarizations
- π phase difference coverage between polarizations

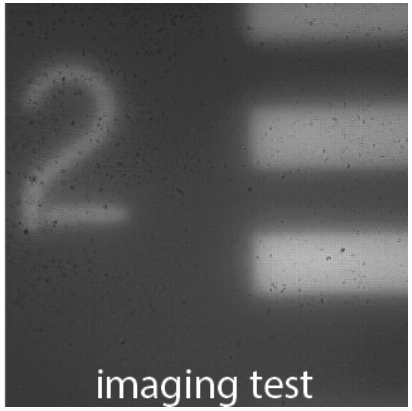
Parfocal zoom lens with polarization multiplexing





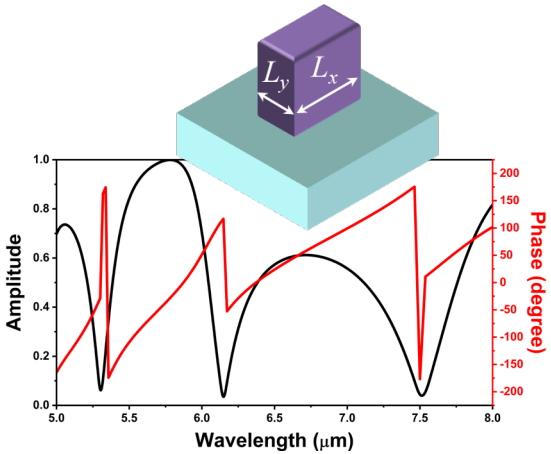




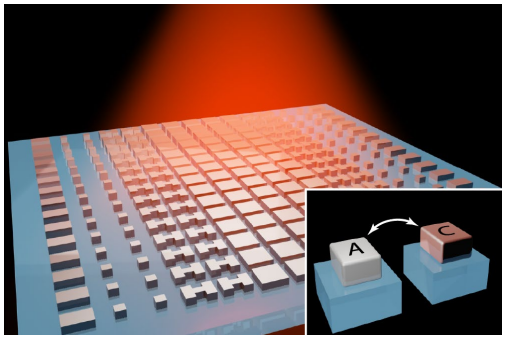


10x parfocal zoom with diffraction limited imaging performance and minimum distortion

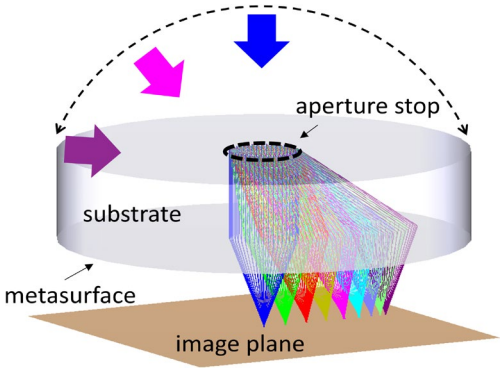
Tackling challenges for multi-functional metasurface design



Phase change



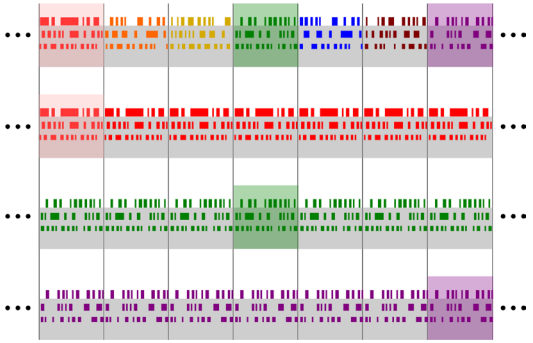
Wide FOV



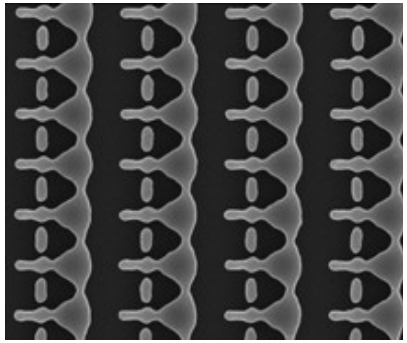
- Multi-functional meta-optics rapidly increase design complexity
- Complicated optical responses and enormous design space
- Brute-force searching becomes prohibitively inefficient
- Efficient design tools are demanded

Tackling the metasurface design challenge

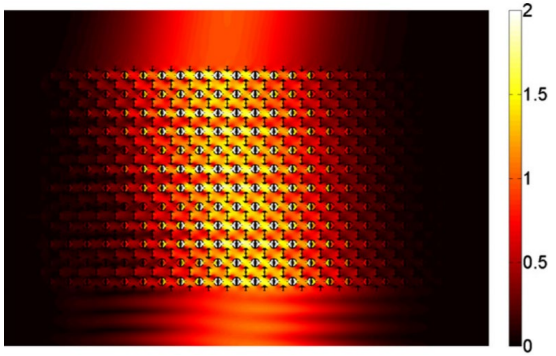
Topological optimization



Opt. Express **27**, 15765 (2019)

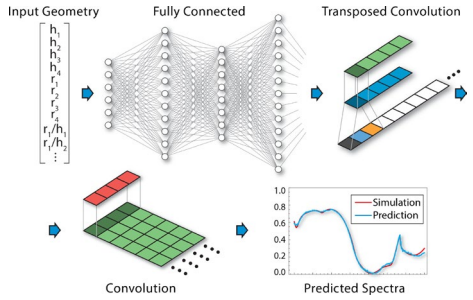


Nano Lett. **17**, 3752 (2017)

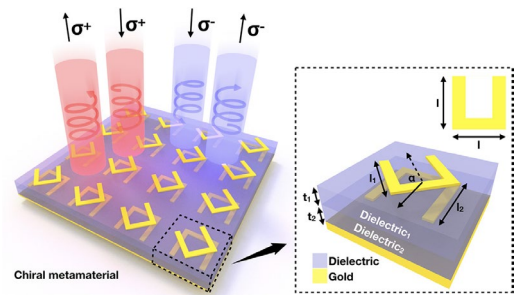


Struct. Multidisc. Optim. **54**, 469 (2016)

Machine-learning assisted design

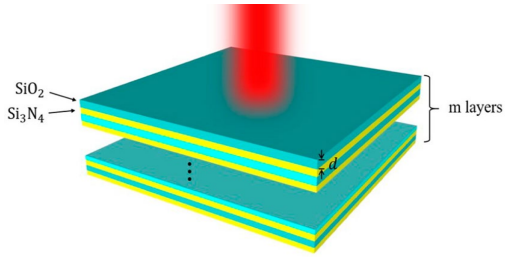


Opt. Express **27**, 27523 (2019)



ACS Nano **12**, 6326 (2018)

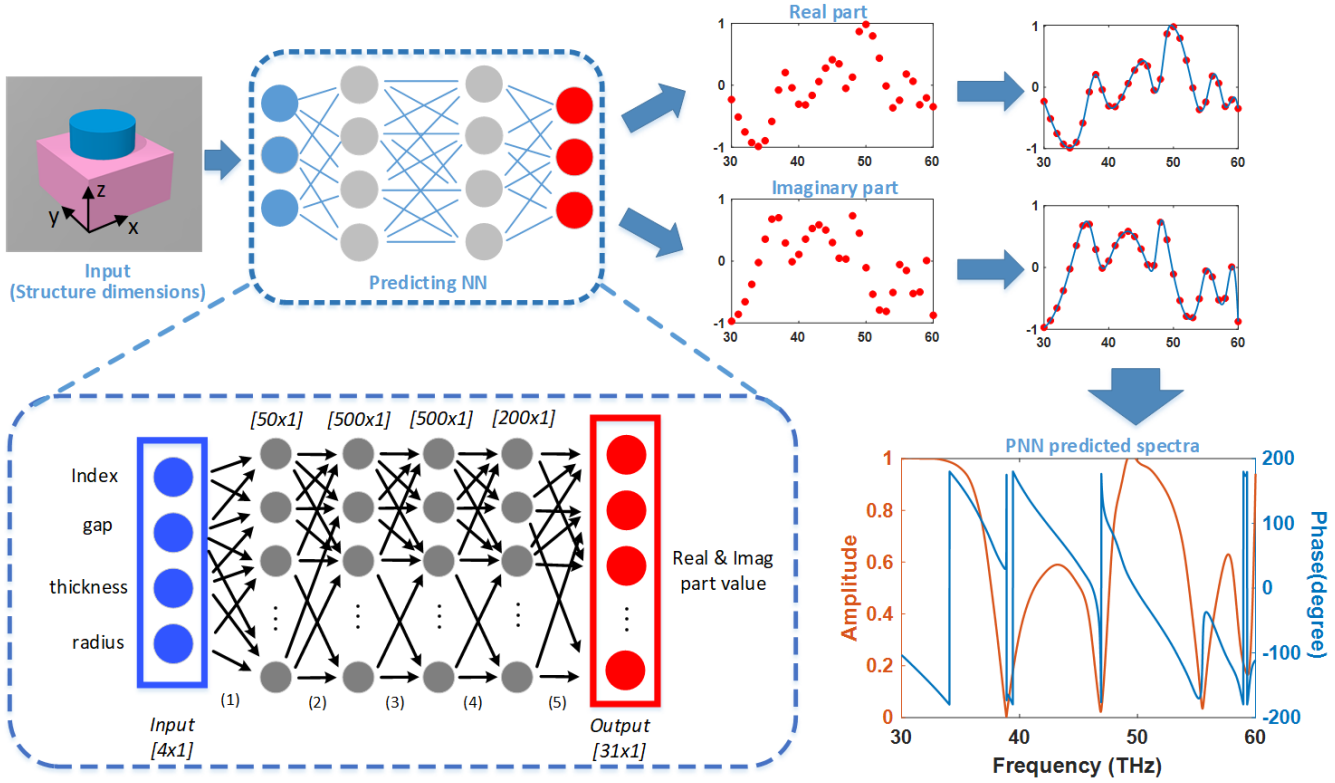
and many others…



ACS Photonics **5**, 1365 (2018)

Nanophotonics, **9**, 3505 (2020)

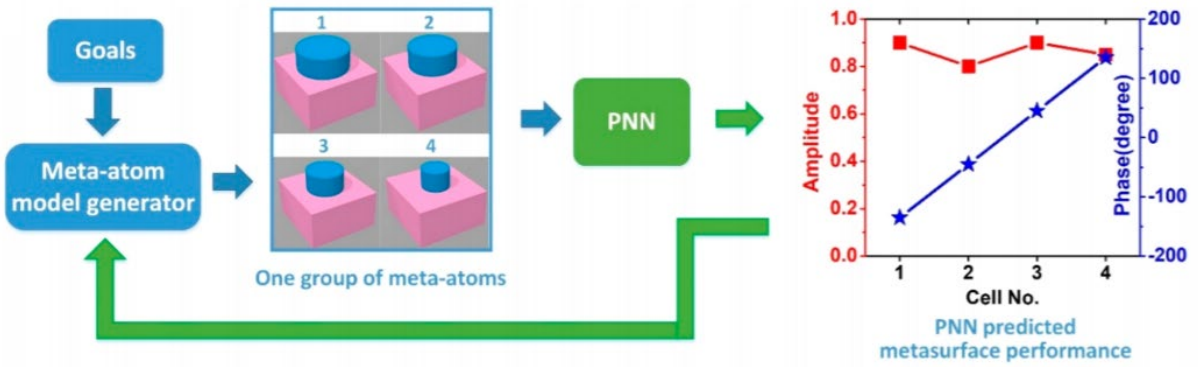
Data-driven predicting neural network (PNN)

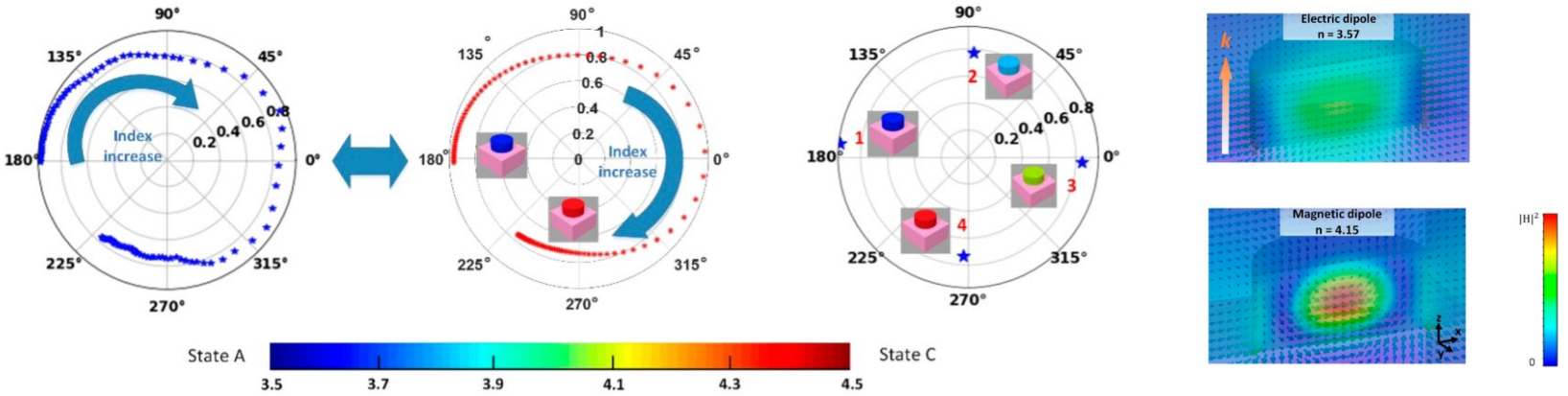


DNN-based data-driven approach for fast and accurate characterization of dielectric meta-devices

ACS Photonics, **6**, 3196 (2019)

Meta-atom design network

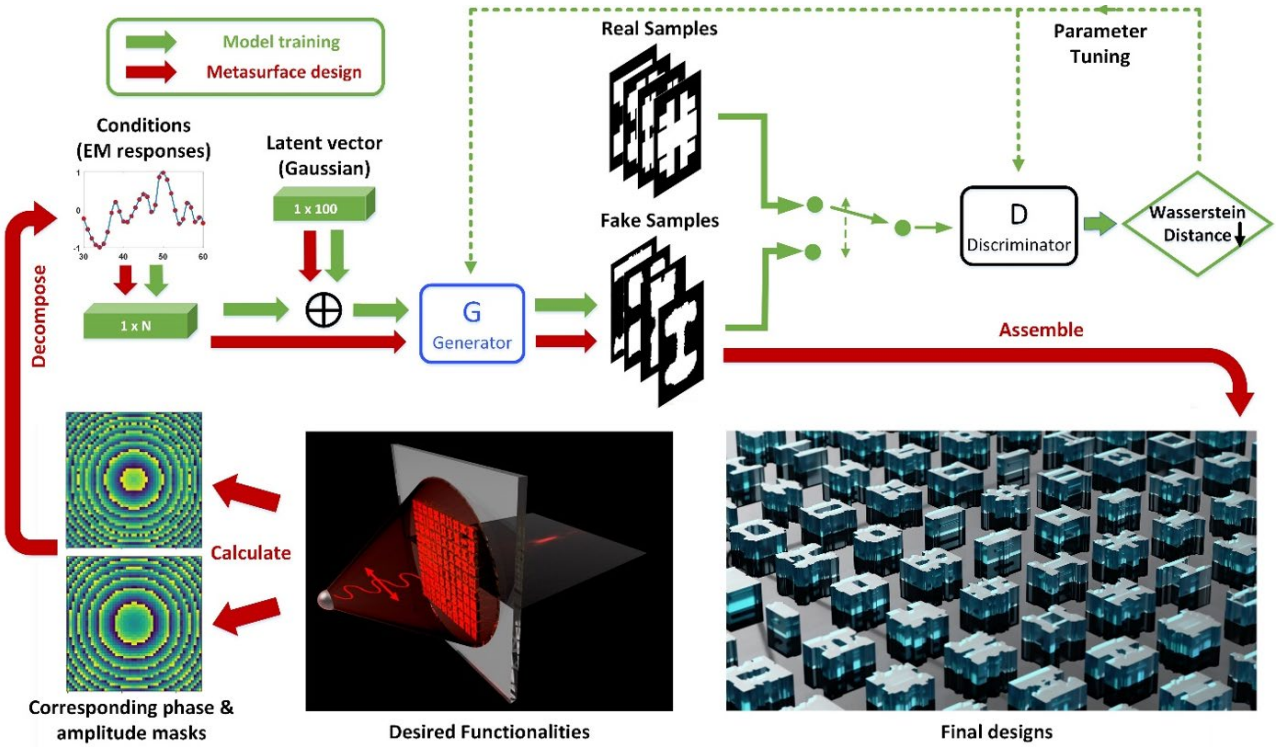


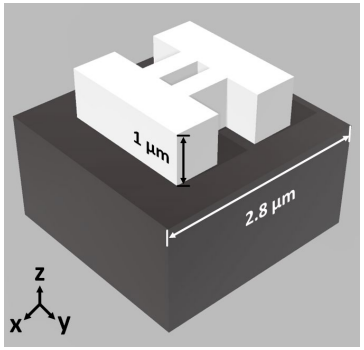


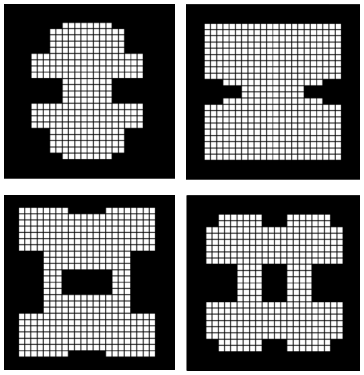
On-demand, rapid meta-atom design using PNN

ACS Photonics, **6**, 3196 (2019)

A Generative Adversarial Network (GAN) for free-form metasurface design generation



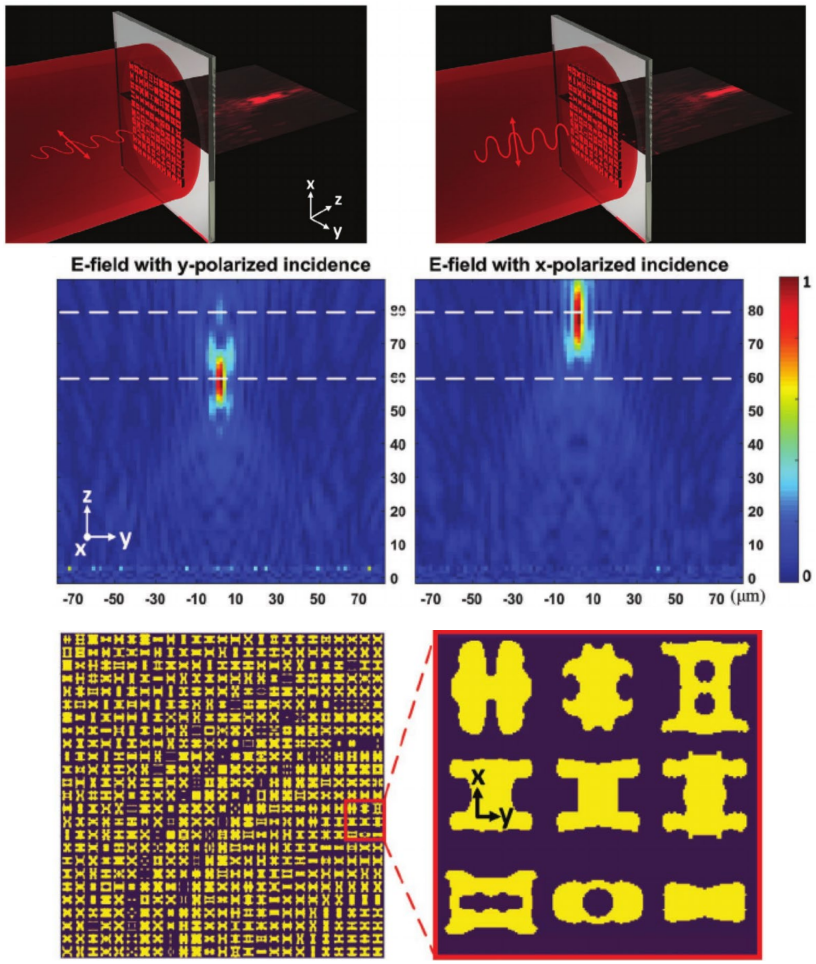




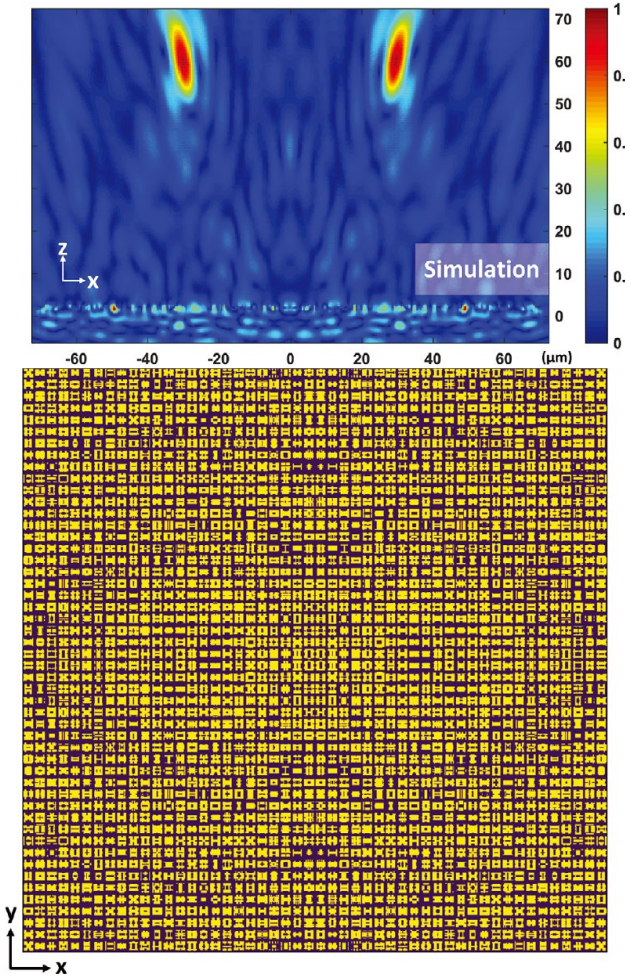
Adv. Optical Mater. 2001433. (2021)

Design examples using a fully-trained GAN model

Polarization-multiplexed metalens

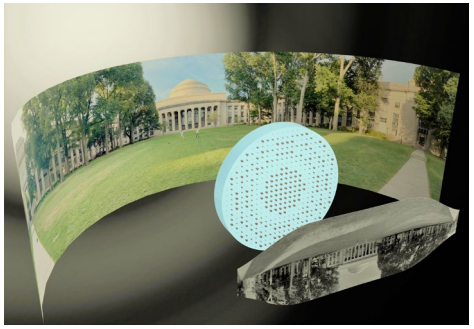


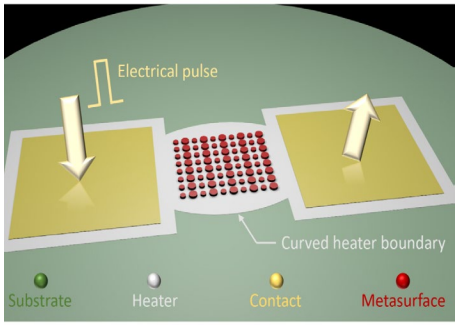
Bifocal metalens

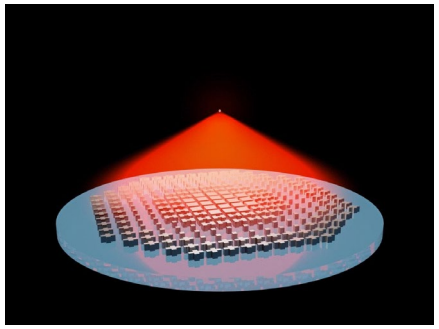


Adv. Optical Mater. 2001433. (2021)

Summary







Ultra-compact meta-optics

- ✓ High optical efficiency
- ✓ Diffraction-limited imaging
- ✓ Record hemispherical FOV
- ✓ Single-element architecture

Active optics platform

- ✓ Broadband transparency
- ✓ Reversible & reproducible multi-cycle switching
- ✓ On-chip electrical tuning

Reconfigurable meta-optics

- ✓ Arbitrary function switching
- ✓ Aberration-free, high-contrast reconfigurable zoom lens
- ✓ Multifunctional flat optics
- ✓ Advanced design methods

"Reconfigurable metasurfaces towards commercial success," *Nat. Photon.* **17**, 48–58 (2023).

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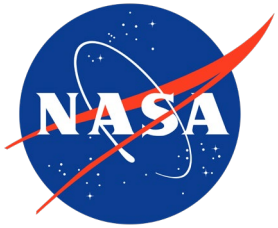

Thank you!