Selected Topics in Advanced Optics

Week 13 – part 1

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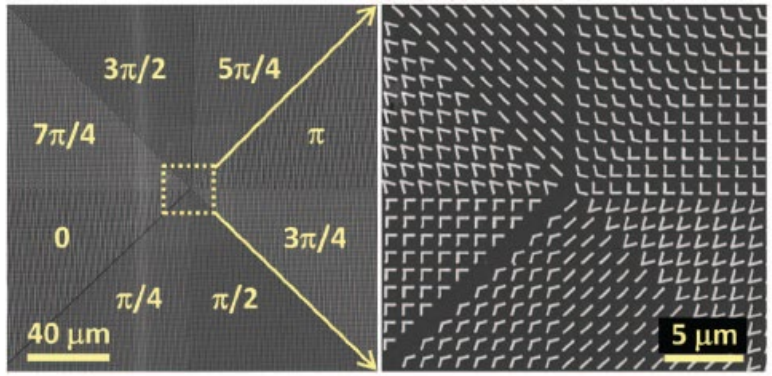
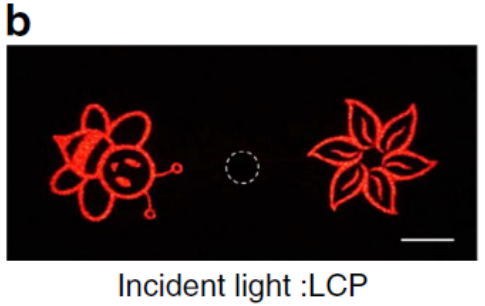
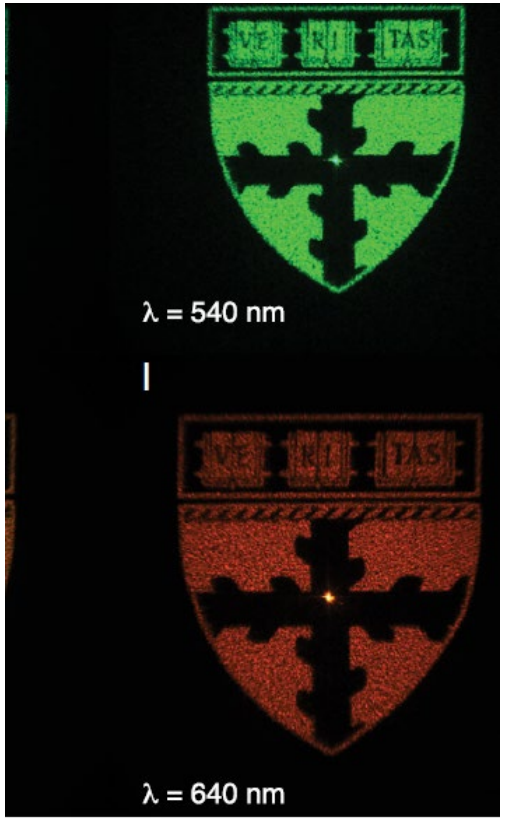
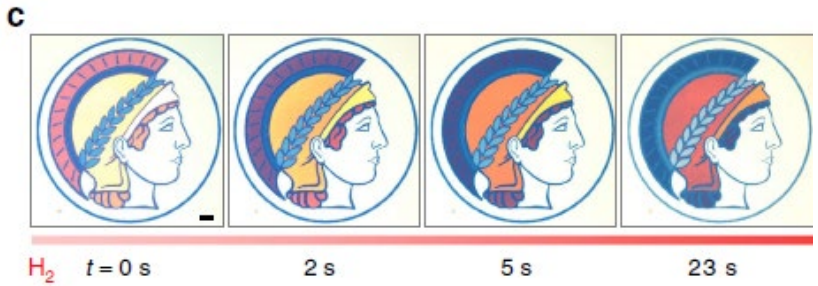
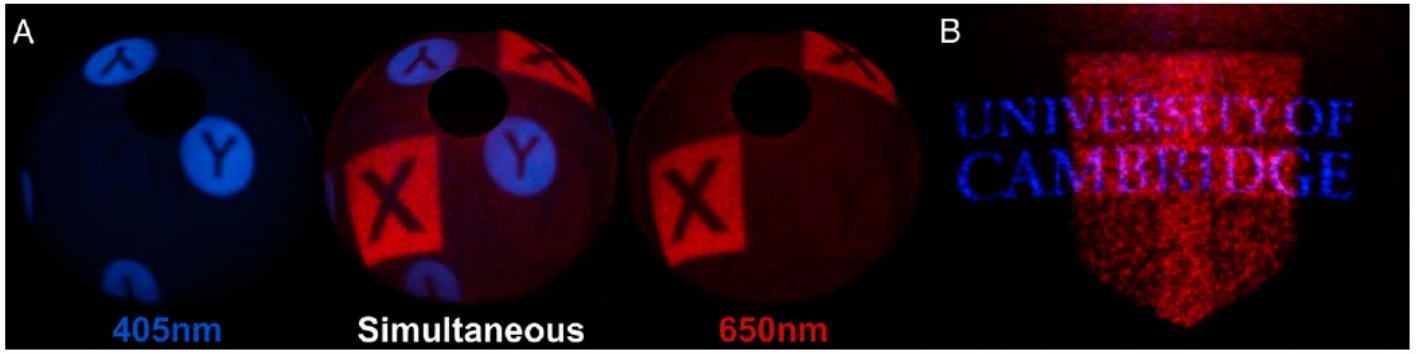
Metasurfaces – A potpourri of applications





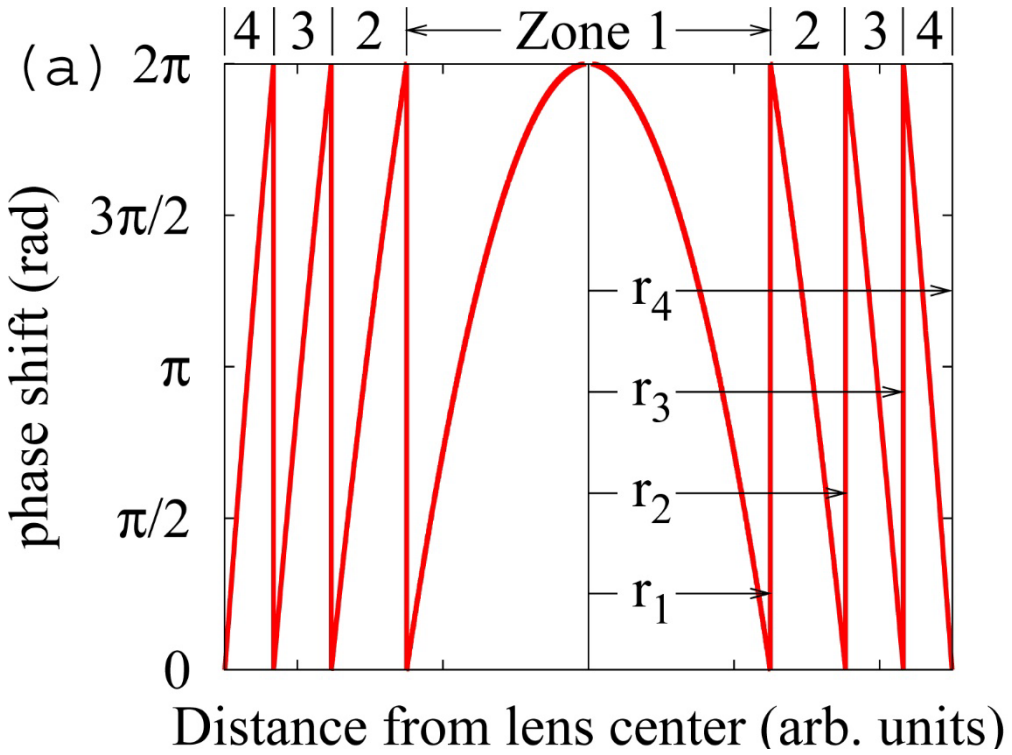






Metalenses

- In analogy with Fresnel lenses, a collection of plasmonic nanostructures can produce focusing effects, or more complex beam shaping



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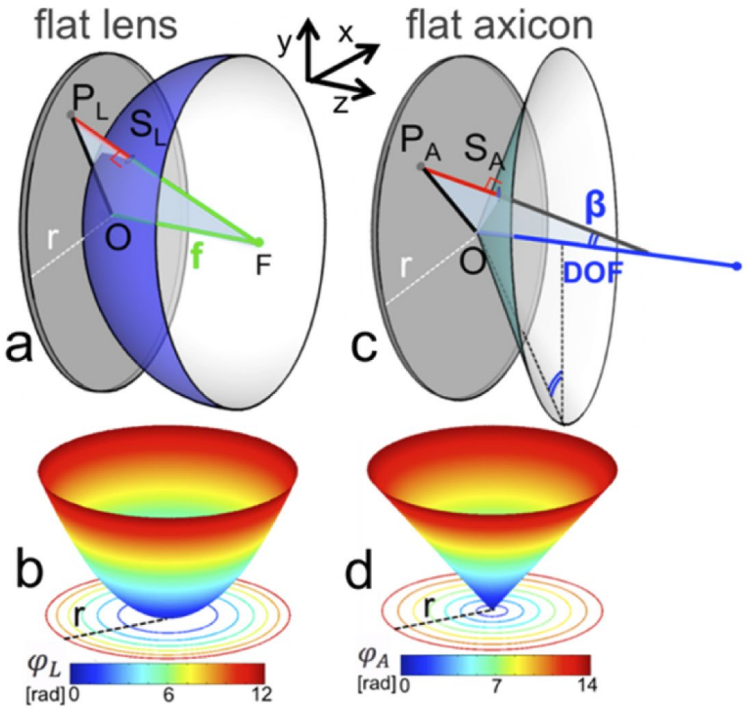
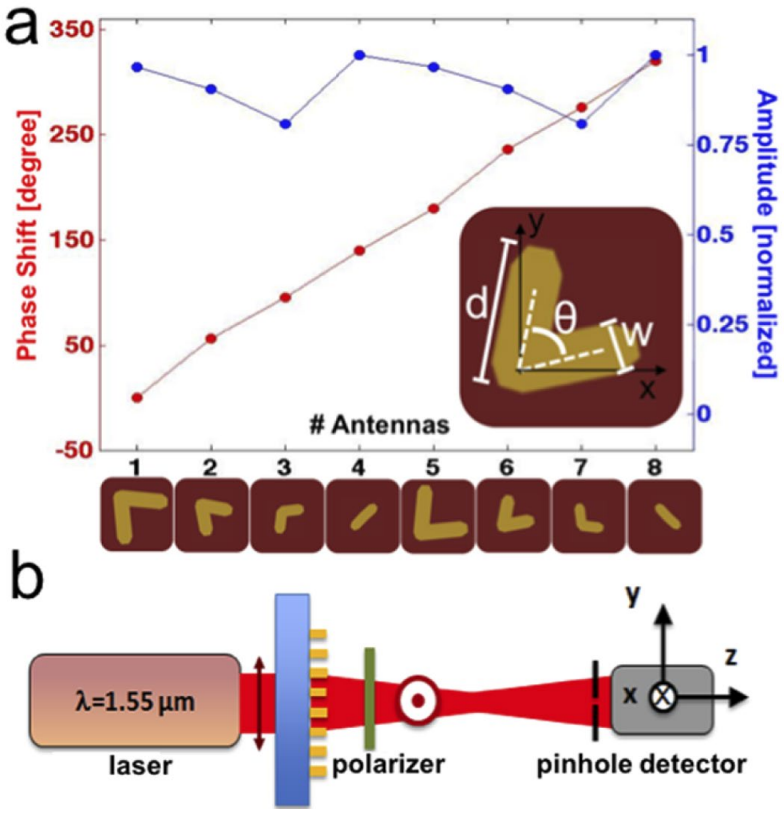
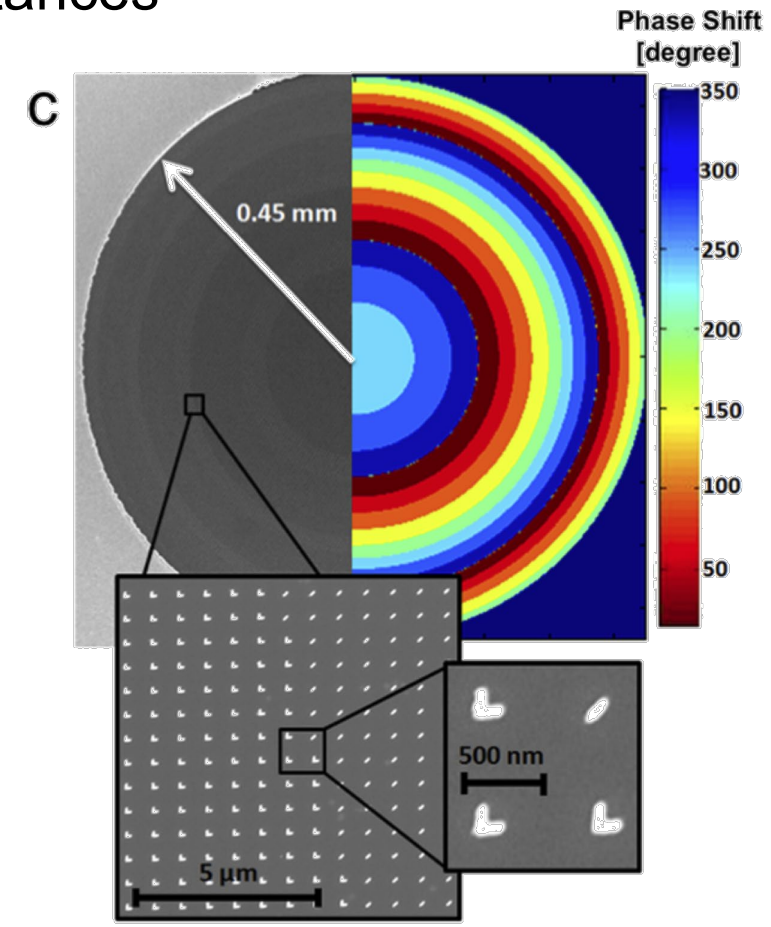


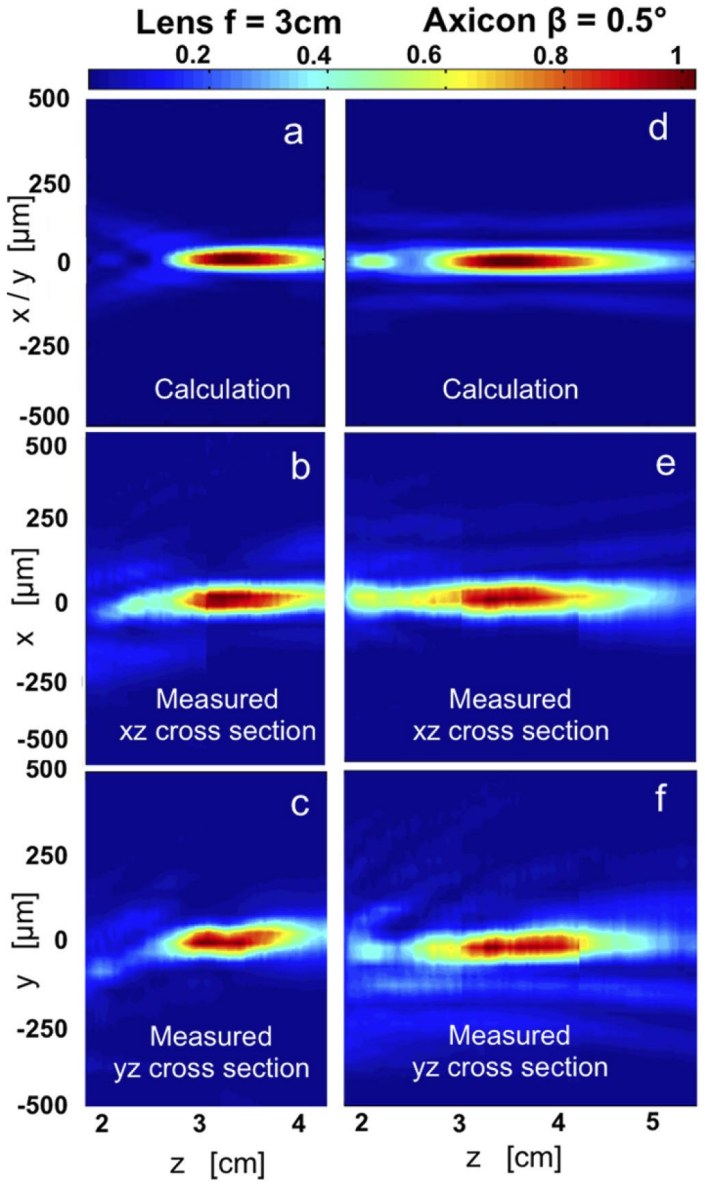


Nano Letters vol. 12, p. 4932 (2012)

Metalenses

- V-shaped nanostructures provide the different phases required for the axicon
- The produce beam can focus on very long distances

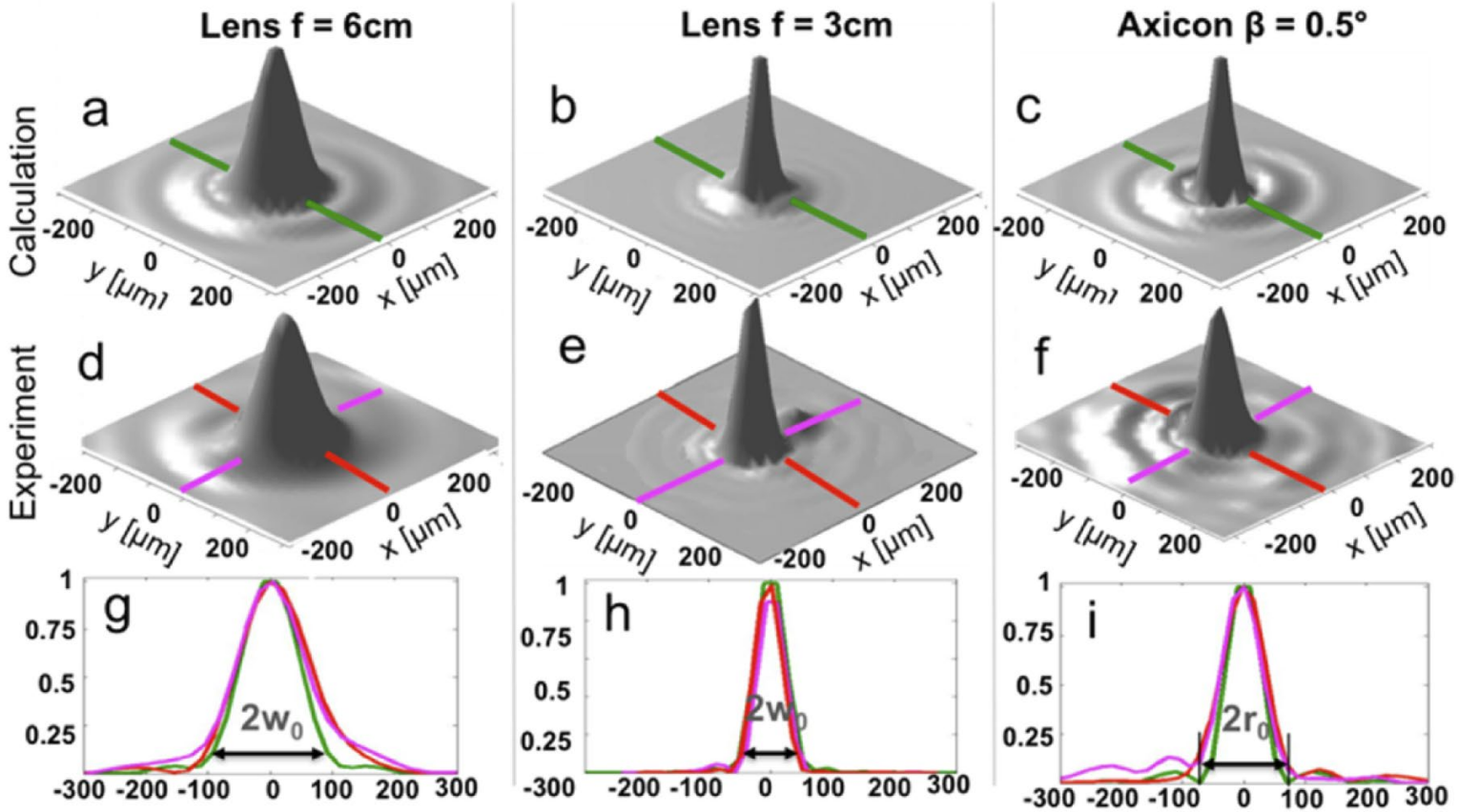




Nano Letters vol. 12, p. 4932 (2012) Olivier J.F. Martin

Metalenses

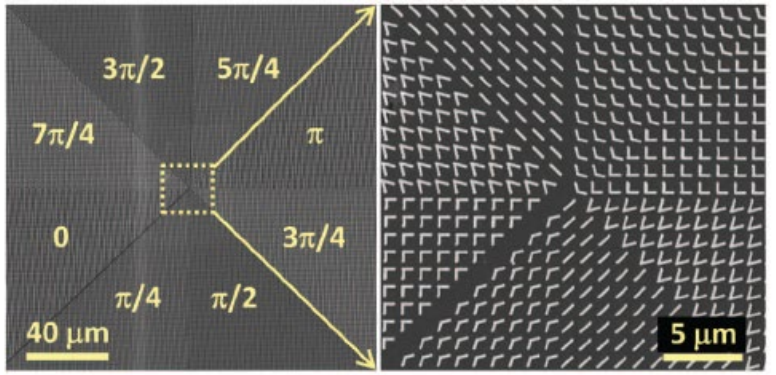
- Same focus spot as a real lens

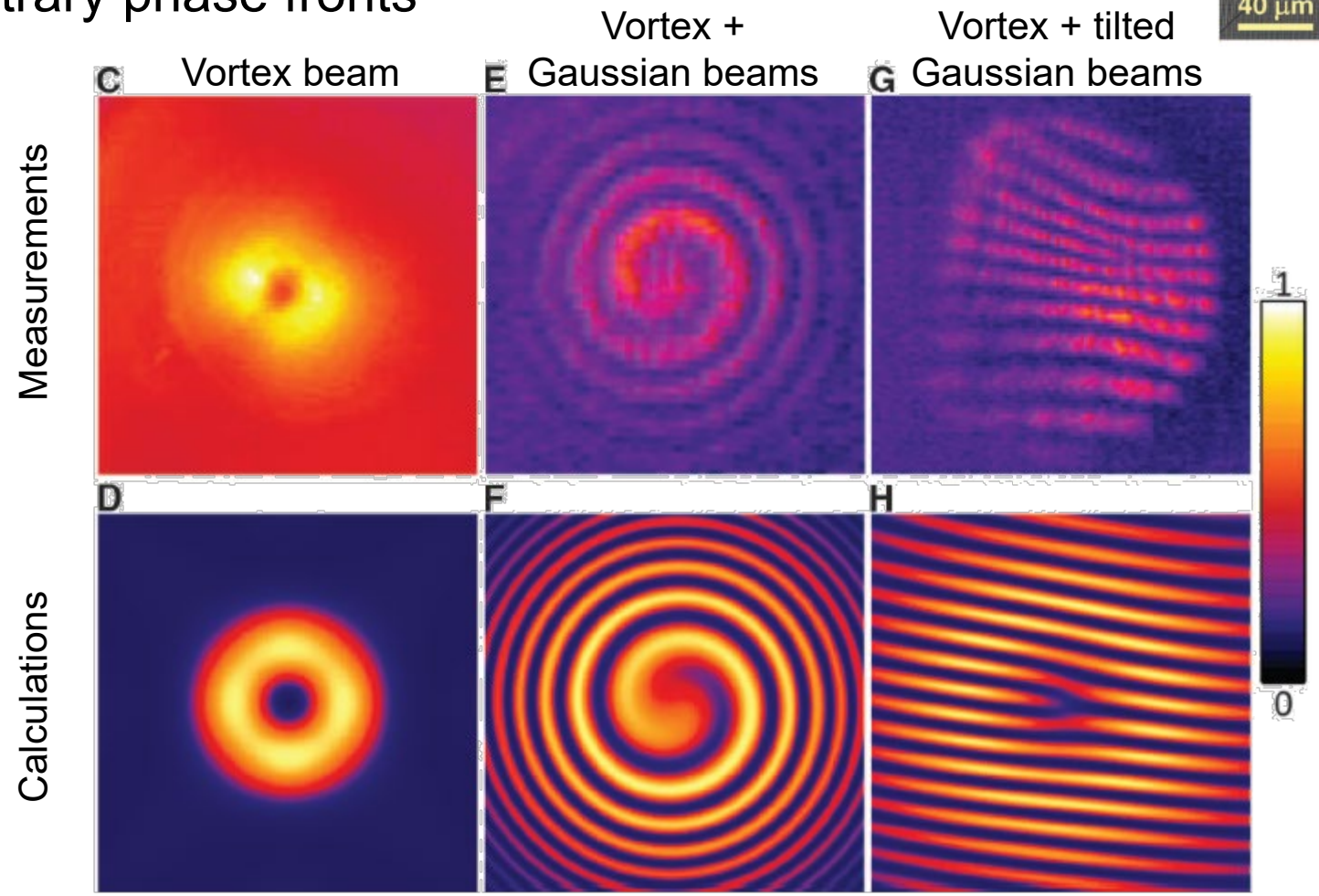


Nano Letters vol. 12, p. 4932 (2012) Olivier J.F. Martin

Optical vortex

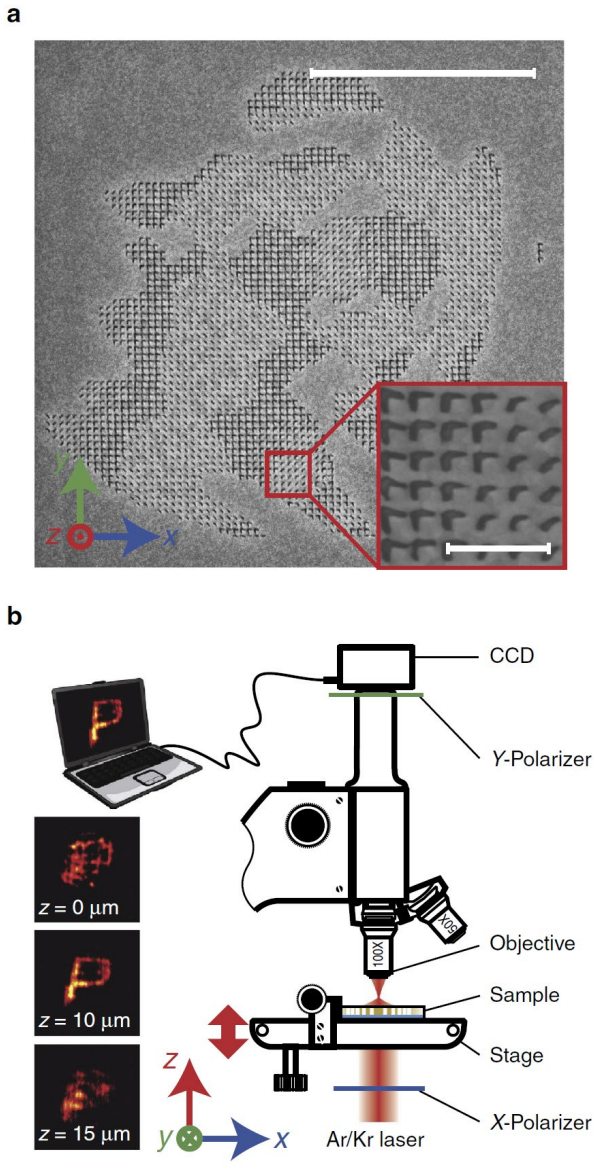
- Crystalline phase plates are difficult to manufacture
- Metasurfaces provide a good alternative to produce arbitrary phase fronts





Science vol. 334, p. 333 (2011) Olivier J.F. Martin

Meta-holograms



- Apertures in a metal film are used to produce the different phase elements
- Rather than a true hologram, these metasurfaces mostly produce “pictures”

Nature Communications vol. 4, p. 2807 (2013) Olivier J.F. Martin

Meta-holograms

- There is still quite some differences between the quality of the simulation and that of the realized sample…

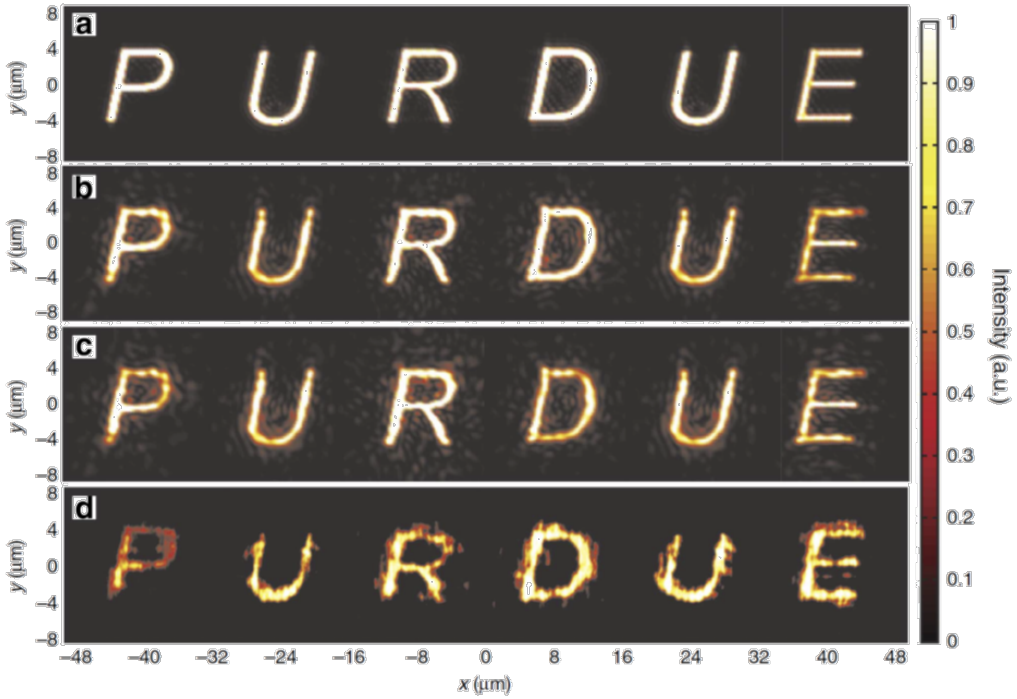
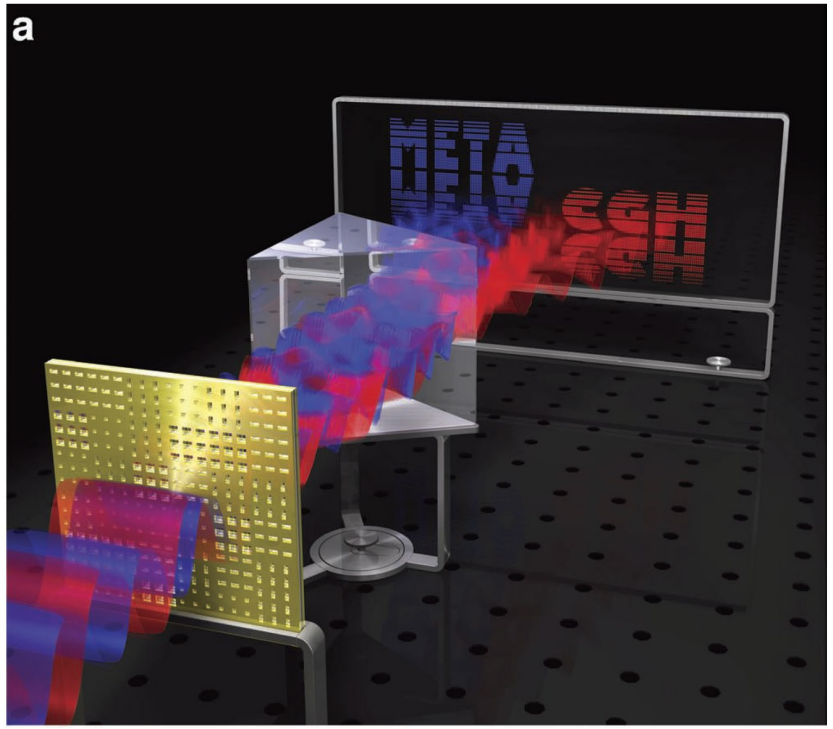


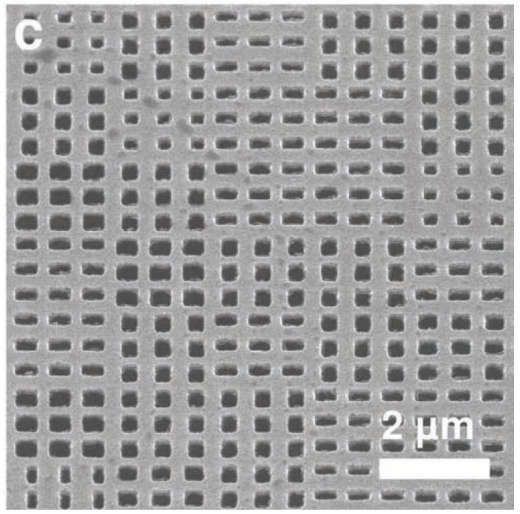
Figure 4 | Simulated holographic images compared with the experimental images. (**a**) The simulated holographic images created by an ideal metasurface hologram with smooth phase and amplitude modulations. (**b**) The simulated holographic images created by a metasurface hologram with an eight-level phase modulation and a four-level amplitude modulation. (**c**) The simulated holographic images created by a metasurface hologram with an eight-level phase modulation and a two-level amplitude modulation. (**d**) Holographic images obtained experimentally from the fabricated samples. All the images are taken from the same image plane 10 μm above and parallel to the metasurface hologram.

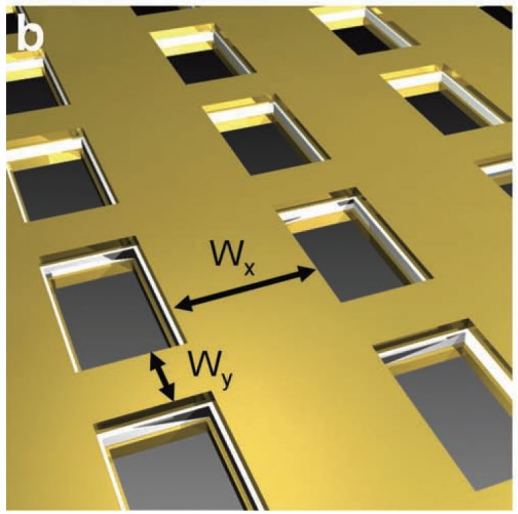
Nature Communications vol. 4, p. 2807 (2013)

Meta-holograms and wavelength multiplexing effects

- Different apertures will produce different phases when illuminated with different wavelengths



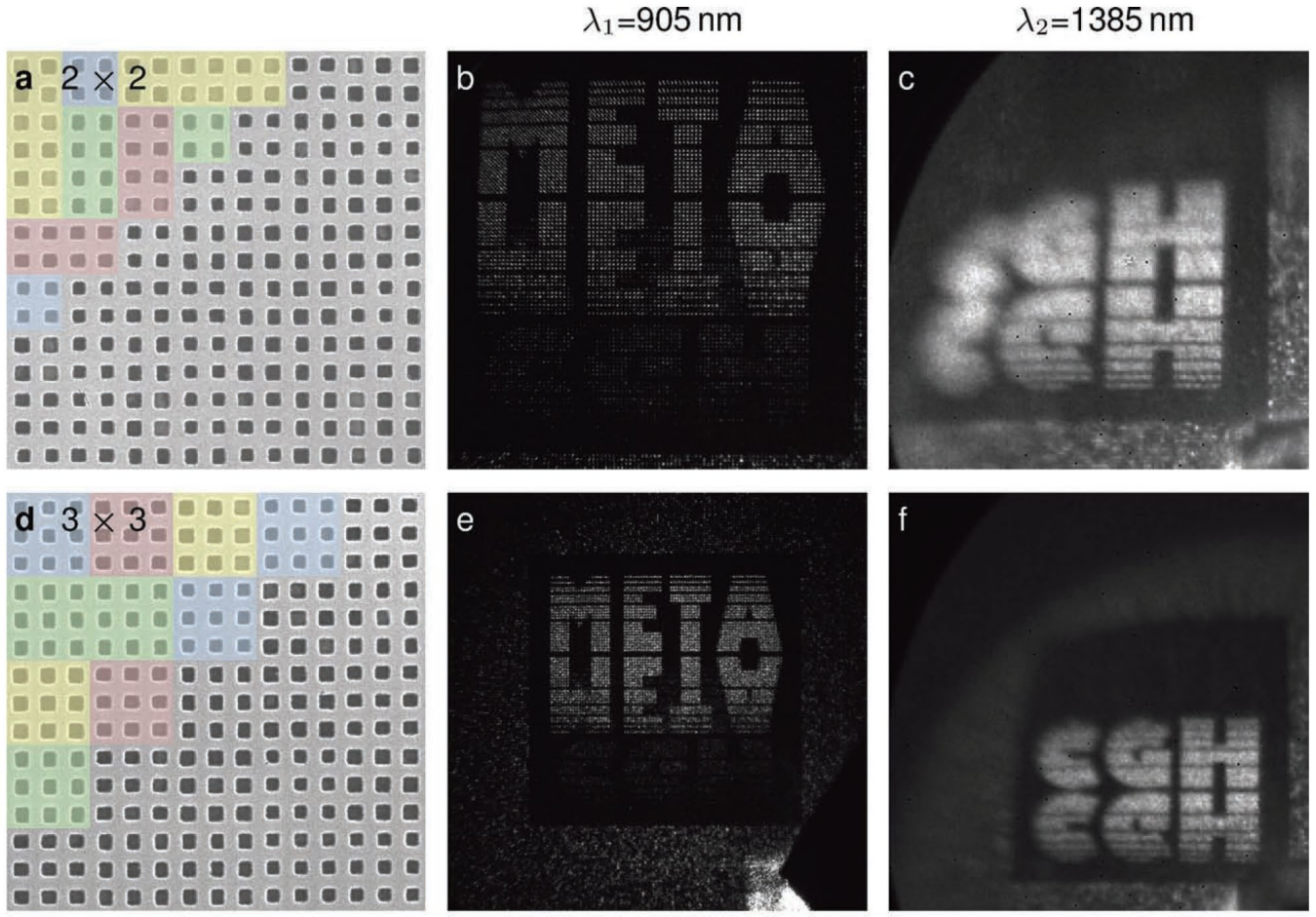




Advanced Materials vol. 24, p. 6300 (2012) Olivier J.F. Martin

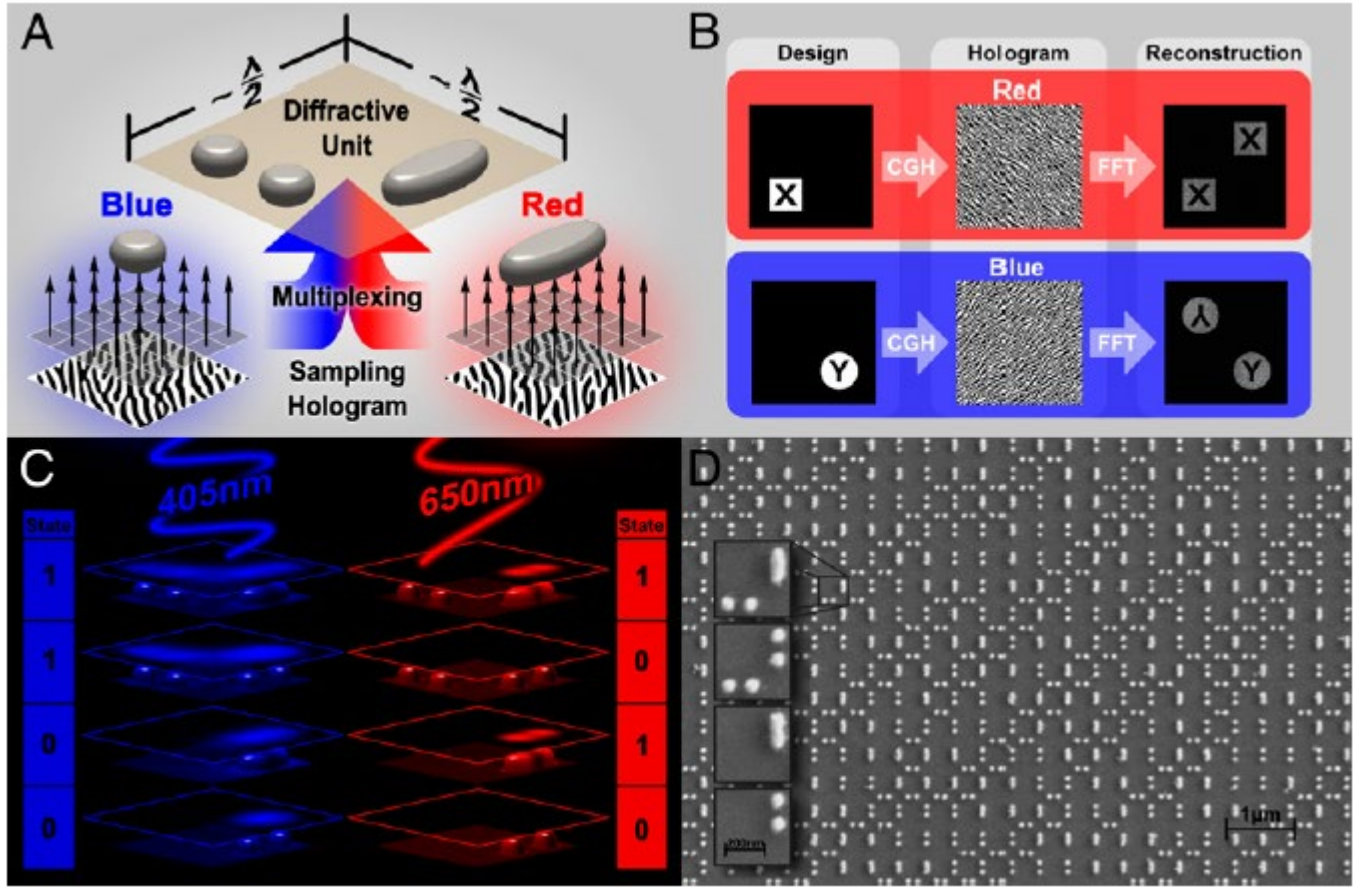
Meta-holograms and wavelength multiplexing effects

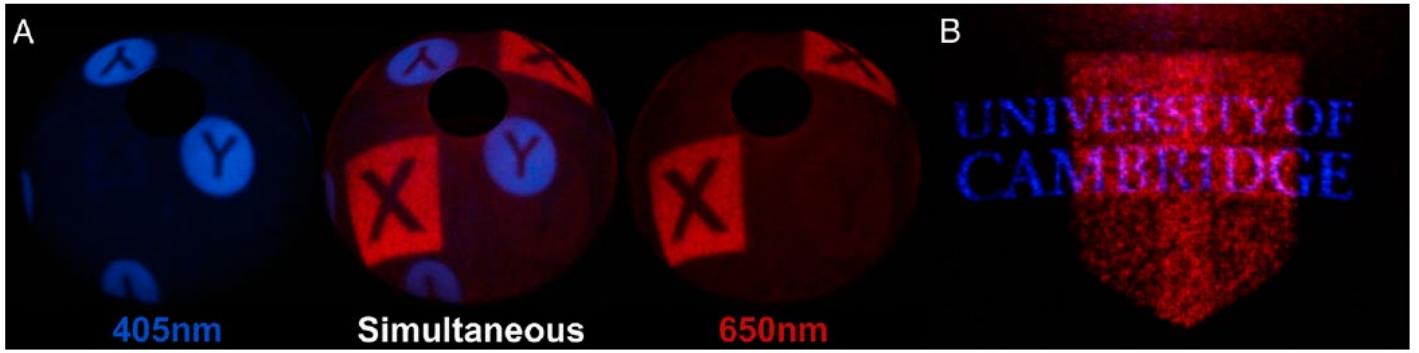
- The number of unit cells used to define one hologram pixel influences the hologram quality



Advanced Materials vol. 24, p. 6300 (2012)

Meta-holograms and wavelength multiplexing effects



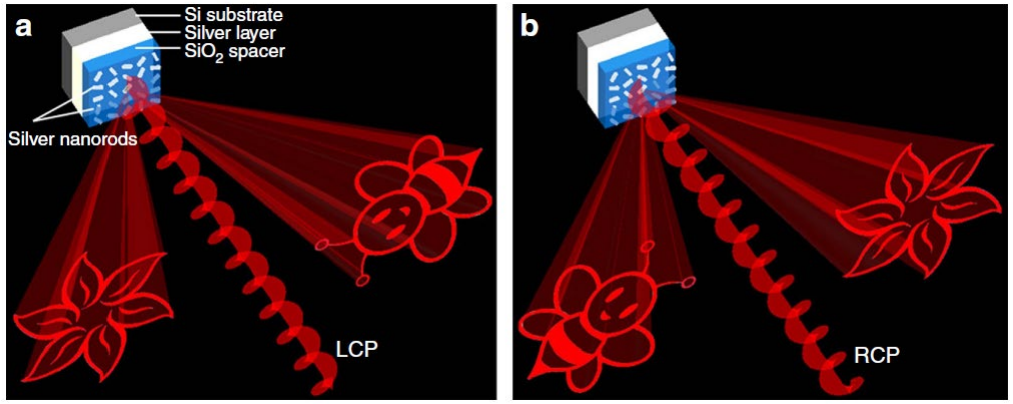


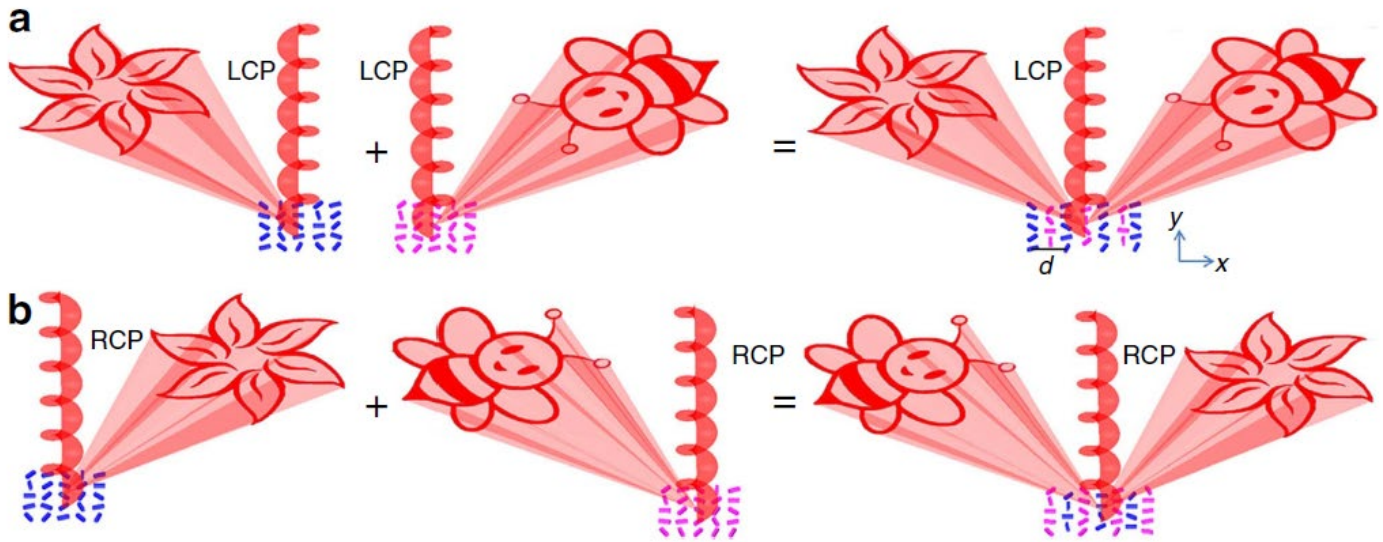
PNAS, vol. 111, p. 12679 (2014)

Olivier J.F. Martin

Meta-holograms and polarization multiplexing effects

- Two different meta-holograms with different responses for left and right circular polarizations can be superposed on the same sample

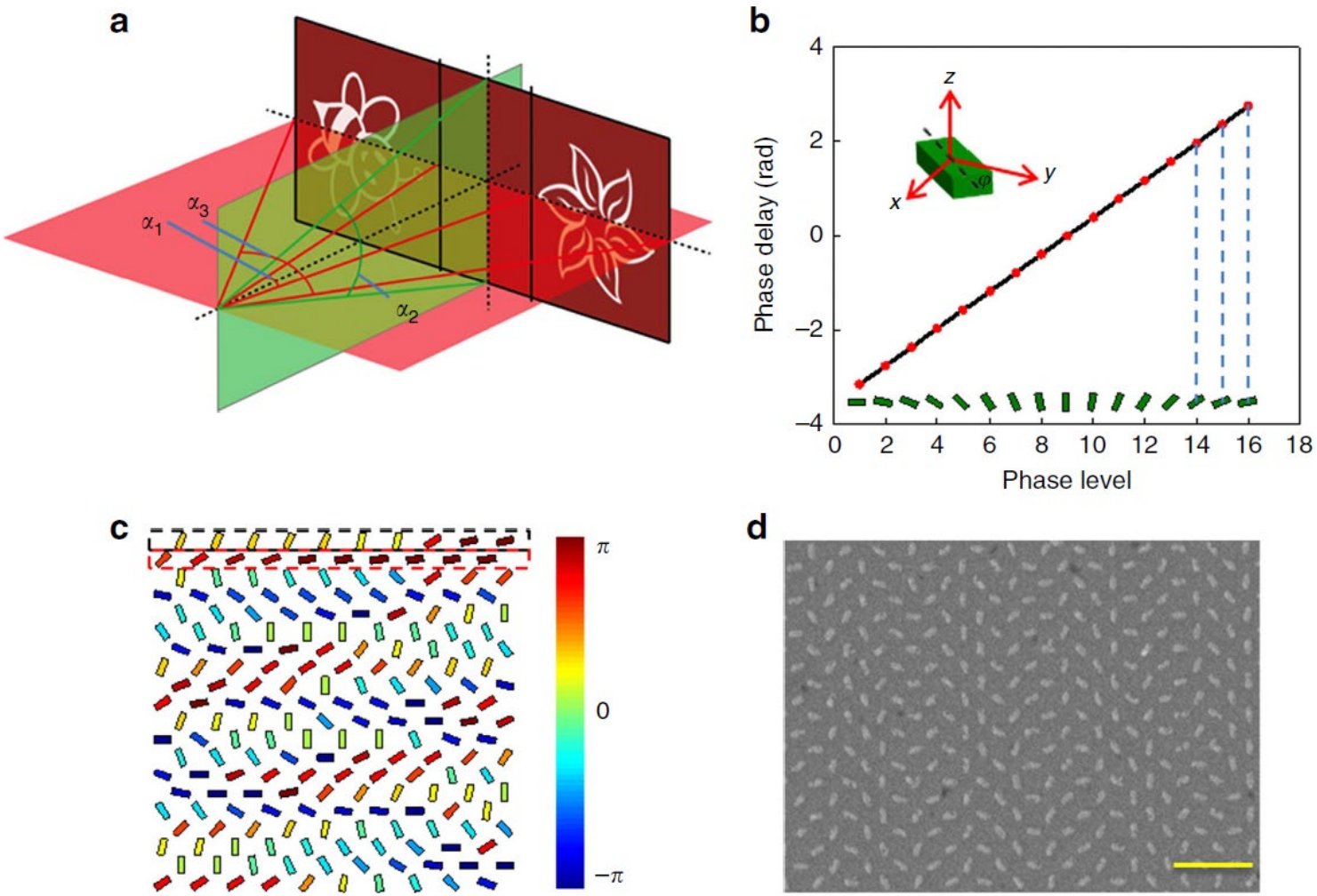




Nature Communications vol. 6, p. 8241 (2015) Olivier J.F. Martin

Meta-holograms and polarization multiplexing effects

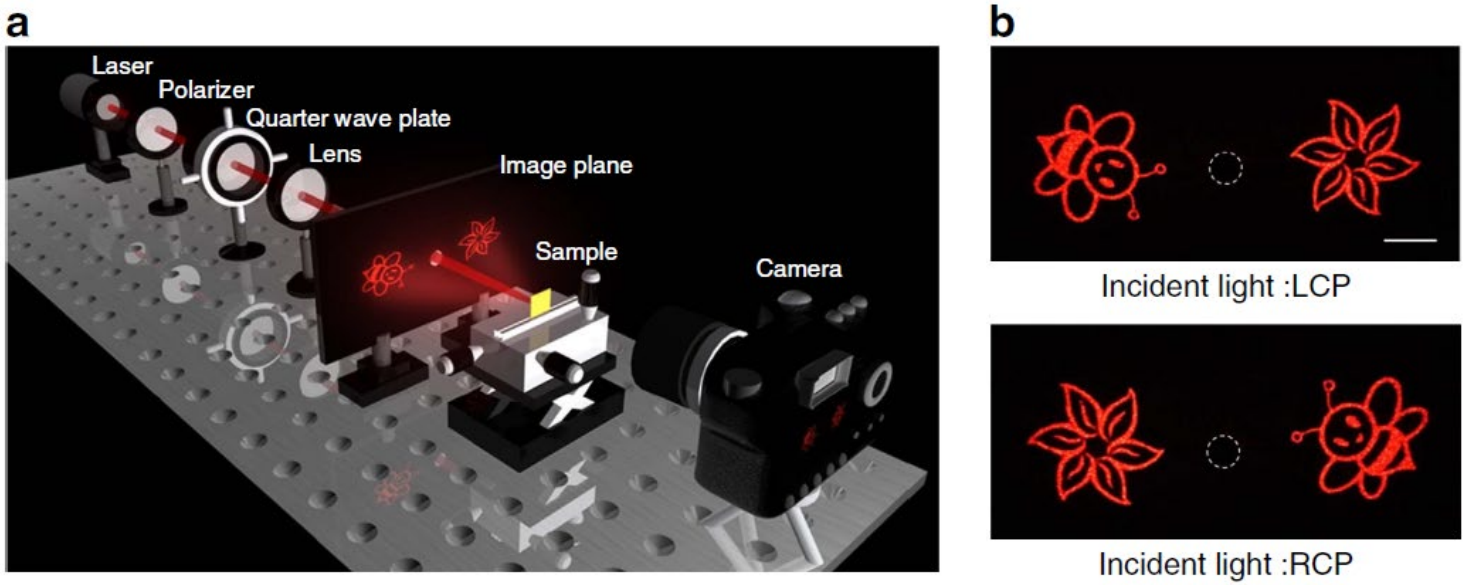
- Each hologram is defined using plasmonic nanostructures



Nature Communications vol. 6, p. 8241 (2015)

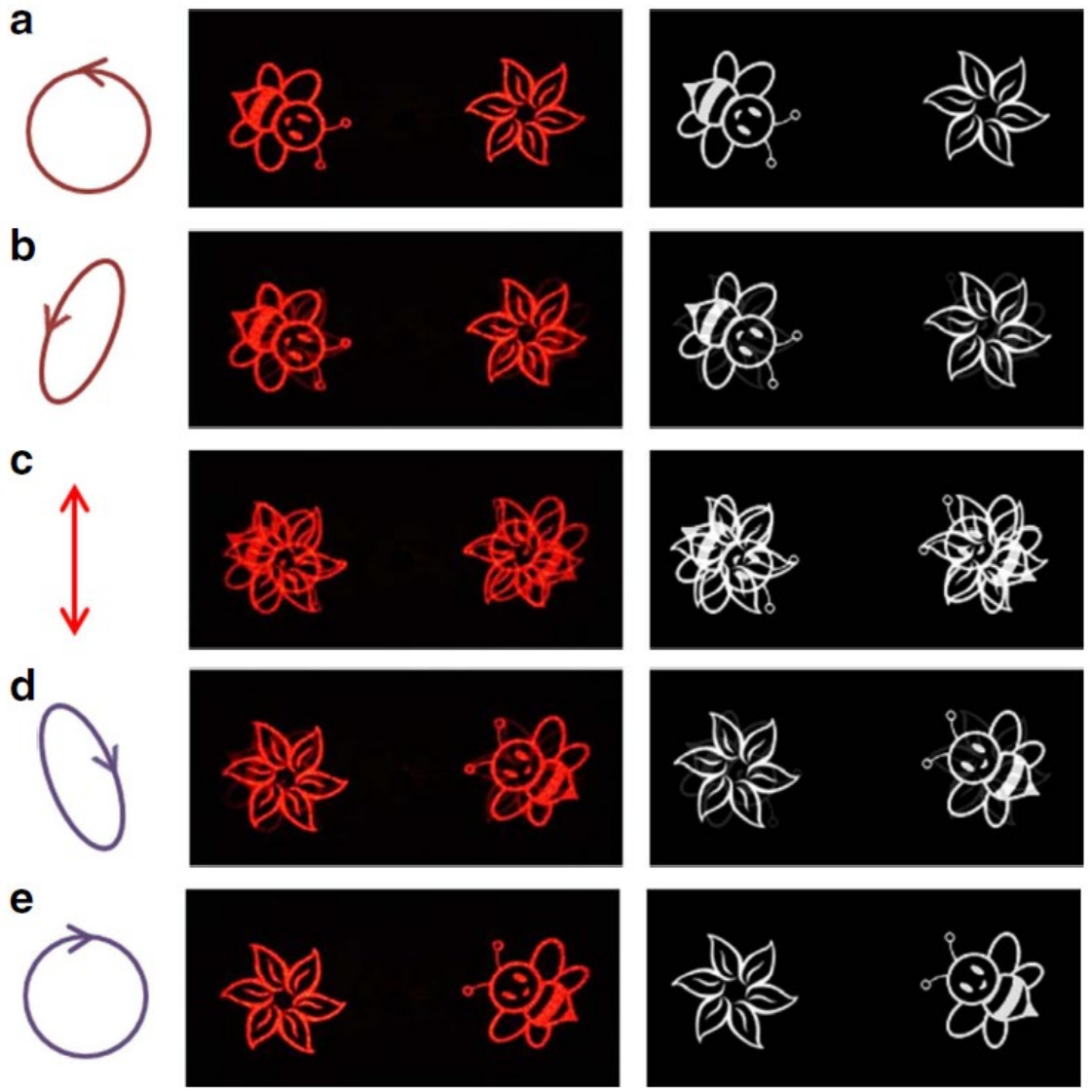
Meta-holograms and polarization multiplexing effects

- A different response is obtained, depending on the helicity (left or right) of the illumination



Nature Communications vol. 6, p. 8241 (2015)

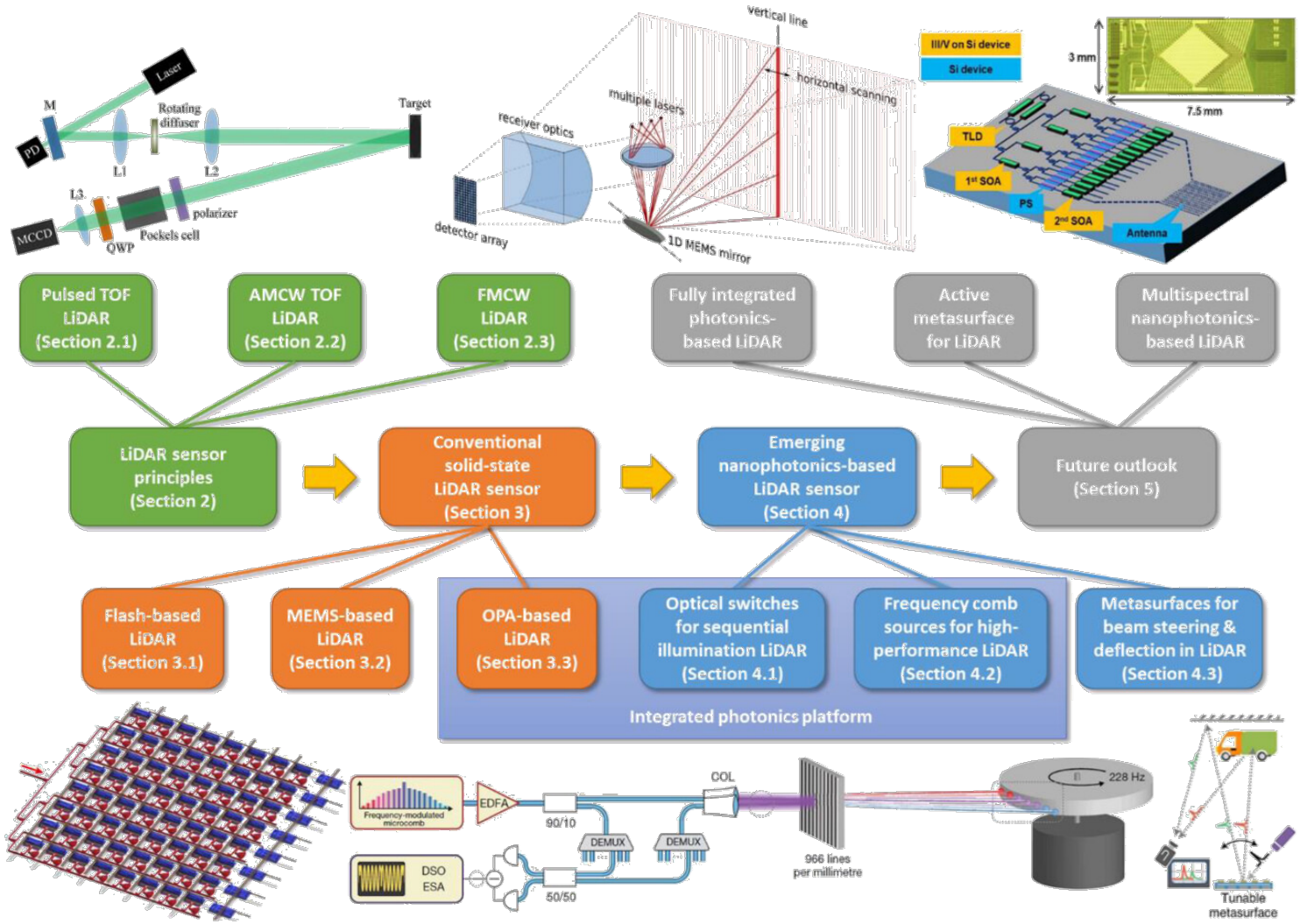
Meta-holograms and polarization multiplexing effects



Nature Communications vol. 6, p. 8241 (2015) Olivier J.F. Martin

LiDAR

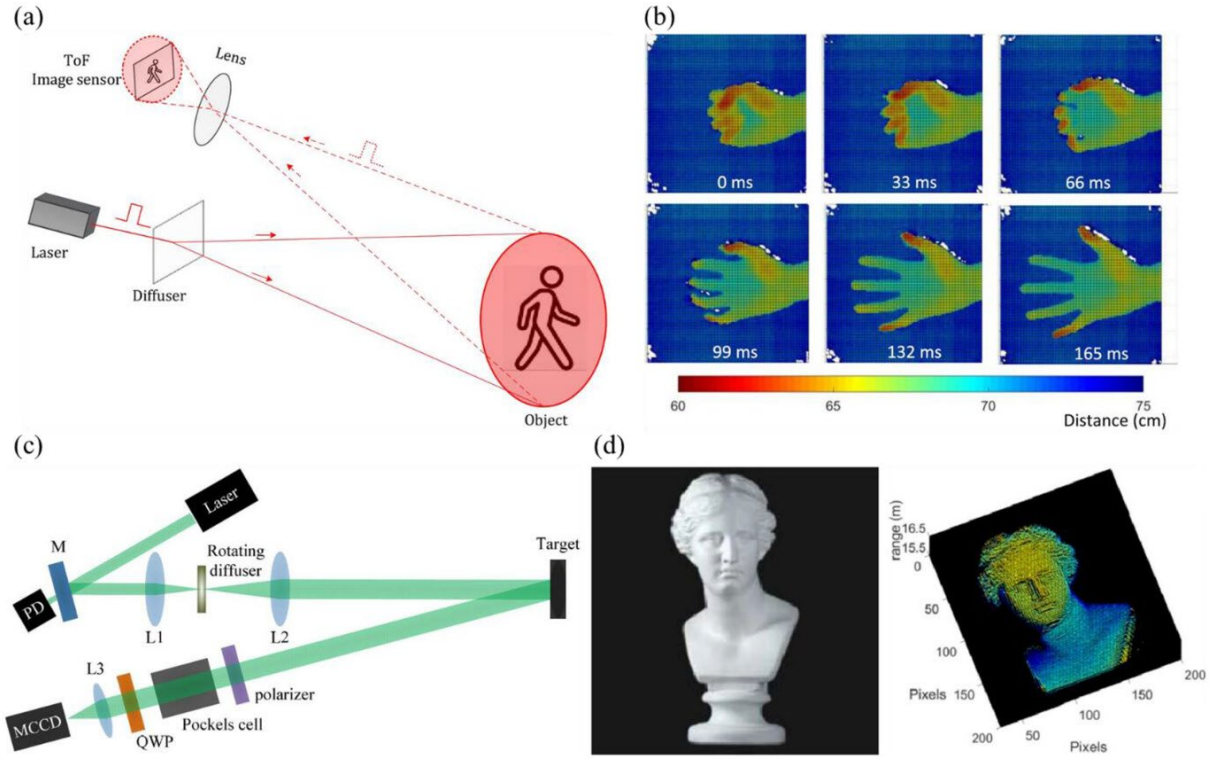
- Light detection and ranging: the time of flight determines the distance

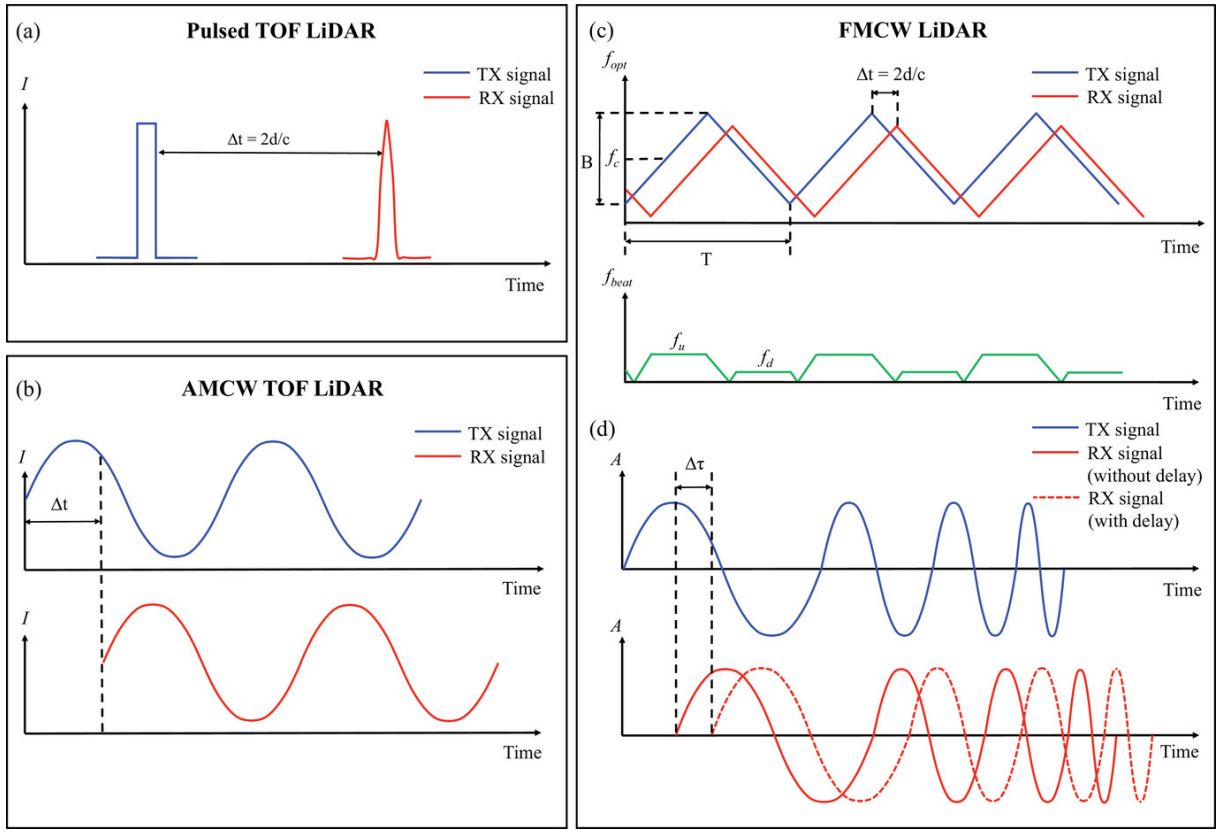


Laser & Photonics Reviews, vol. 16, p. 2100511 (2022) Olivier J.F. Martin

LiDAR

- Different implementations and principles of operation

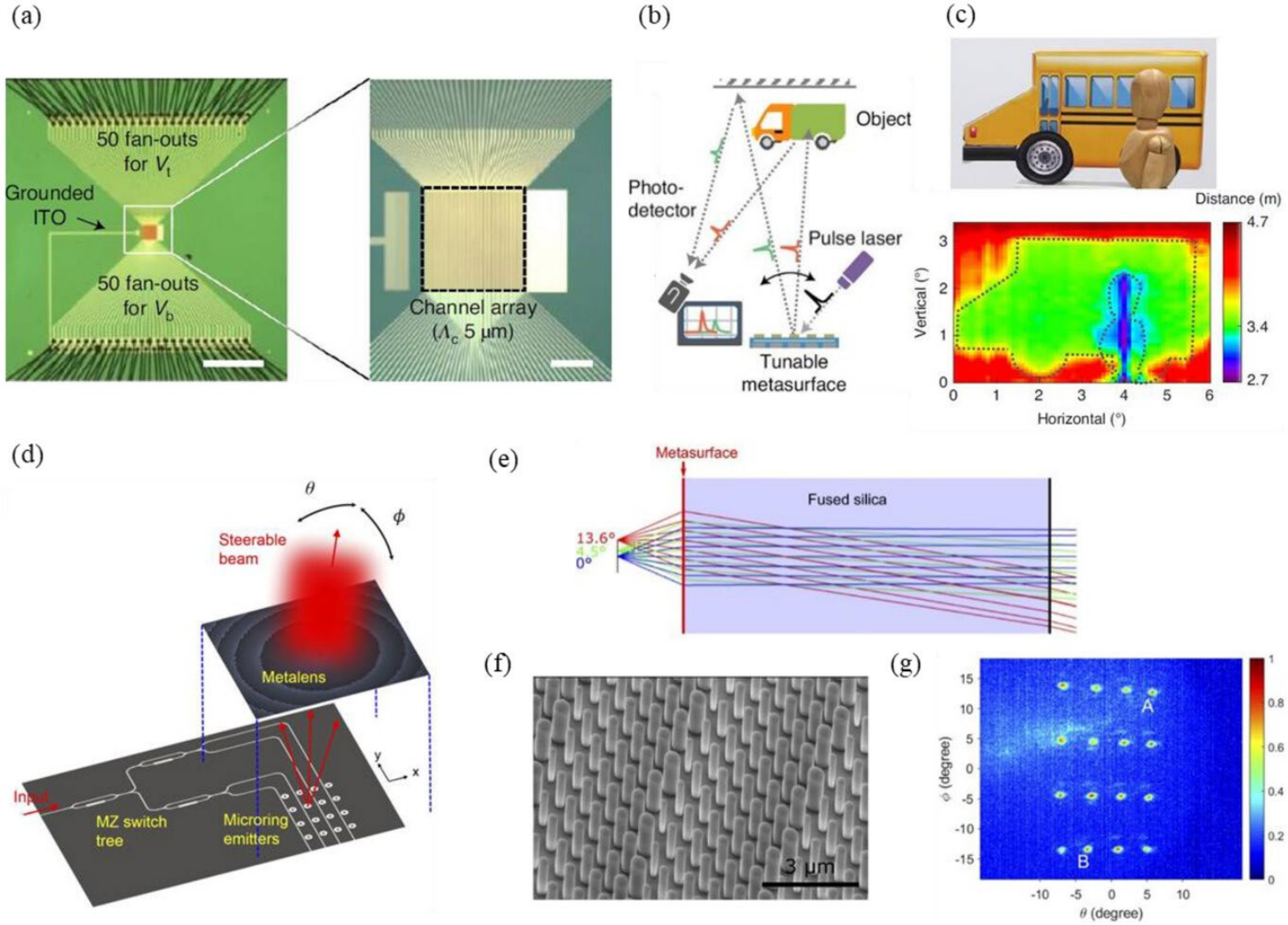




Laser & Photonics Reviews, vol. 16, p. 2100511 (2022) Olivier J.F. Martin

LiDAR

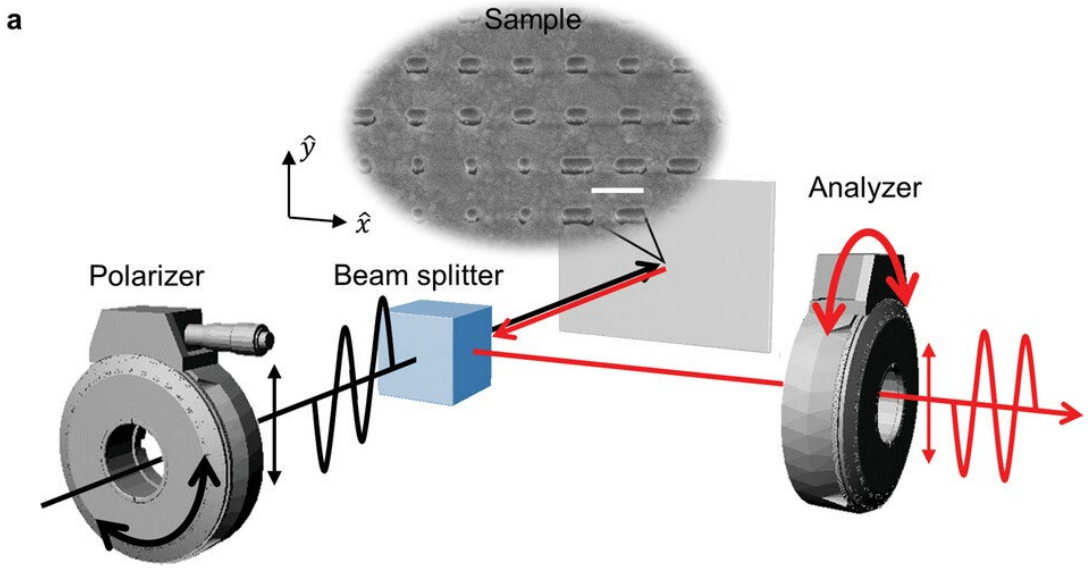
- Metasurfaces are usually used for scanning the scene, either statically or dynamically

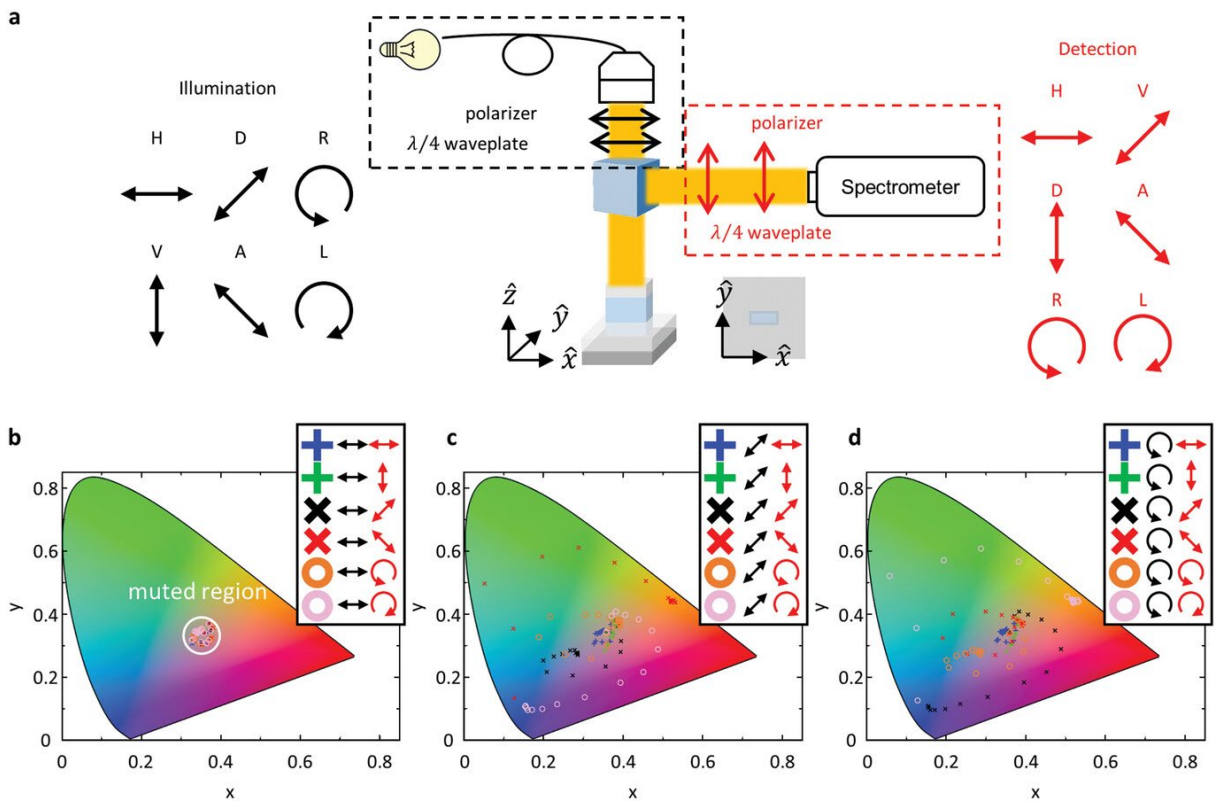


Laser & Photonics Reviews, vol. 16, p. 2100511 (2022) Olivier J.F. Martin

Art…?

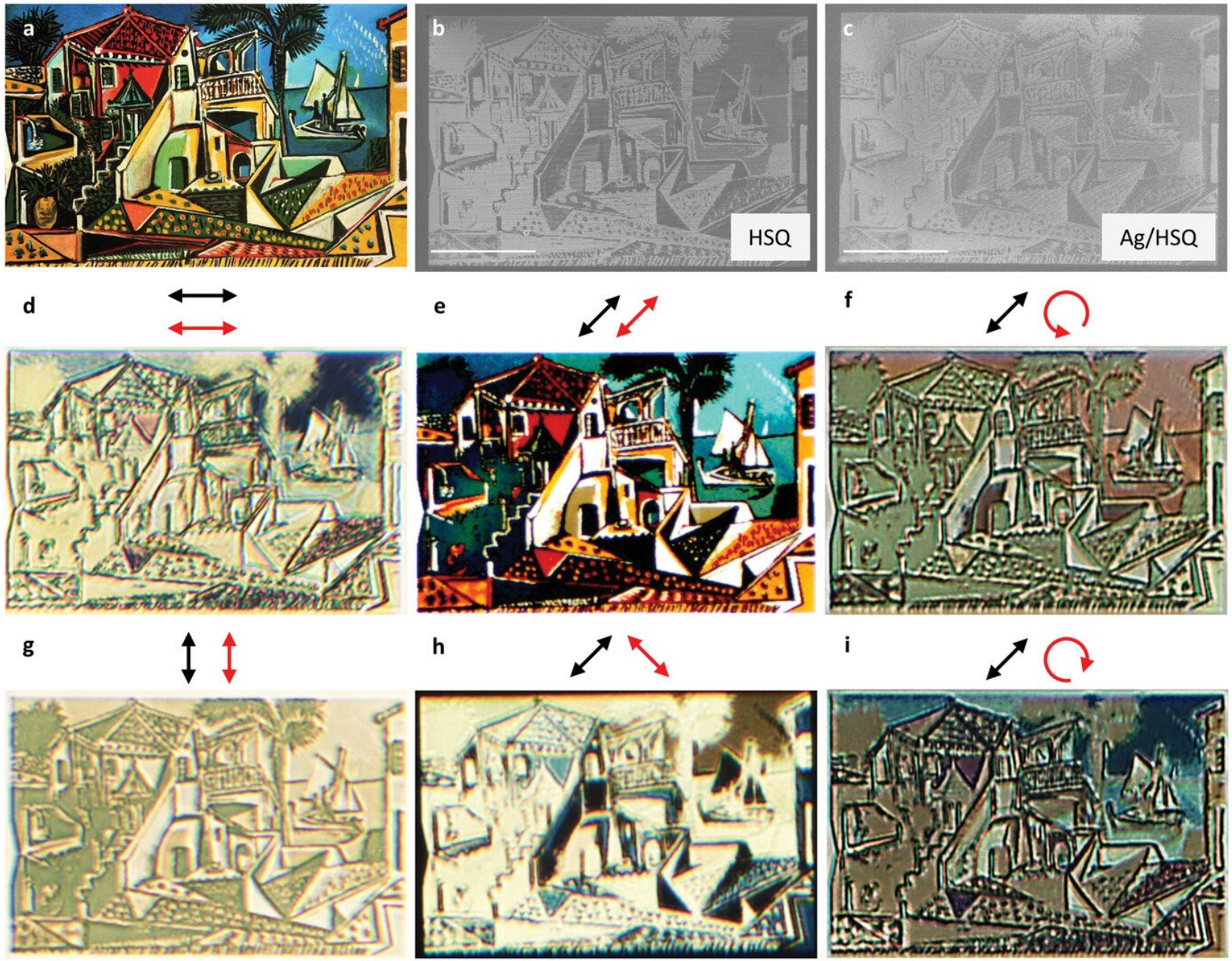
- Metasurfaces can also produce some interesting colorful effects





Advanced Optical Materials vol. 2023, p. 2202165 (2023) Olivier J.F. Martin

Art…?



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Selected Topics in Advanced Optics

Week 13 – part 2

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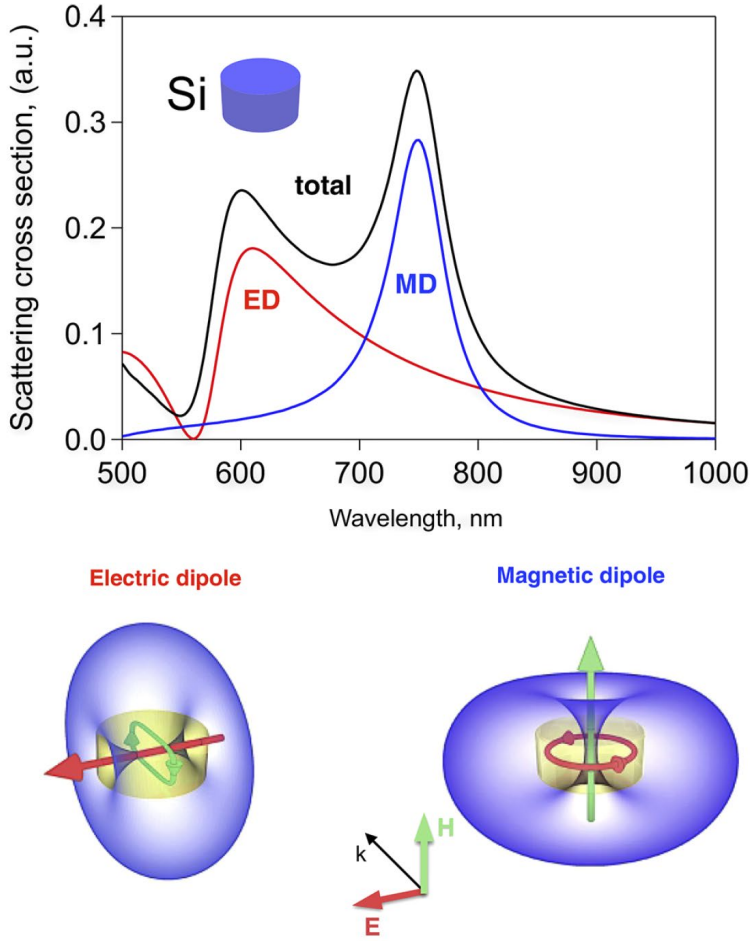
Metasurfaces governed by Mie resonances

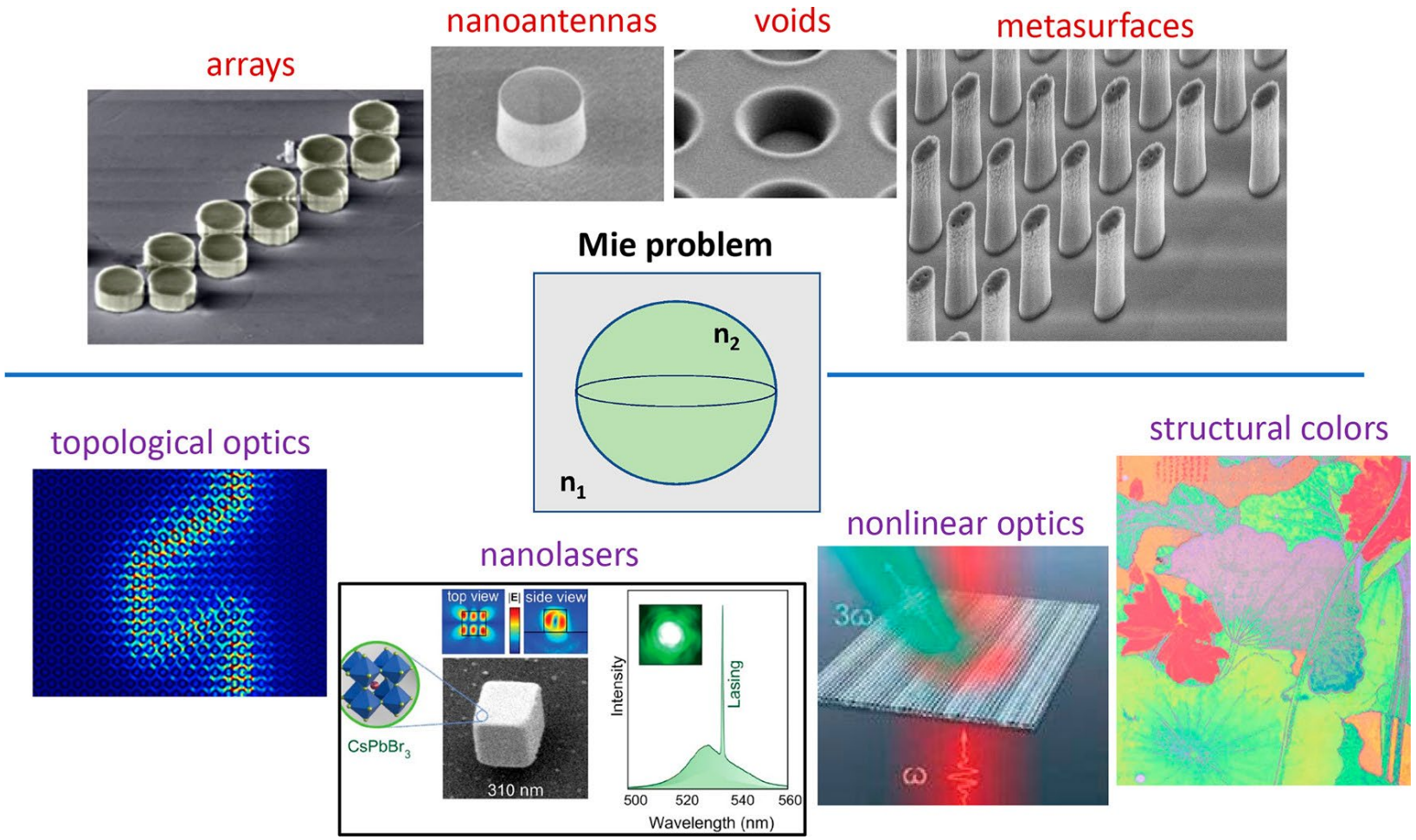
- Dielectric resonators have lower losses than plasmonic ones and are also associated with phase shifts



ACS Photonics vol. 4, p. 2638 (2017)

The rise of Mie-tronics

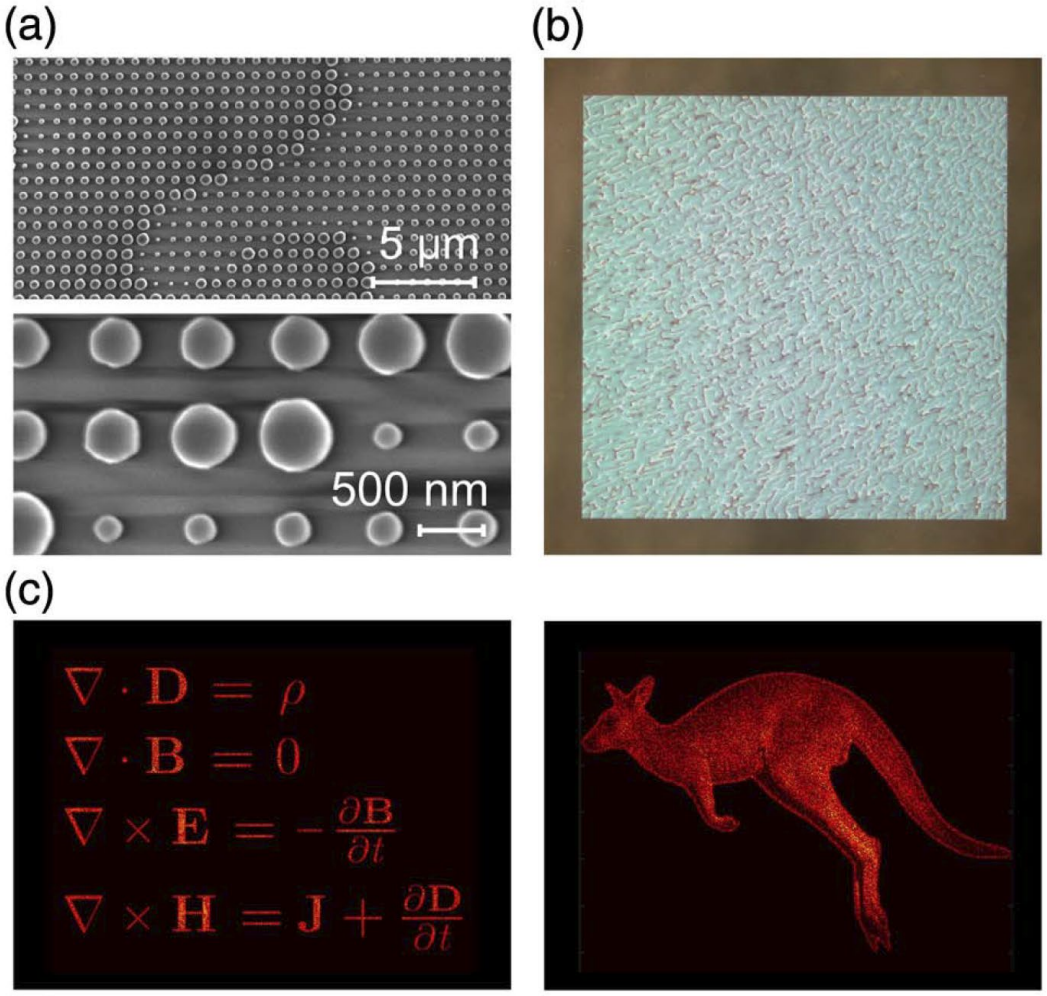
- A huge diversity of dielectric nanostructures can be used to produce interesting optical effects



Nano Letters vol. 22, p. 3513 (2022)

Dielectric metasurfaces

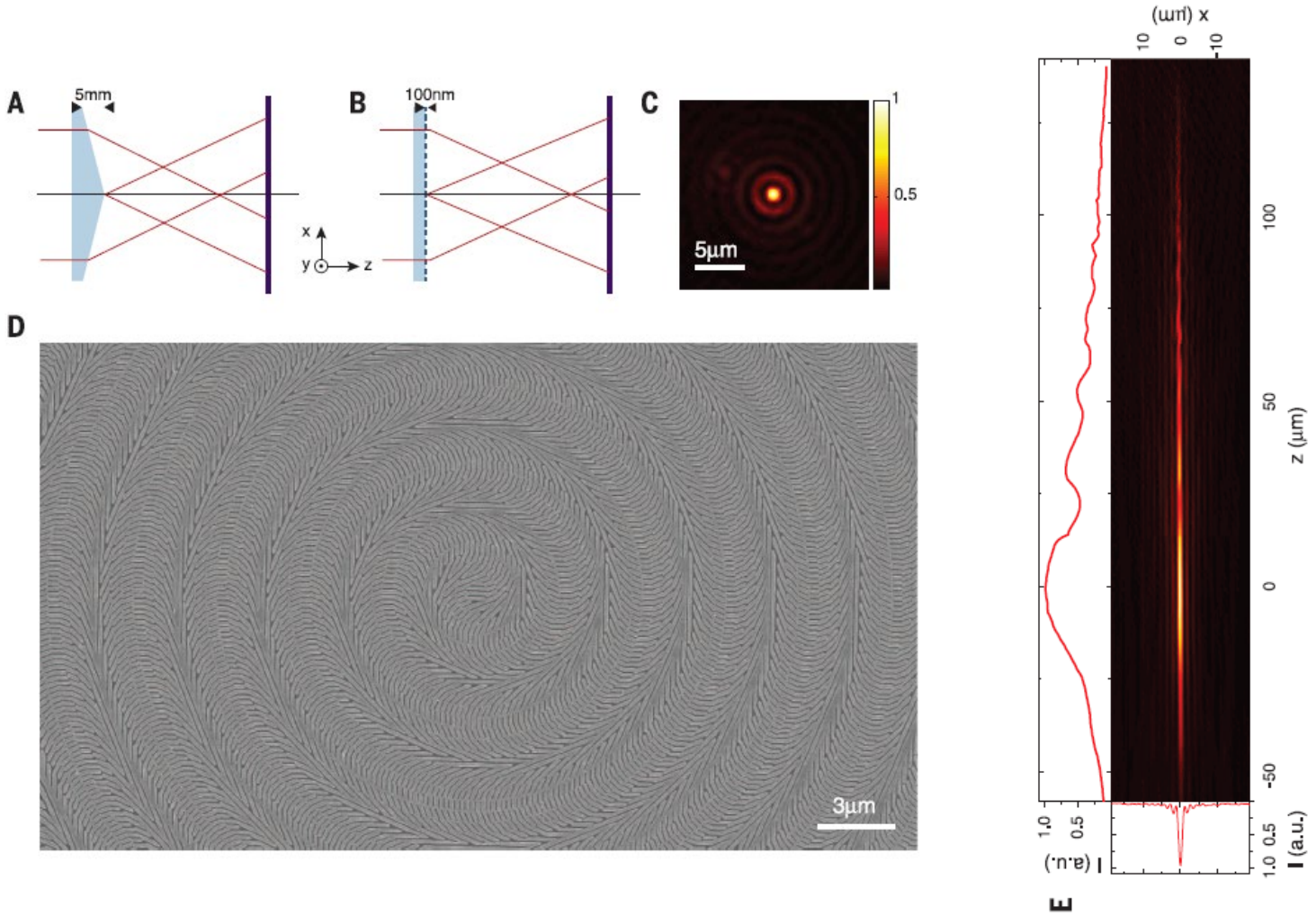
- The phase is engineered with transparent nanostructures of varying dimensions



Optica vol. 3, p. 1504 (2016) Olivier J.F. Martin

Dielectric metasurfaces

- A phase shift can also be obtained using steep structures in Si



Science vol. 345, p. 298 (2015)

Dielectric metasurfaces

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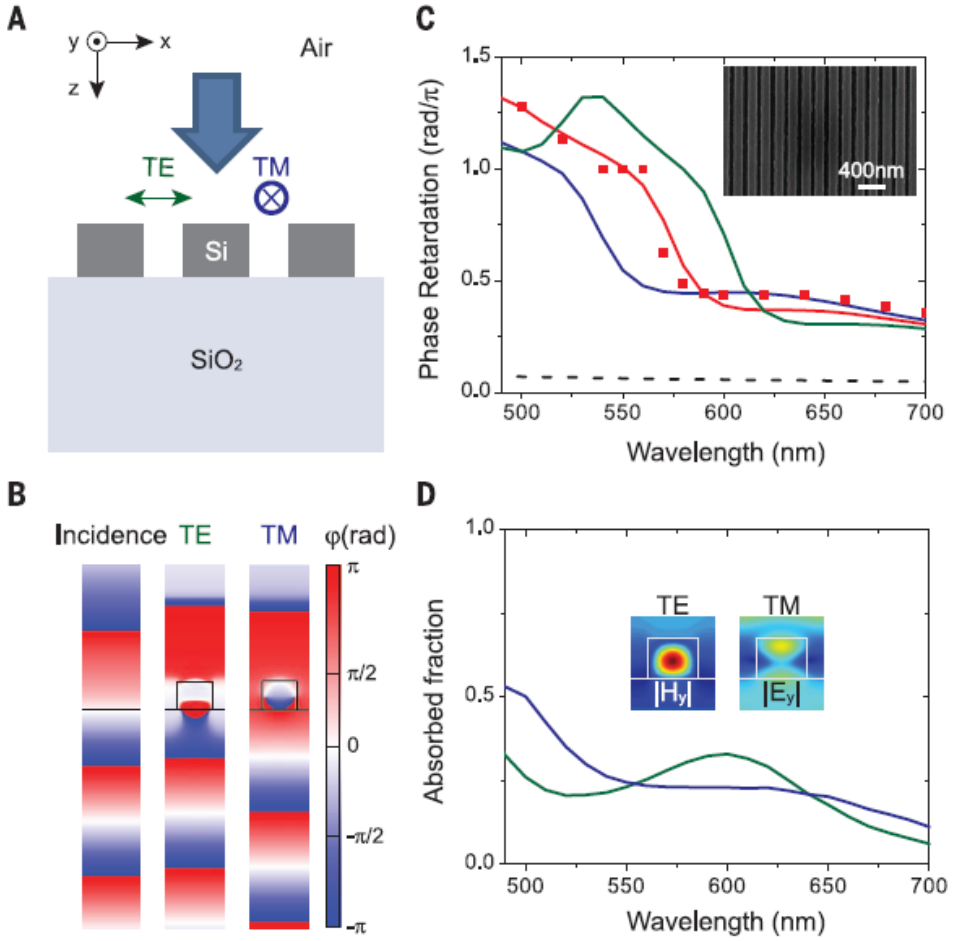
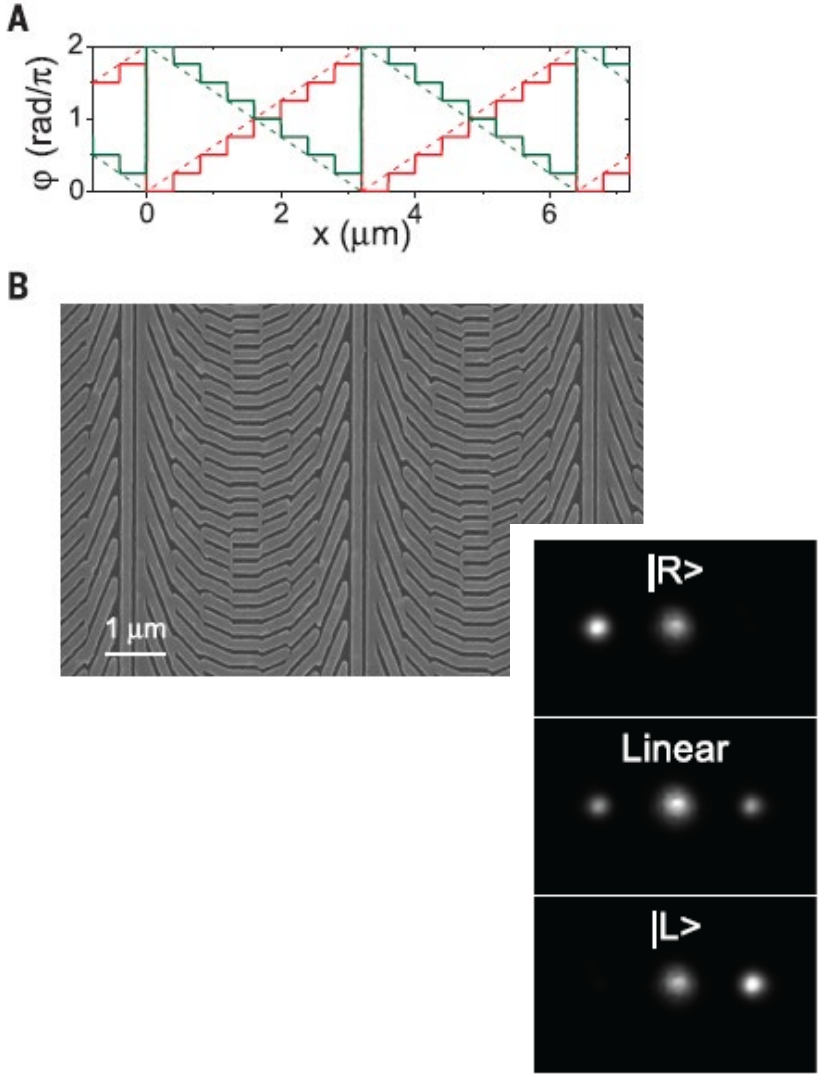
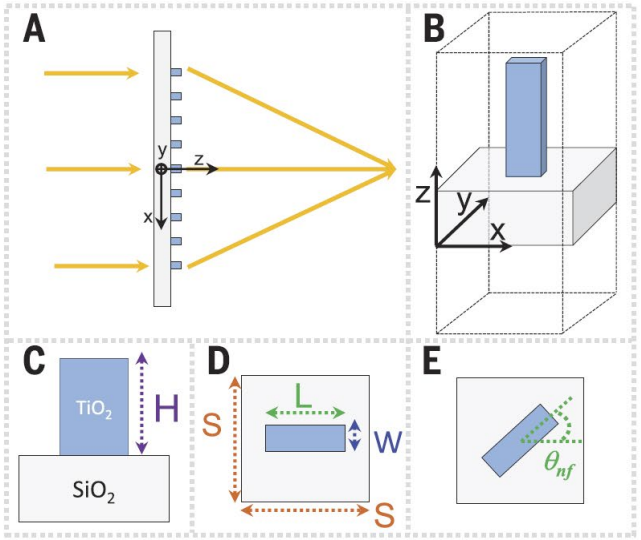


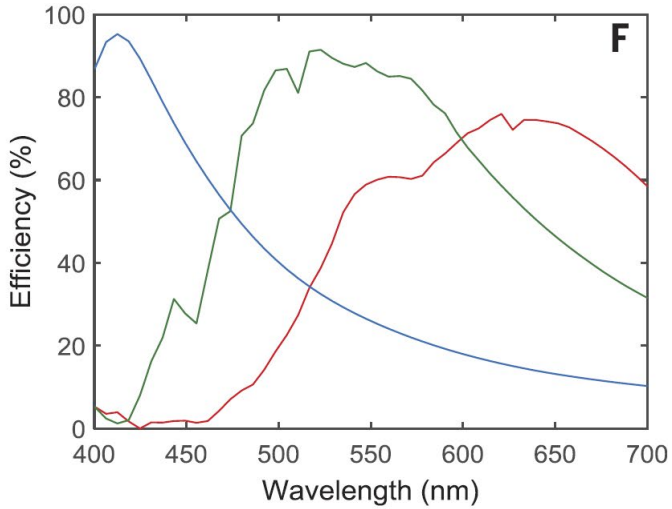


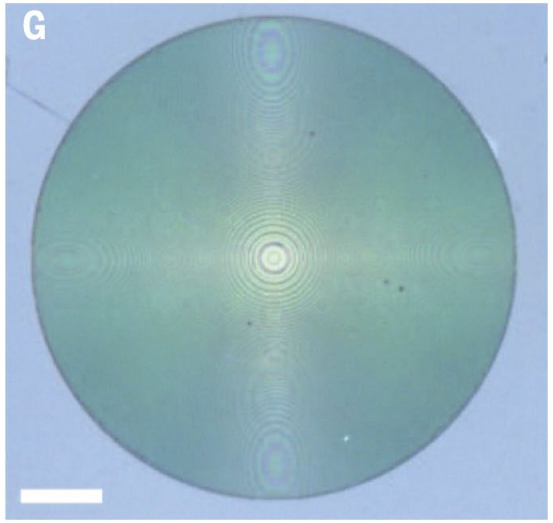
Science vol. 345, p. 298 (2015) Olivier J.F. Martin

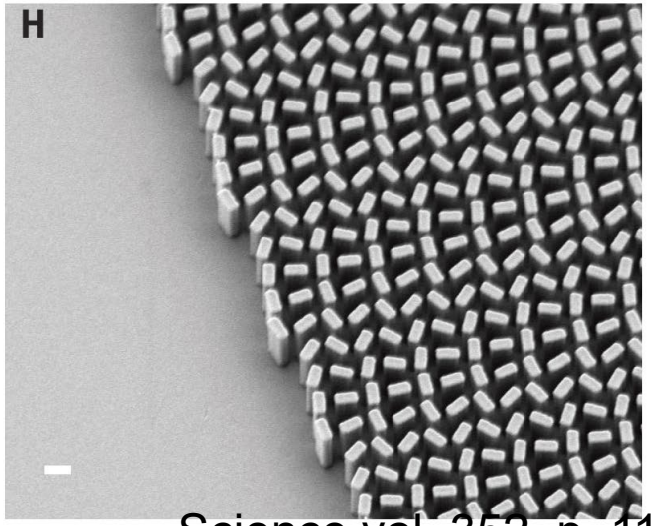
Dielectric metasurfaces

- Design based on TiO_2 nanofins, which orientation determines the phase response





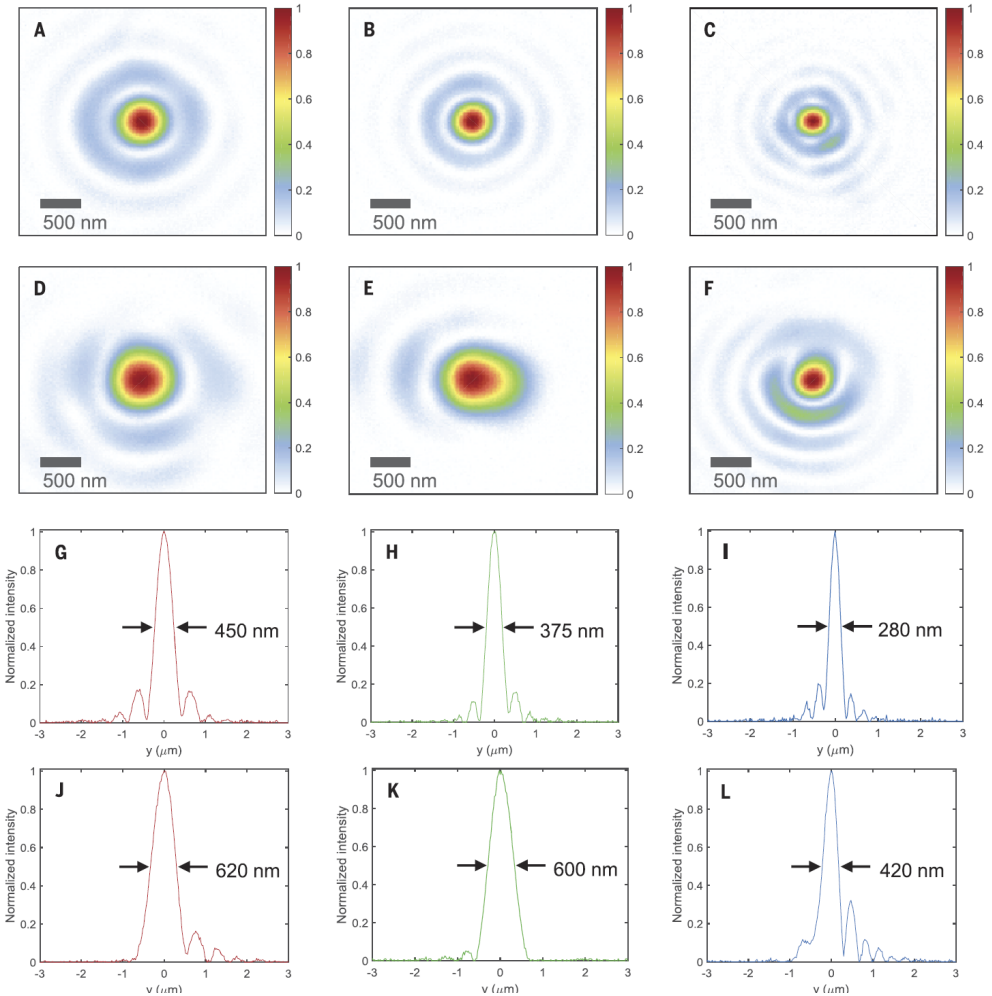


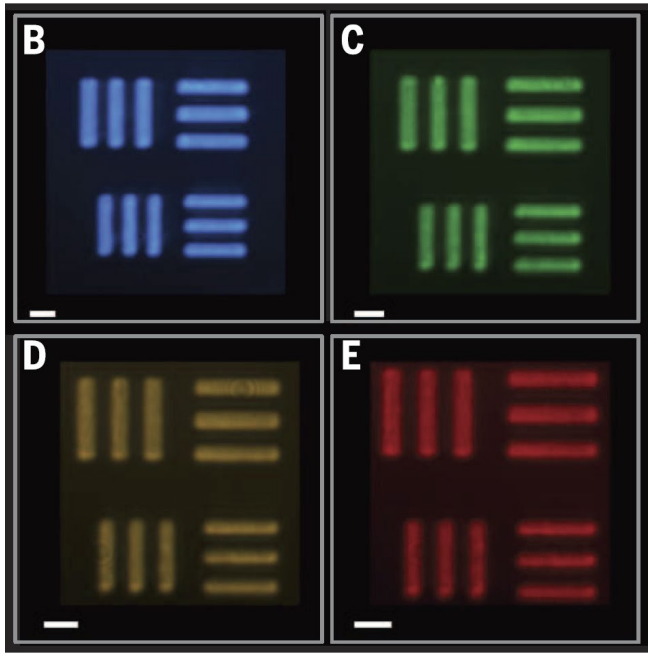


Science vol. 352, p. 1190 (2016) Olivier J.F. Martin

Dielectric metasurfaces

- Such a metasurface can be highly achromatic, better than a plasmonic metasurface

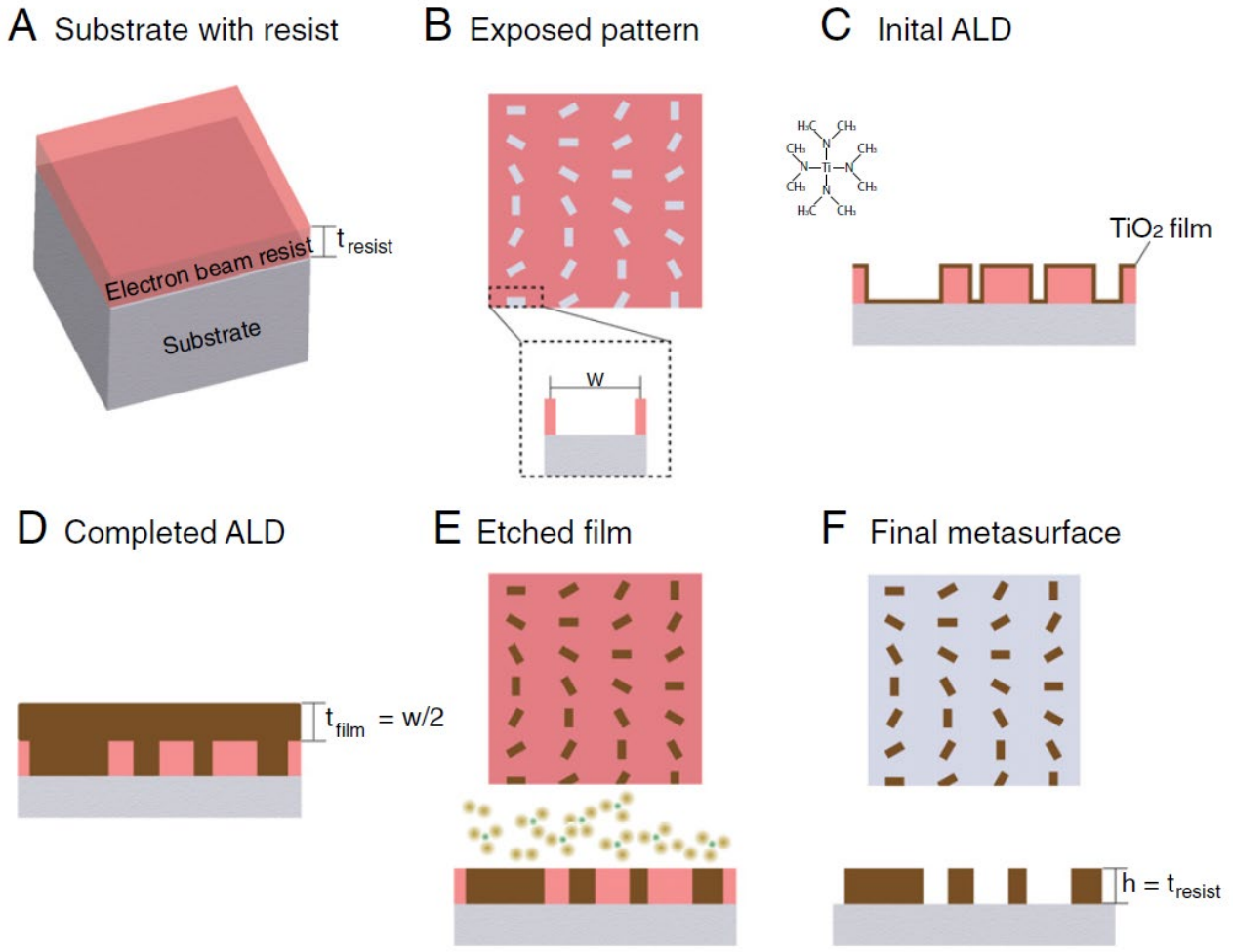




Science vol. 352, p. 1190 (2016) Olivier J.F. Martin

Fabrication of nanofin

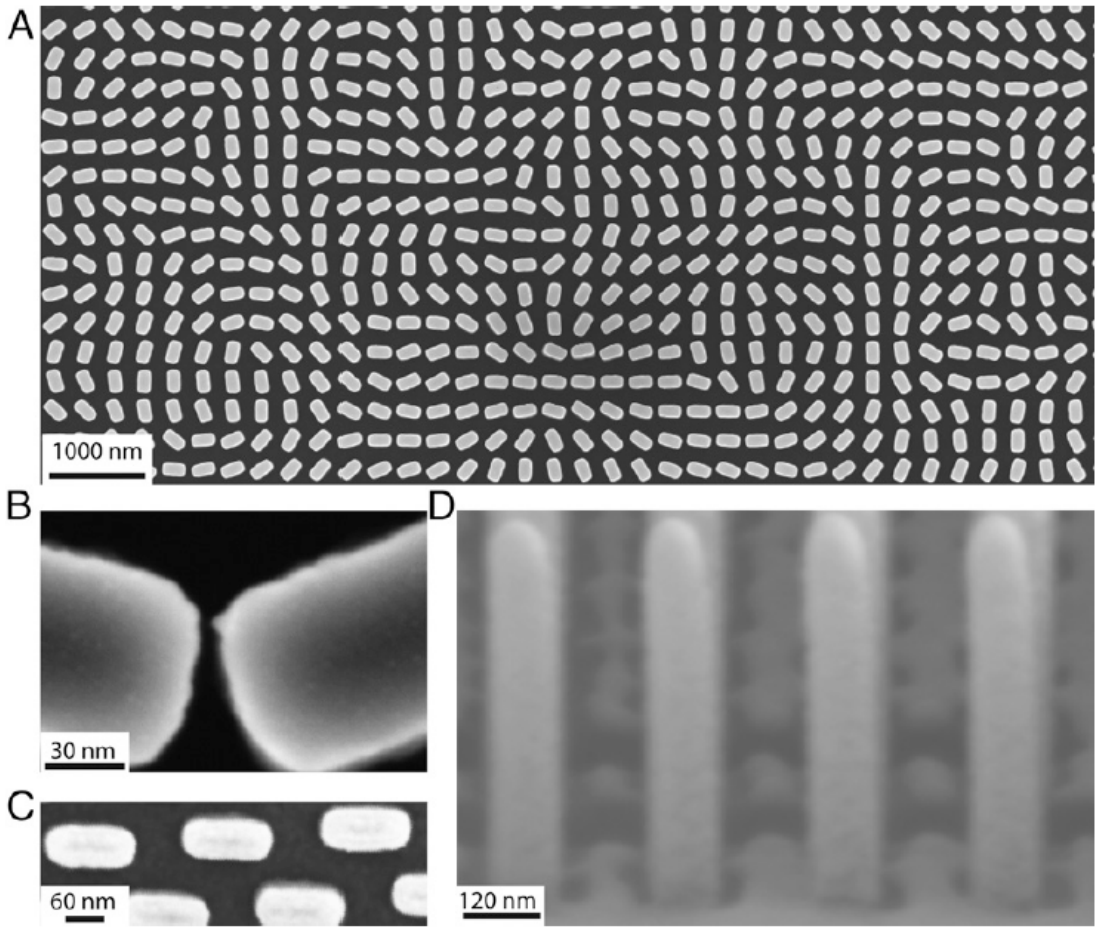
- A very smooth surface is required, clever fabrication in TiO_2 using atomic layer deposition



PNAS vol. 113, p. 10473 (2016) Olivier J.F. Martin

Fabrication of nanofin

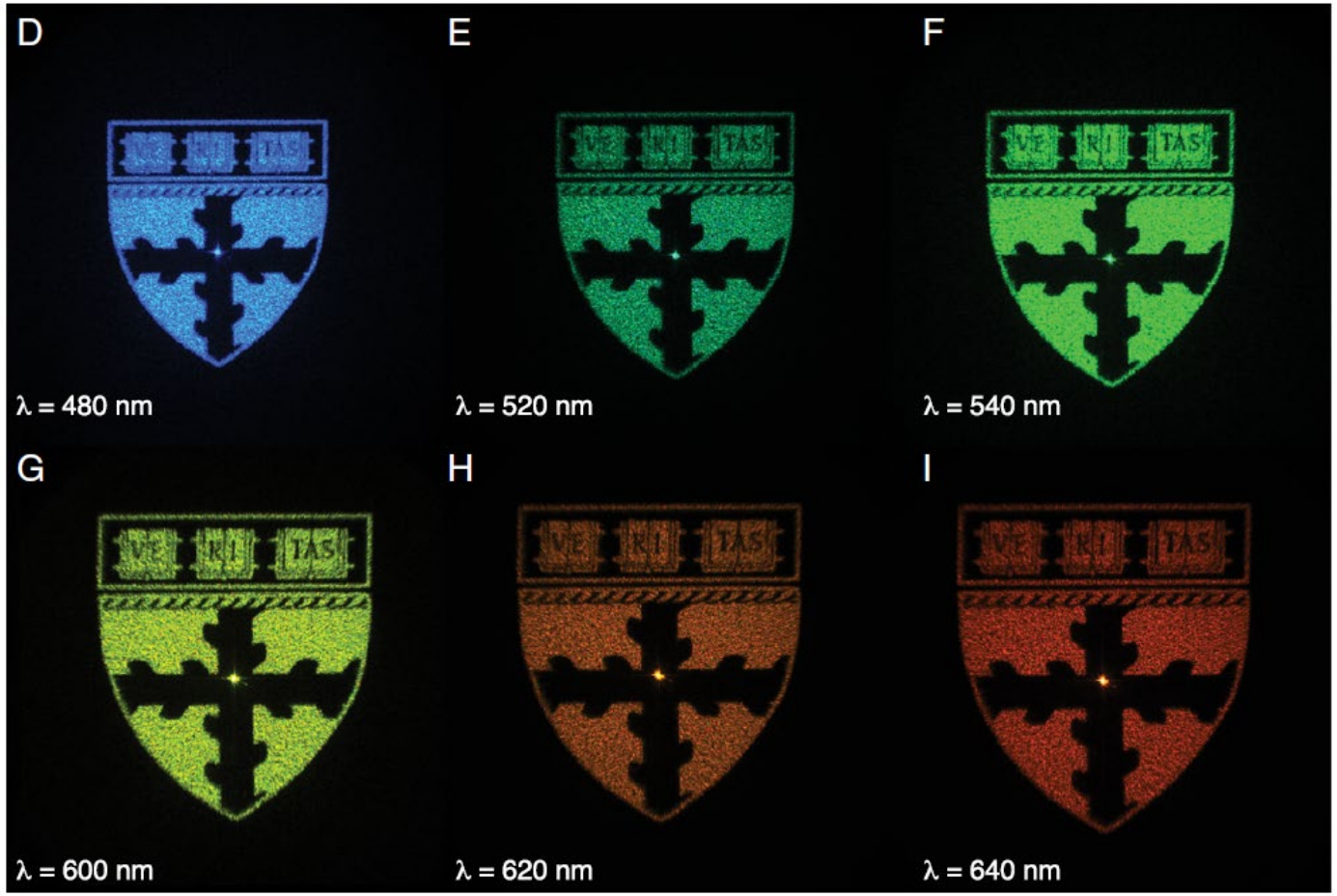
- A very smooth surface is required, clever fabrication in TiO_2 using atomic layer deposition



PNAS vol. 113, p. 10473 (2016)

Fabrication of nanofin

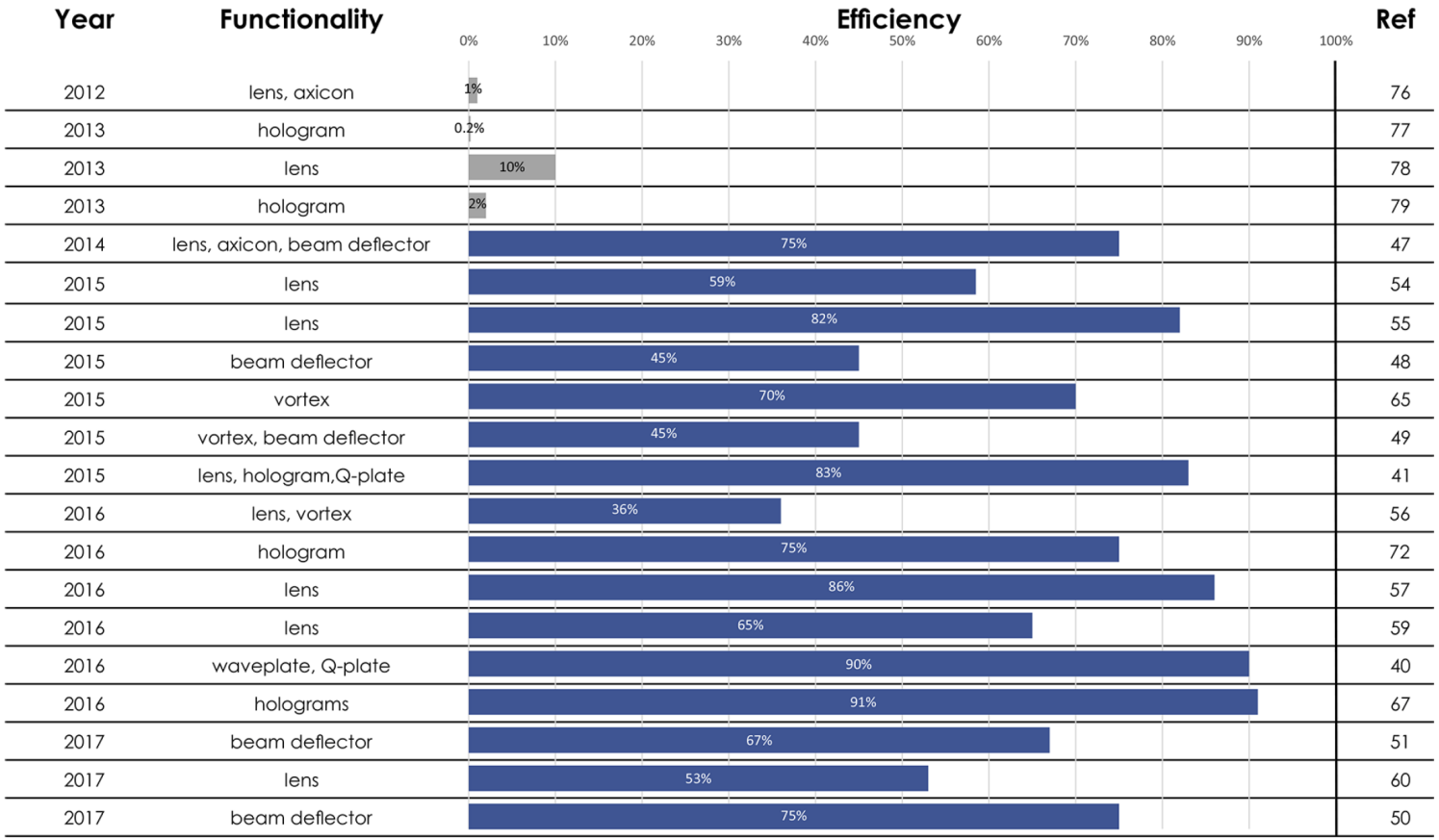
- A very smooth surface is required, clever fabrication in TiO_2 using atomic layer deposition



PNAS vol. 113, p. 10473 (2016)

Metasurfaces governed by Mie resonances

- Such dielectric metasurfaces appear to have superior optical properties (at least in terms of efficiency) than plasmonic metasurfaces

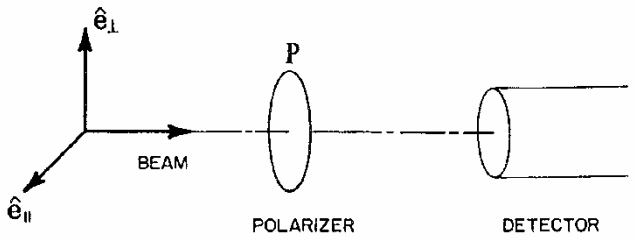


ACS Photonics vol. 4, p. 2638 (2017)

Polarimetry

- Polarimetry provides significant information on materials, objects and their interaction with light
- The polarization of light is described by the Stokes vector, which requires four different measurements

$$S_0 = a_x^2 + a_y^2 = I = E_{\parallel}E_{\parallel}^* + E_{\perp}E_{\perp}^*$$
$$S_1 = a_x^2 - a_y^2 = Q = E_{\parallel}E_{\parallel}^* - E_{\perp}E_{\perp}^*$$
$$S_2 = 2a_x a_y \cos\varphi = U = E_{\parallel}E_{\perp}^* + E_{\perp}E_{\parallel}^*$$
$$S_3 = 2a_x a_y \sin\varphi = V = j\left(E_{\parallel}E_{\perp}^* - E_{\perp}E_{\parallel}^*\right)$$



I : irradiance

$I^2 \geq Q^2 + U^2 + V^2$ in general

$I^2 = Q^2 + U^2 + V^2$ for polarized light

$Q = U = V = 0$ for unpolarized light

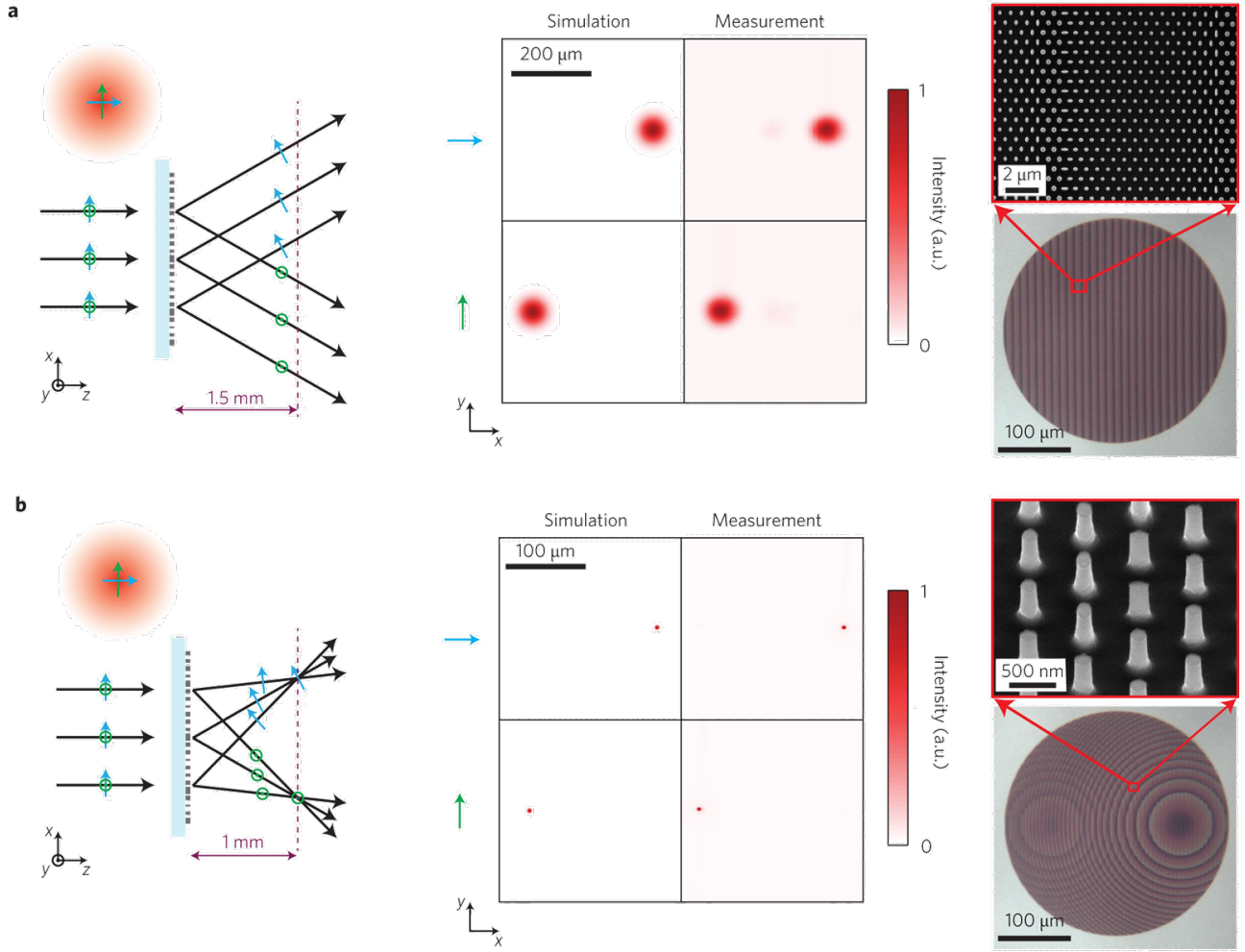
degree of polarization : $\sqrt{Q^2 + U^2 + V^2} / I$ (between 0 and 1)

degree of linear polarization : $\sqrt{Q^2 + U^2} / I$ (between 0 and 1)

degree of circular polarization : V / I (between 0 and 1)

Polarimetry

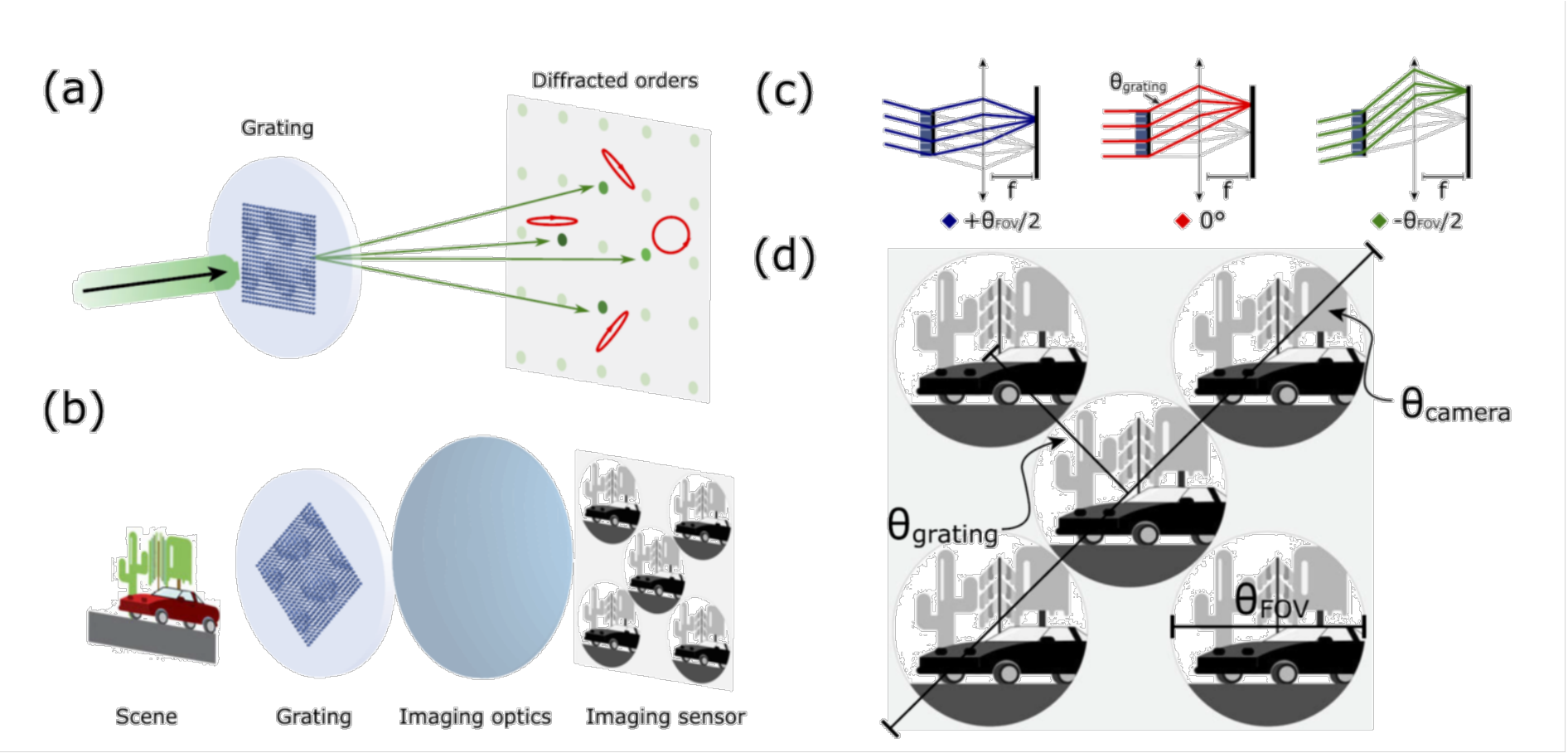
- Metasurfaces have the potential to retrieve the entire polarization state in a single measurement



Nature Nanotechnology vol. 10, p. 937 (2015)

Polarimetry

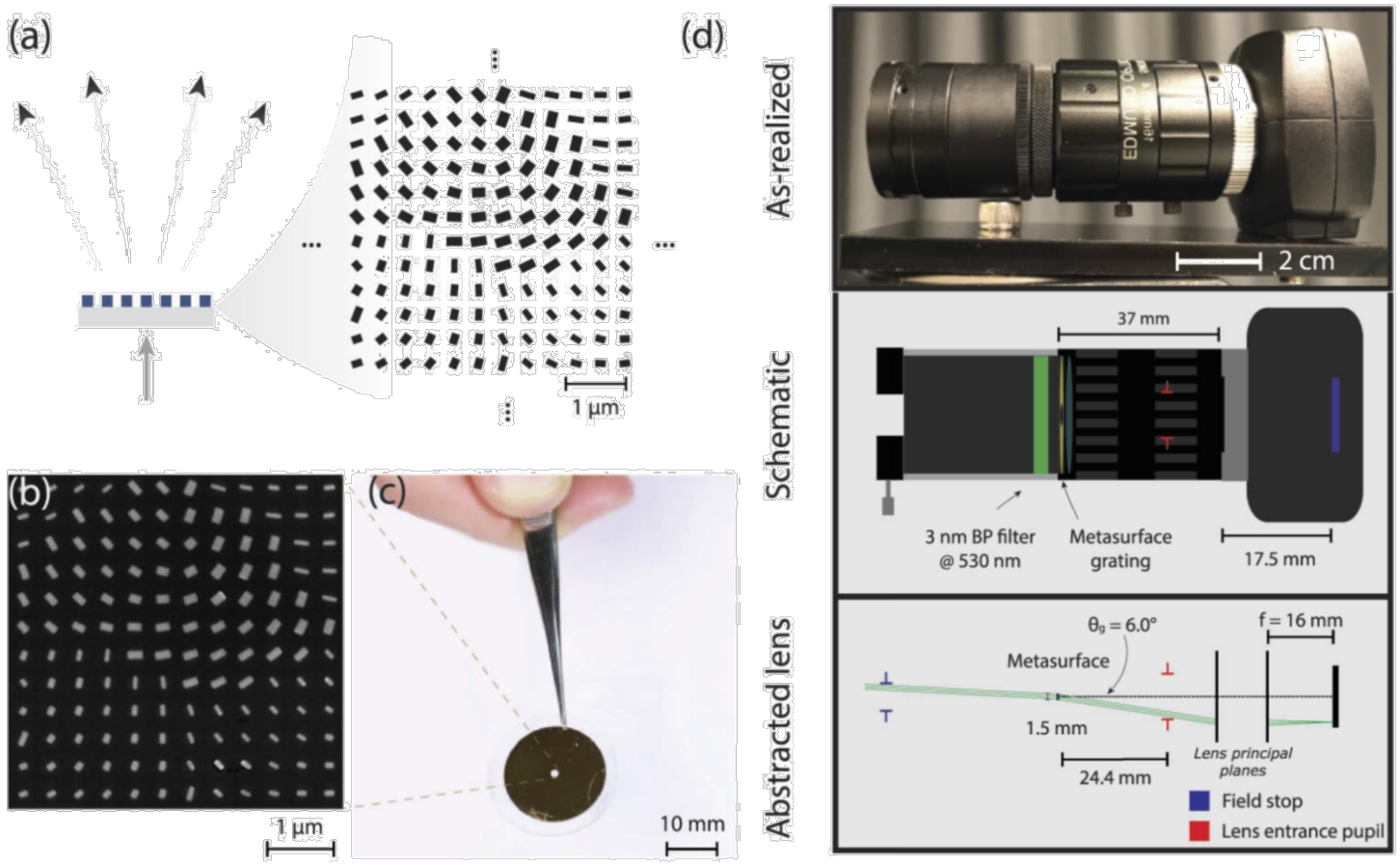
- Metasurfaces have the potential to retrieve the entire polarization state in a single measurement



Optics Express, vol. 30, p. 9389 (2022)

Polarimetry

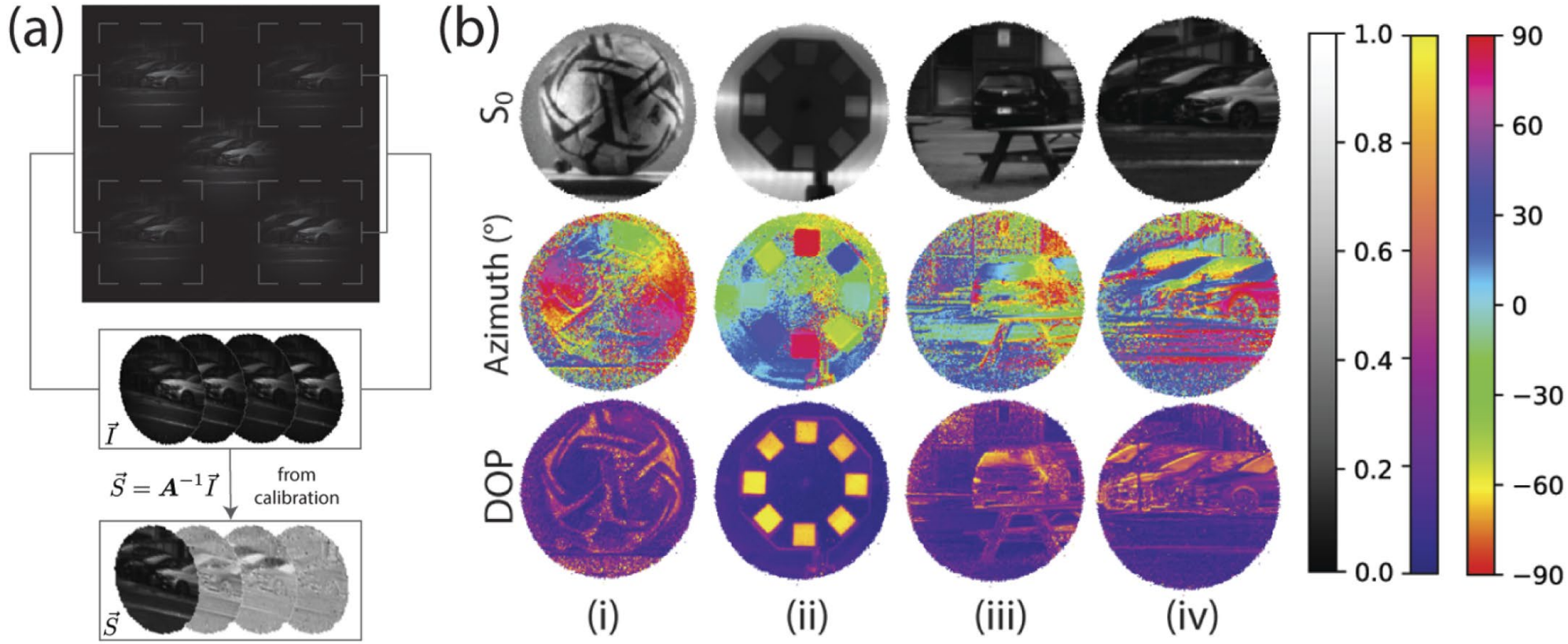
- Metasurfaces have the potential to retrieve the entire polarization state in a single measurement



Optics Express, vol. 30, p. 9389 (2022)

Polarimetry

- Metasurfaces have the potential to retrieve the entire polarization state in a single measurement



Optics Express, vol. 30, p. 9389 (2022)

Selected Topics in Advanced Optics

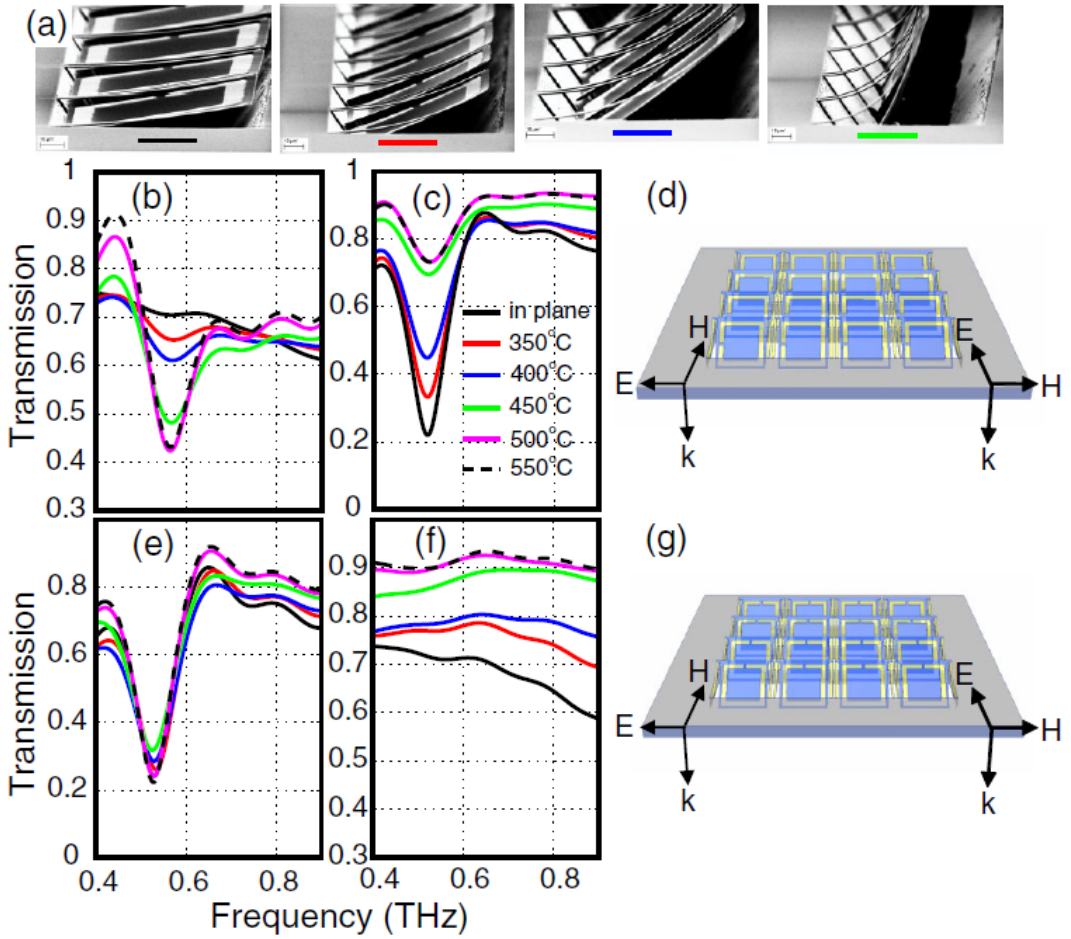
Week 13 – part 3

Olivier J.F. Martin
Nanophotonics and Metrology Laboratory

EPFL

Reconfigurable metasurfaces

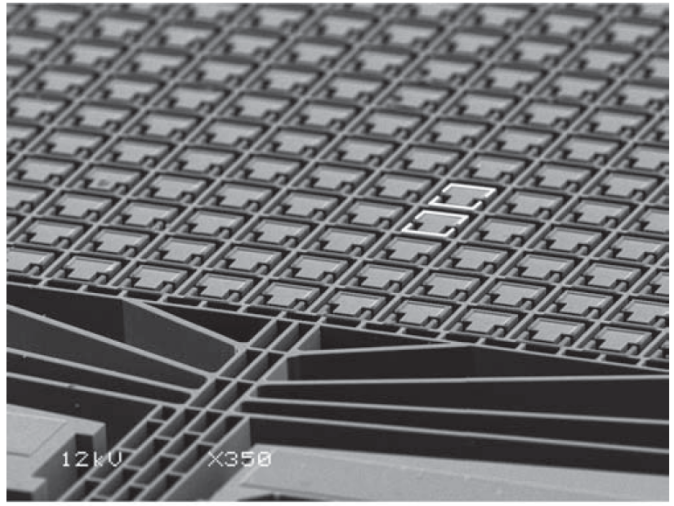
- Reconfigurable split-rings based on active cantilevers made from bimaterials and responding to a thermal stimulus

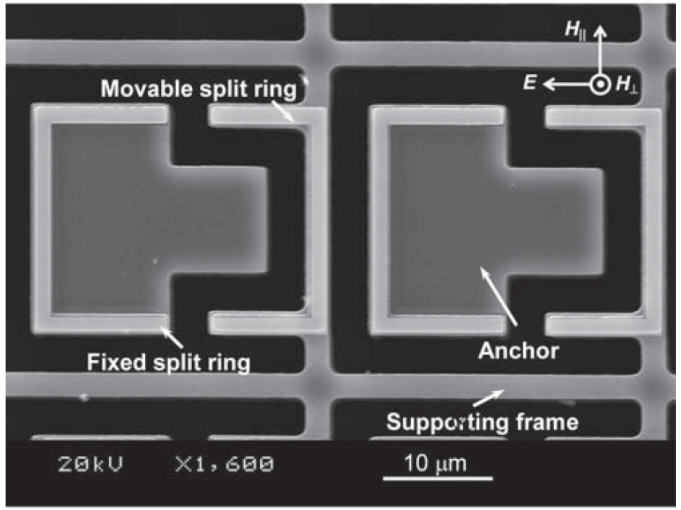


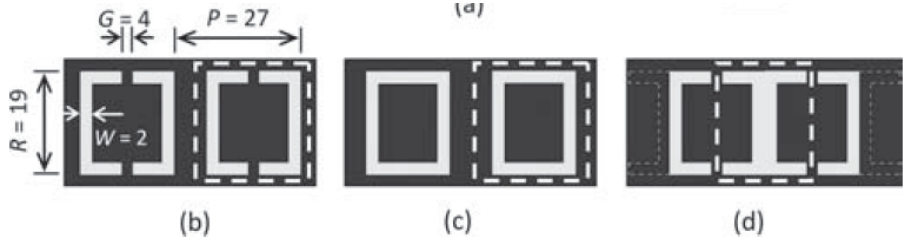
Physical Review Letters vol. 103, p. 147401 (2009)

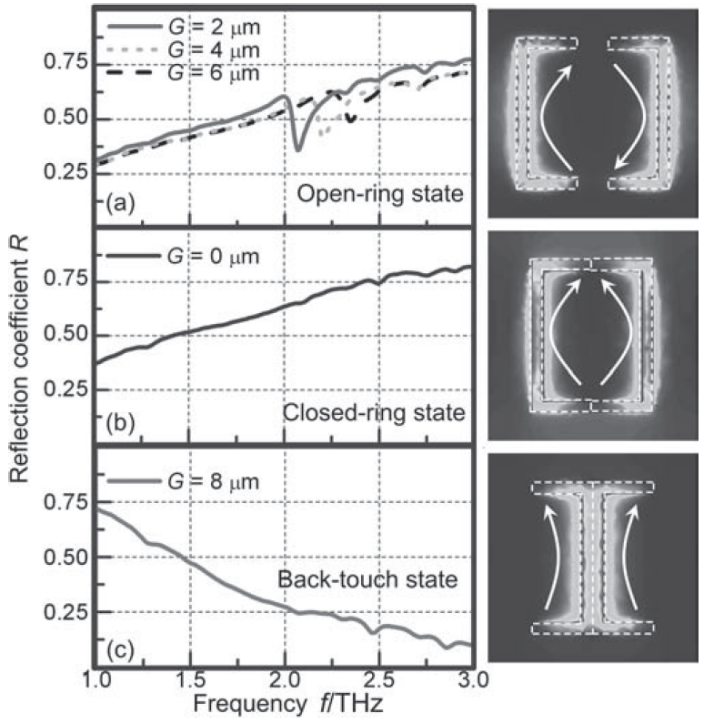
Reconfigurable metasurfaces

- Switchable magnetic metamaterials using micromachining





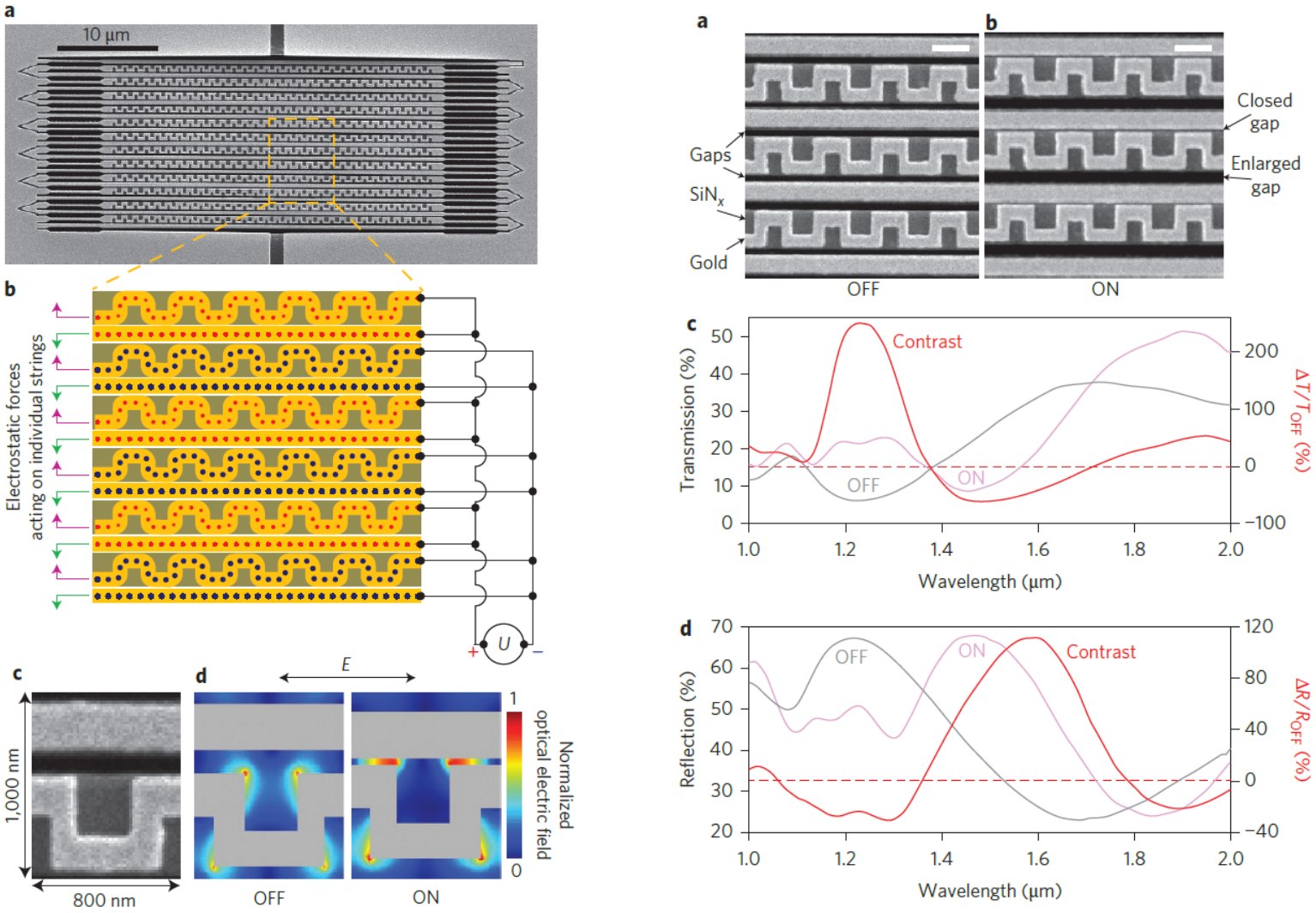




Advanced Materials vol. 23, p. 1792 (2011)

Reconfigurable metasurfaces

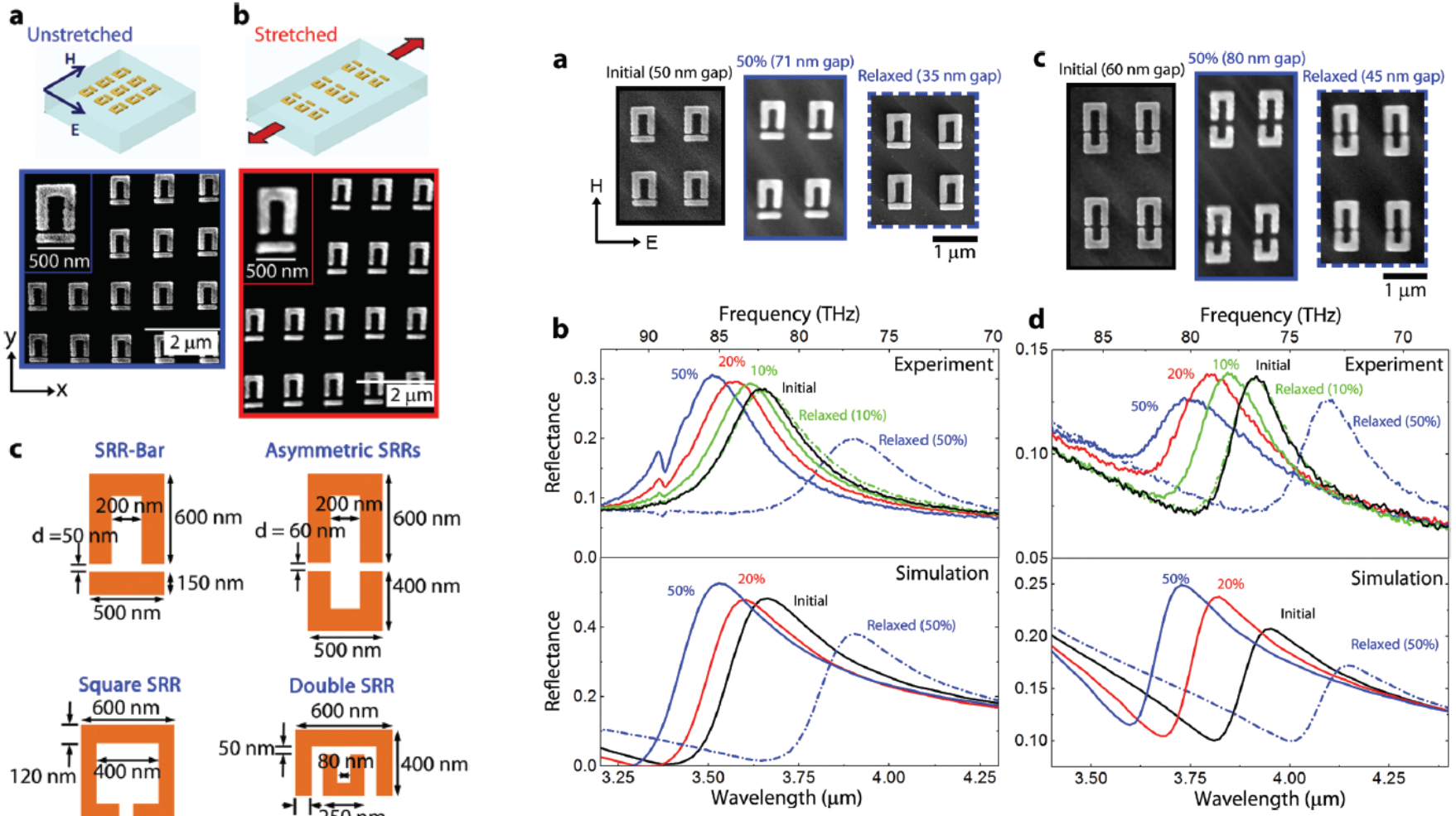
- An electromechanically reconfigurable plasmonic metamaterial



Nature Nanotechnology vol. 8, p. 252 (2013)

Reconfigurable metasurfaces

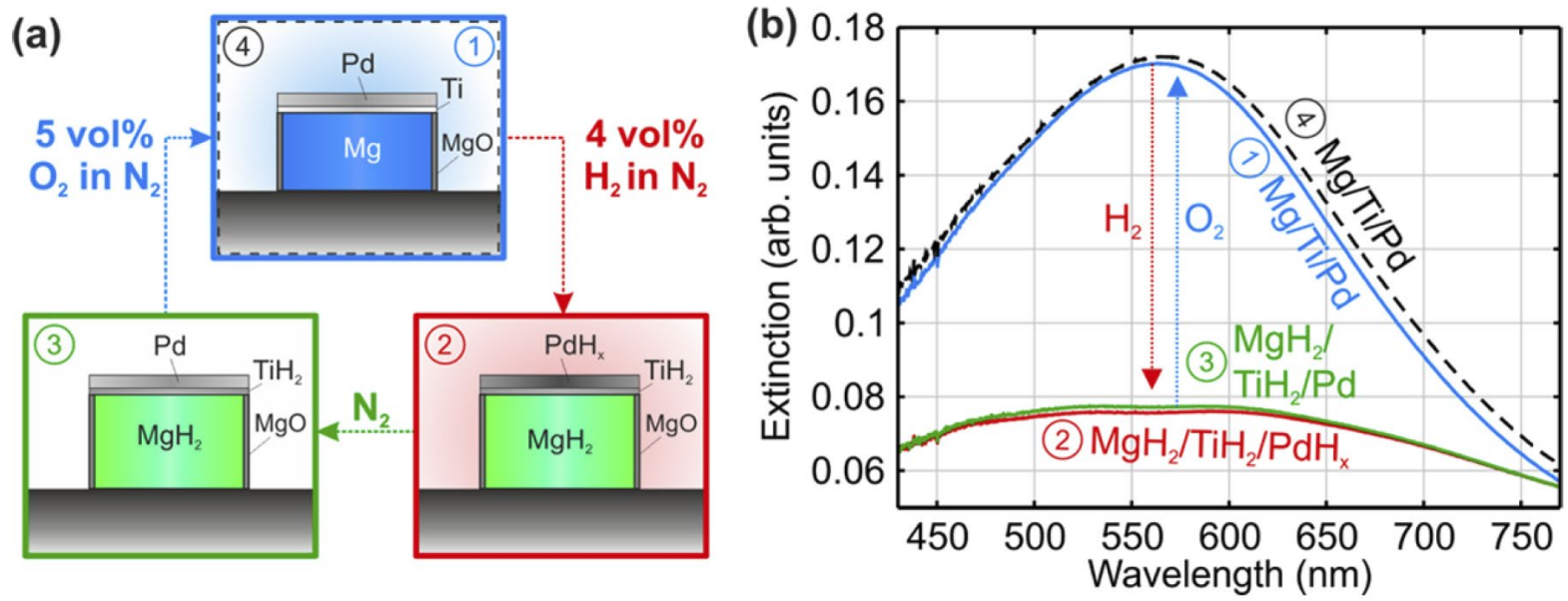
- Stretchable metasurface



Nano Letters vol. 10, p. 4222 (2010)

Responsive metasurface built from Mg nanostructures

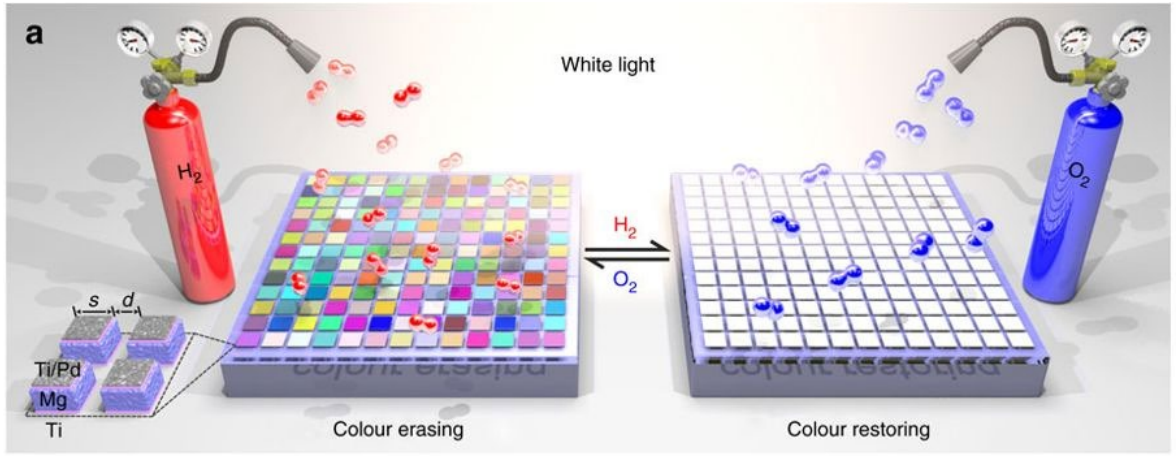
- Mg reacts to hydrogen and changes its optical response
- Switching of magnesium particles to magnesium hydride and vice versa with the aid of a 10 nm catalytic Pd layer and a 5 nm Ti buffer

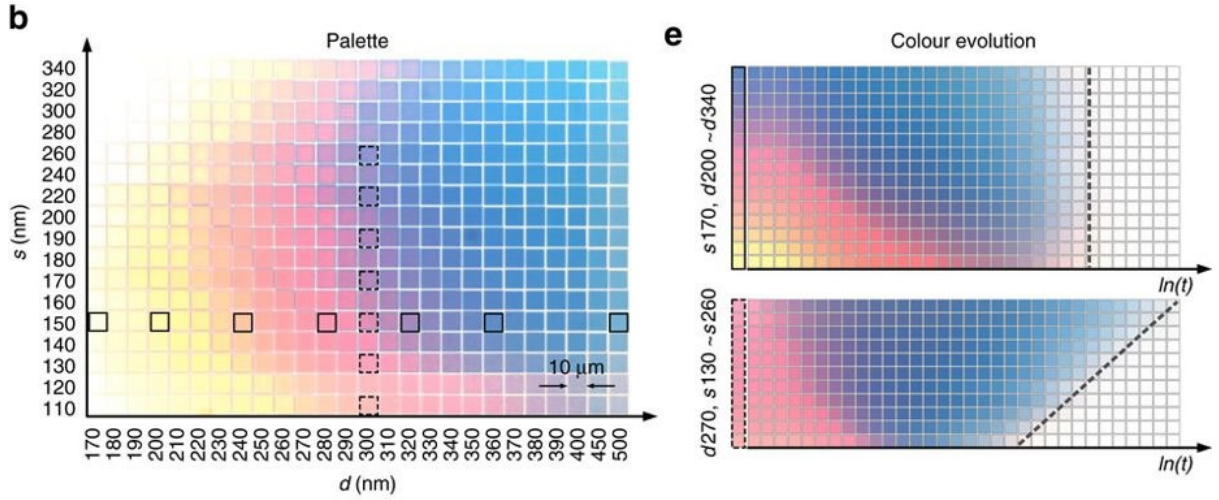


Nano Letters vol. 15, p. 7949 (2015)

Responsive metasurface built from Mg nanostructures

- The optical response changes with the H_2 or O_2 content

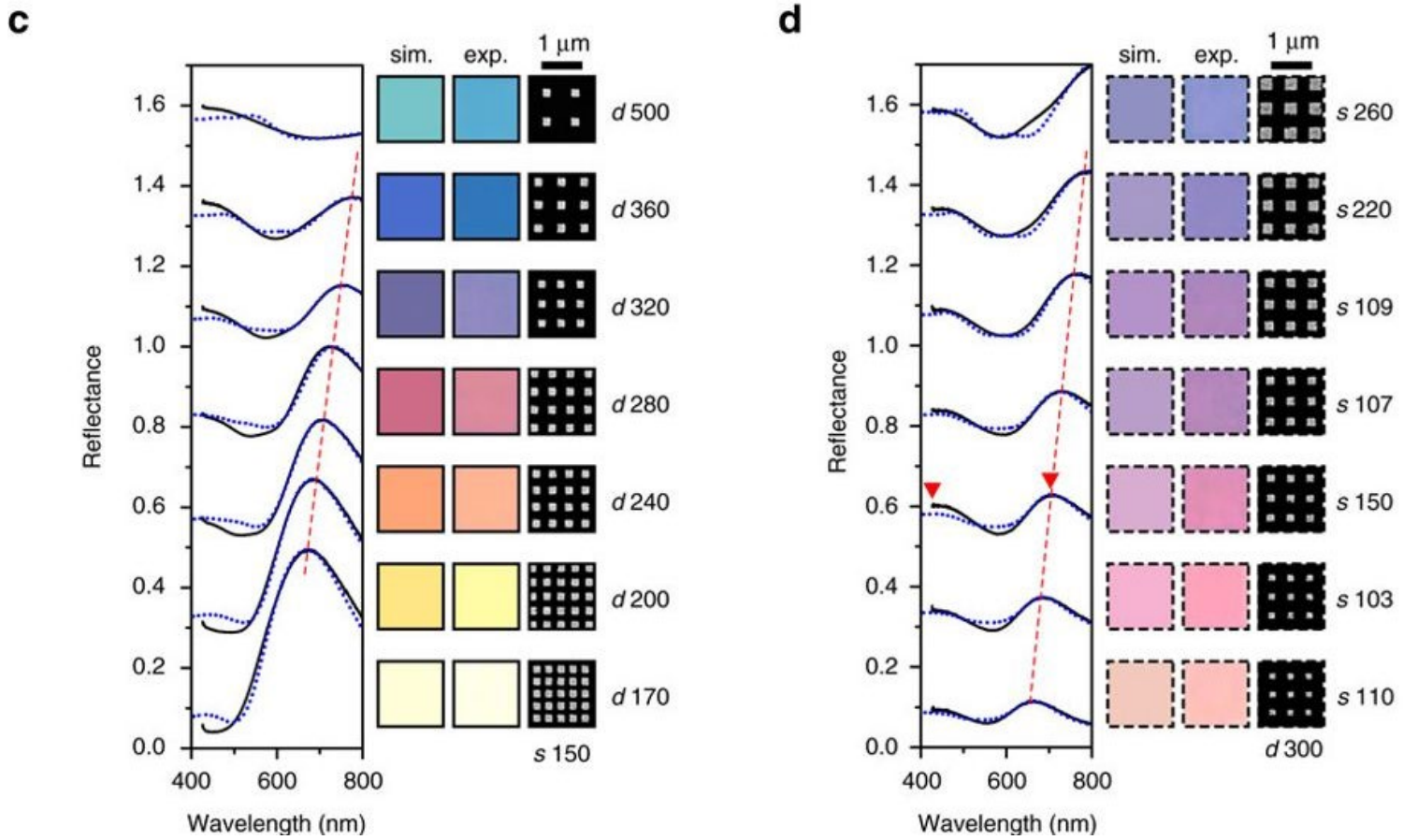




Nature Communications vol. 8, p. 14606 (2017)

Responsive metasurface built from Mg nanostructures

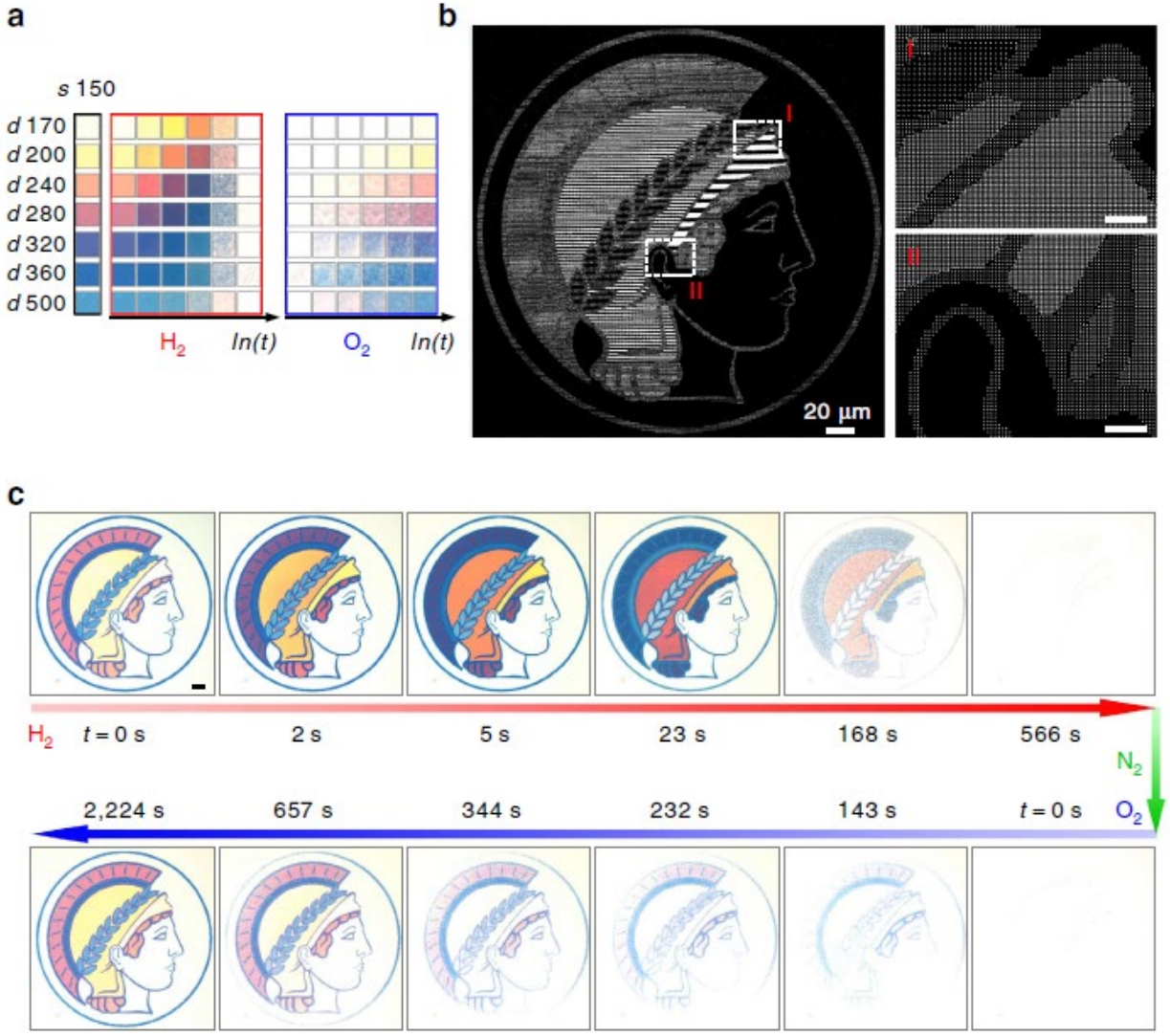
- The optical response changes with the H_2 or O_2 content



Nature Communications vol. 8, p. 14606 (2017)

Responsive metasurface built from Mg nanostructures

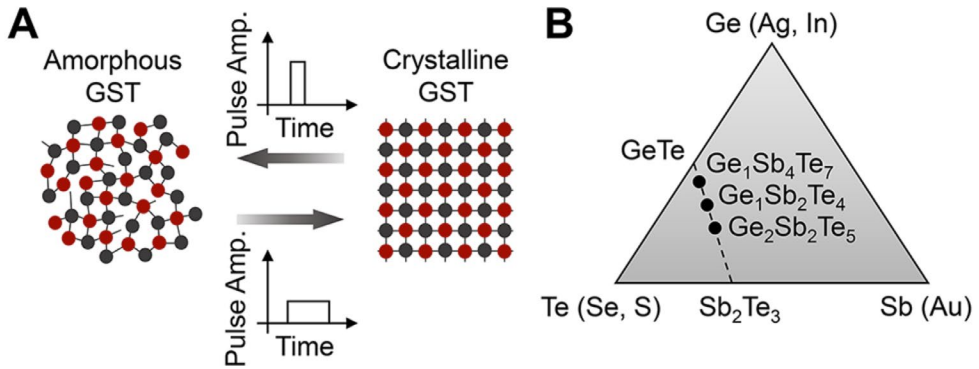
- The optical response changes with the H_2 or O_2 content



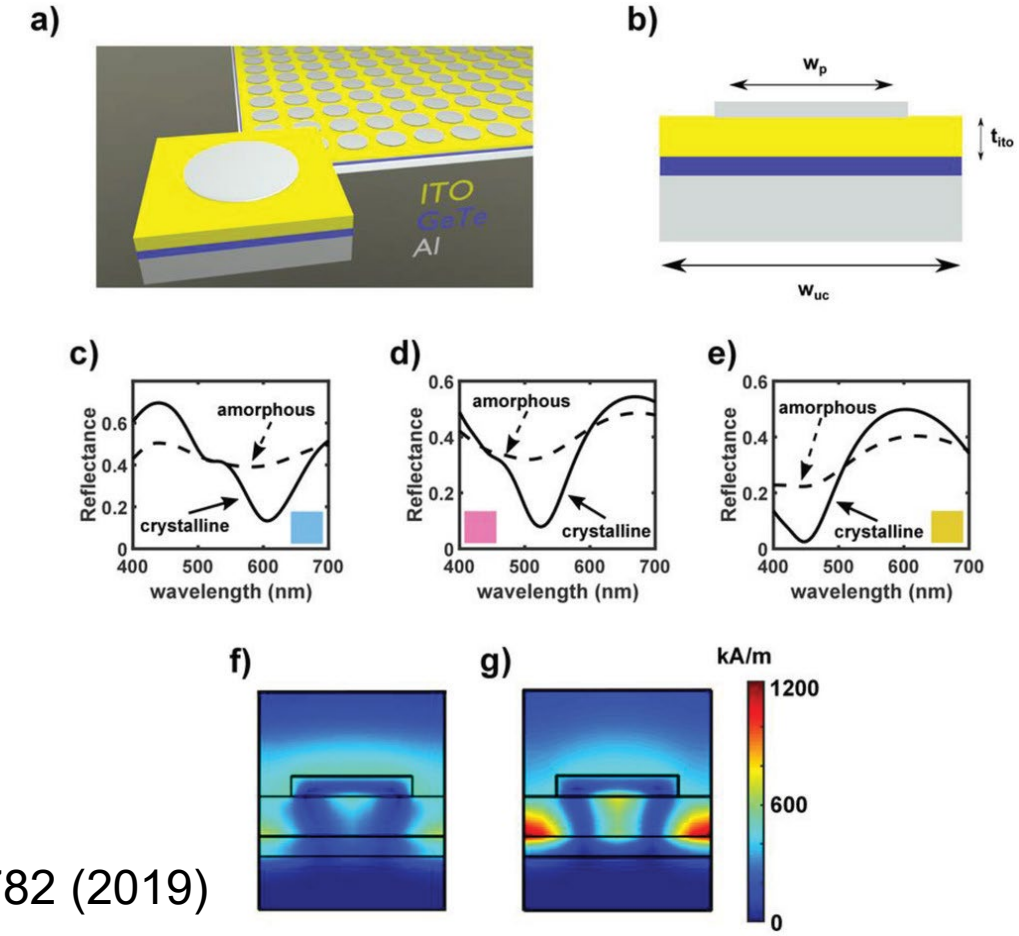
Nature Communications vol. 8, p. 14606 (2017)

Tunable metasurfaces

- Chalcogenide phase-change materials ($Ge_2Sb_2Te_5$, GeTe, …)
- Change from amorphous to crystalline upon temperature cycles or pulsed illumination



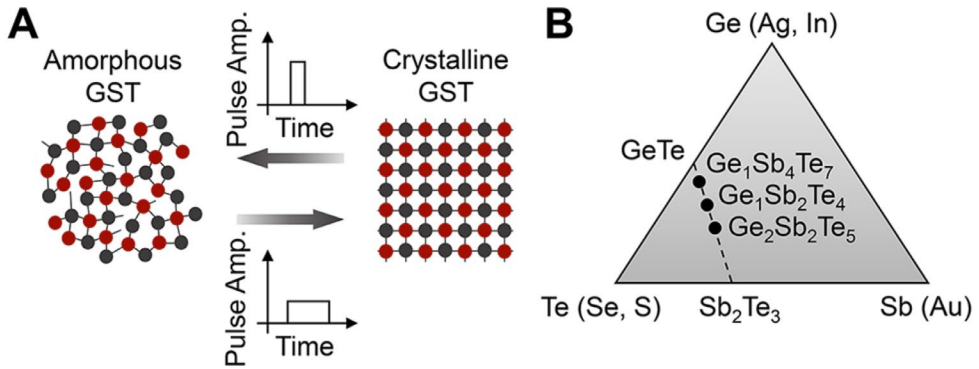
Nanophotonics vol. 9, p. 39 (2020)



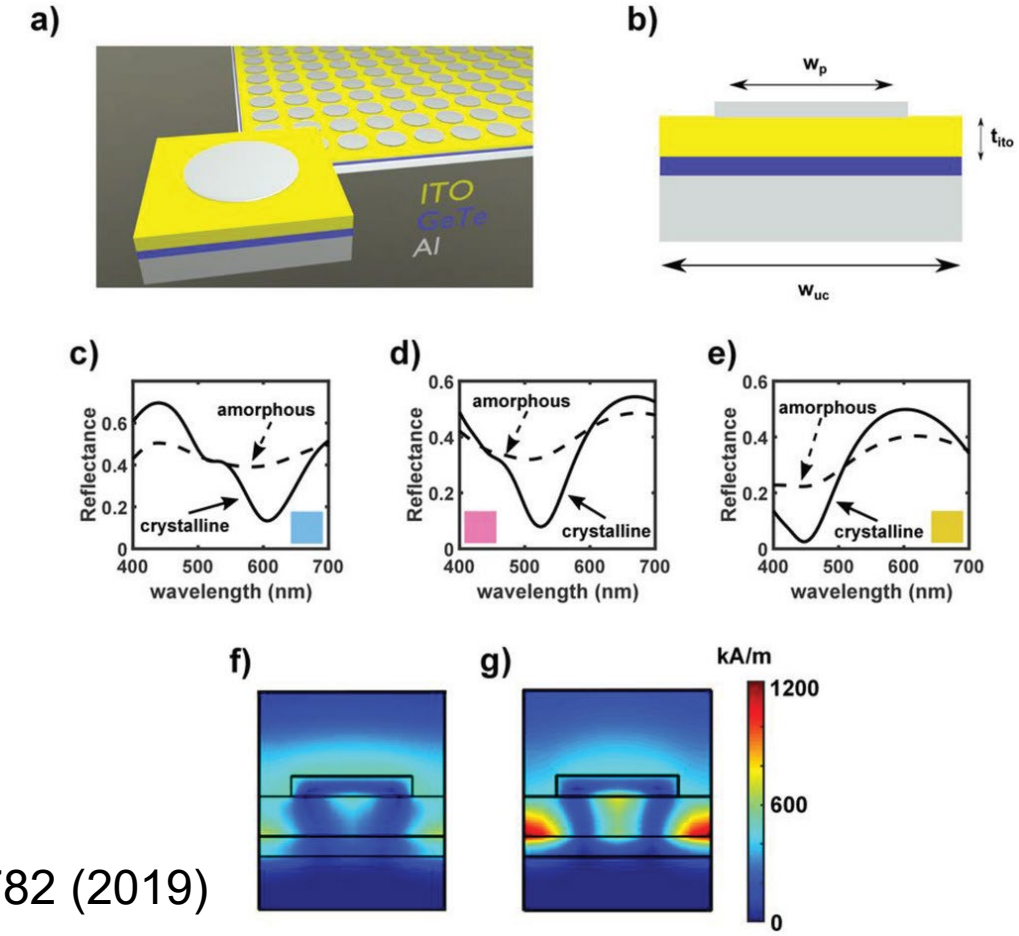
Advanced Optical Materiasl vol. 7, p. 1801782 (2019)

Tunable metasurfaces

- Chalcogenide phase-change materials ($Ge_2Sb_2Te_5$, GeTe, …)
- Change from amorphous to crystalline upon temperature cycles or pulsed illumination



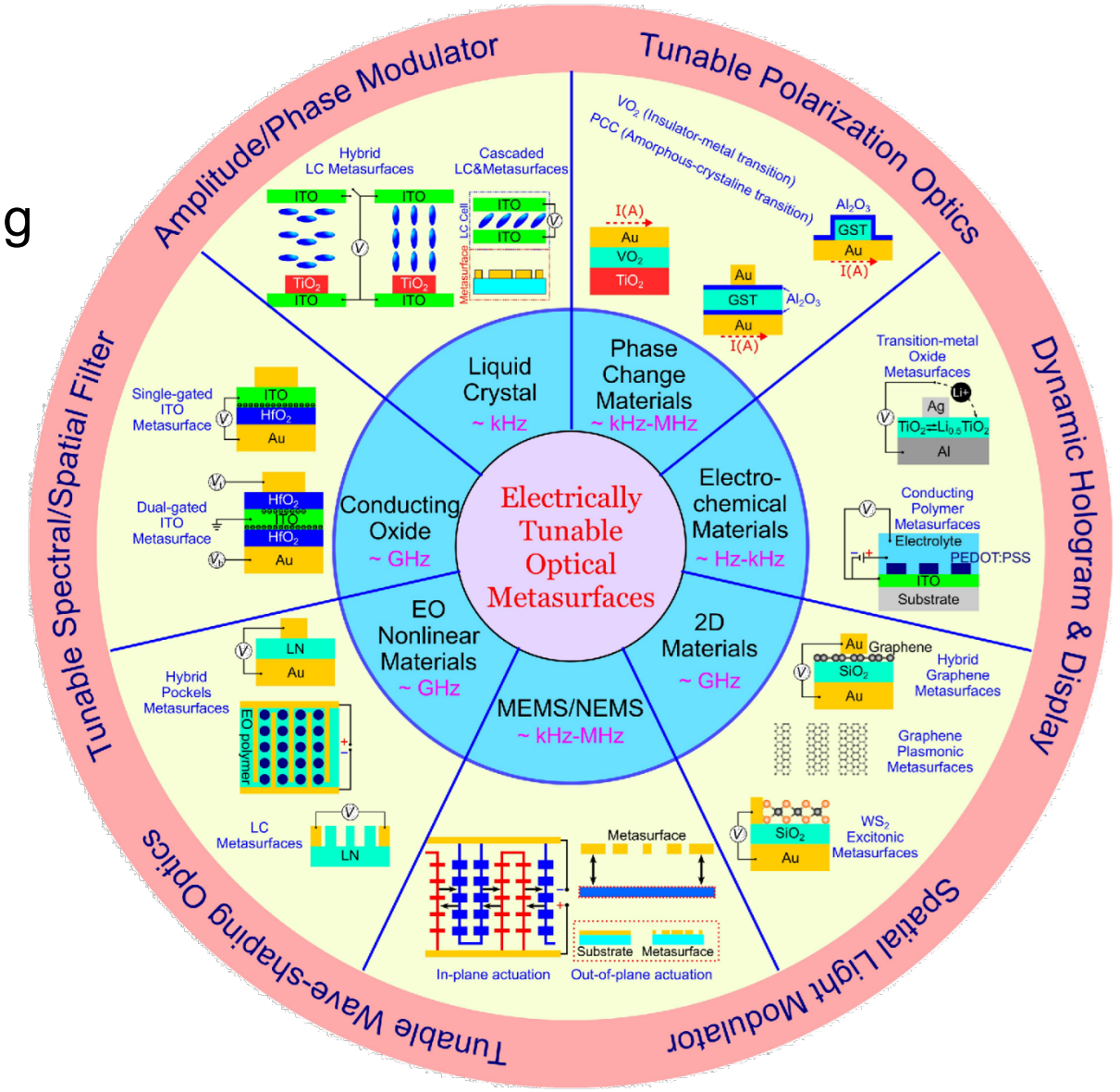
Nanophotonics vol. 9, p. 39 (2020)



Advanced Optical Materiasl vol. 7, p. 1801782 (2019)

Electrically tunable metasurfaces

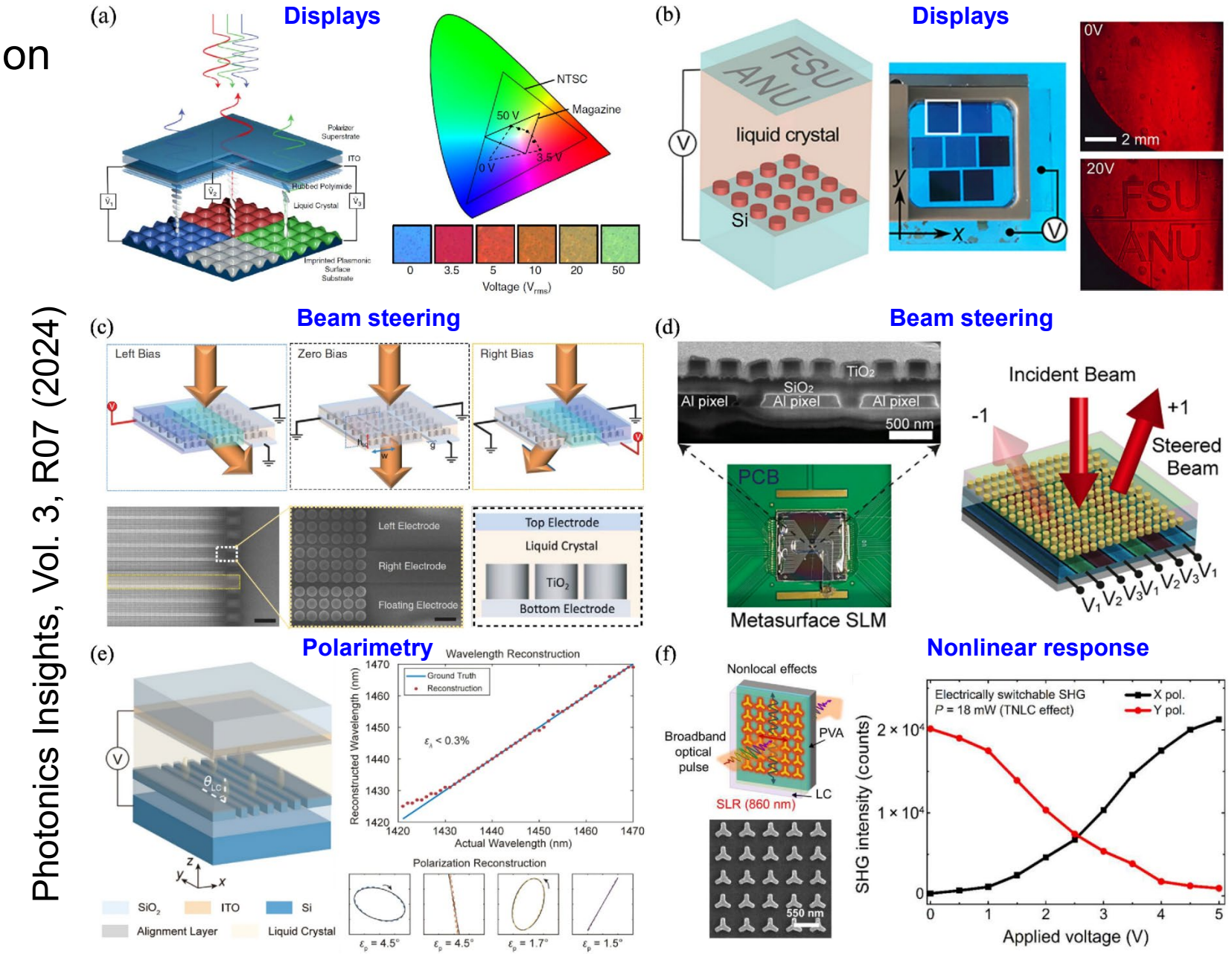
- Emergence of a plurality of tuning mechanism for metasurfaces, providing numerous degrees of freedom



Photonics Insights, Vol. 3, R07 (2024)

Electrically tunable metasurfaces

- Combination with liquid crystals

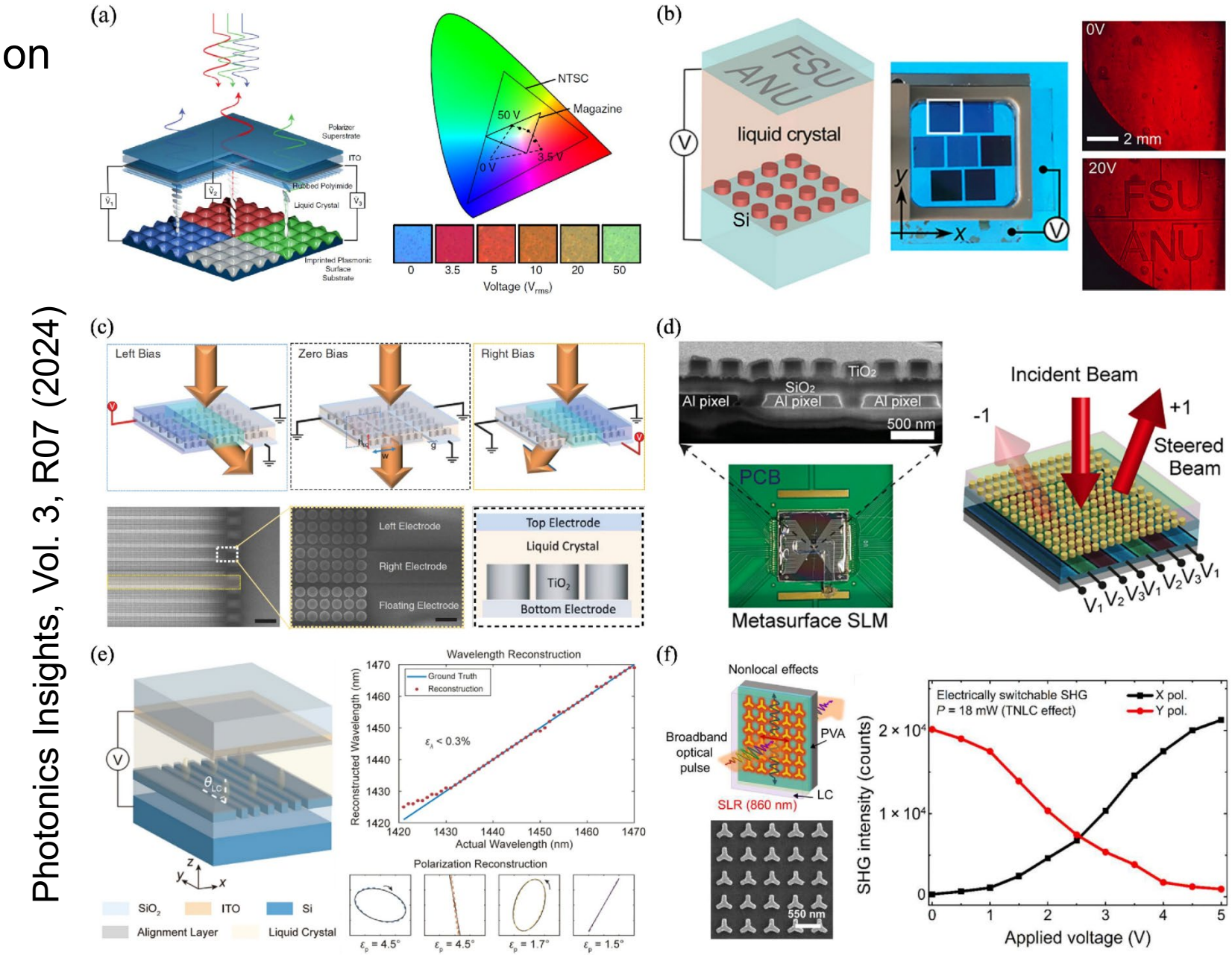


Photonics Insights, Vol. 3, R07 (2024)

Olivier J.F. Martin

Electrically tunable metasurfaces

- Combination with liquid crystals

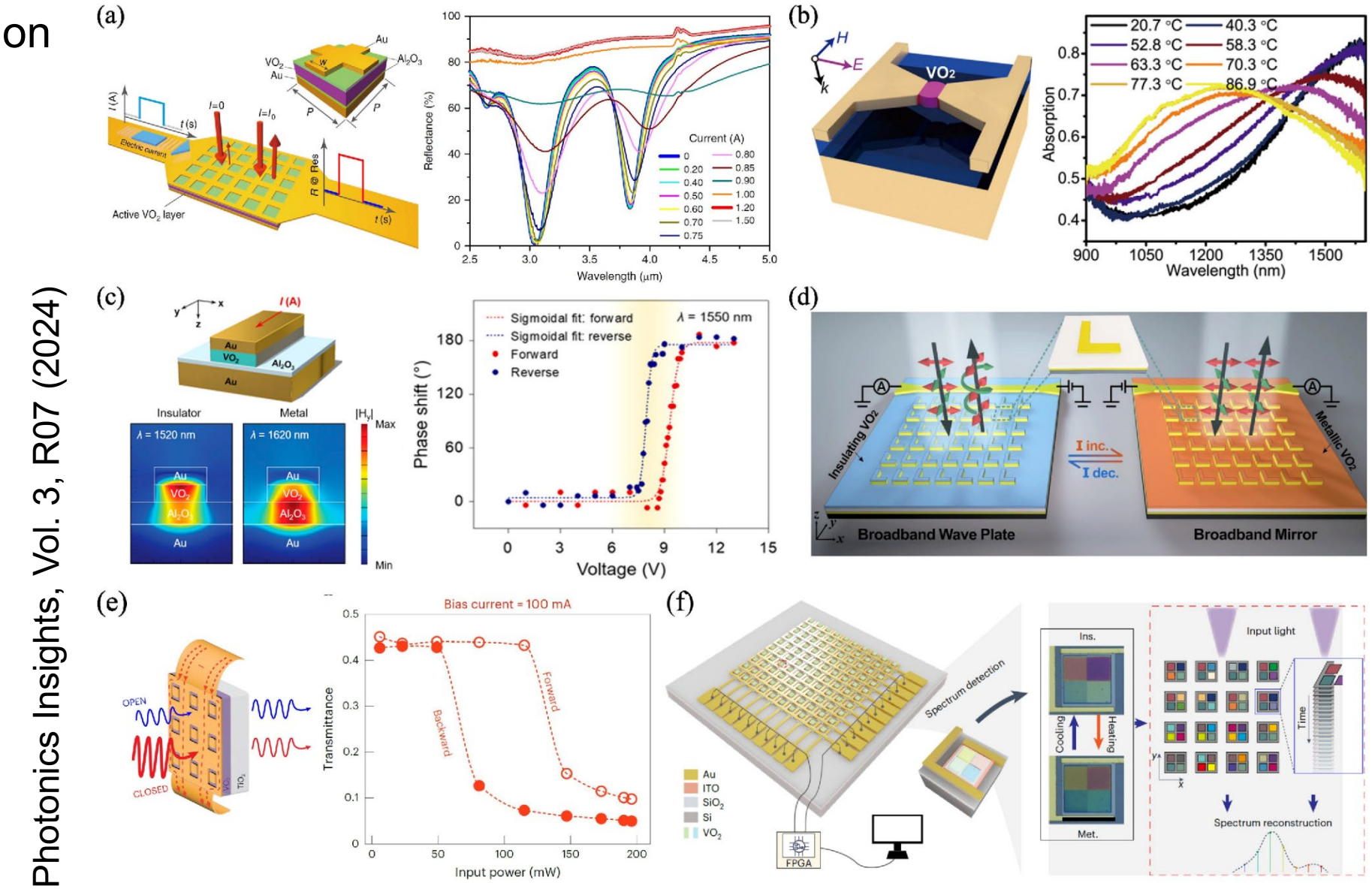


Photonics Insights, Vol. 3, R07 (2024)

Olivier J.F. Martin

Electrically tunable metasurfaces

- Combination with VO_2

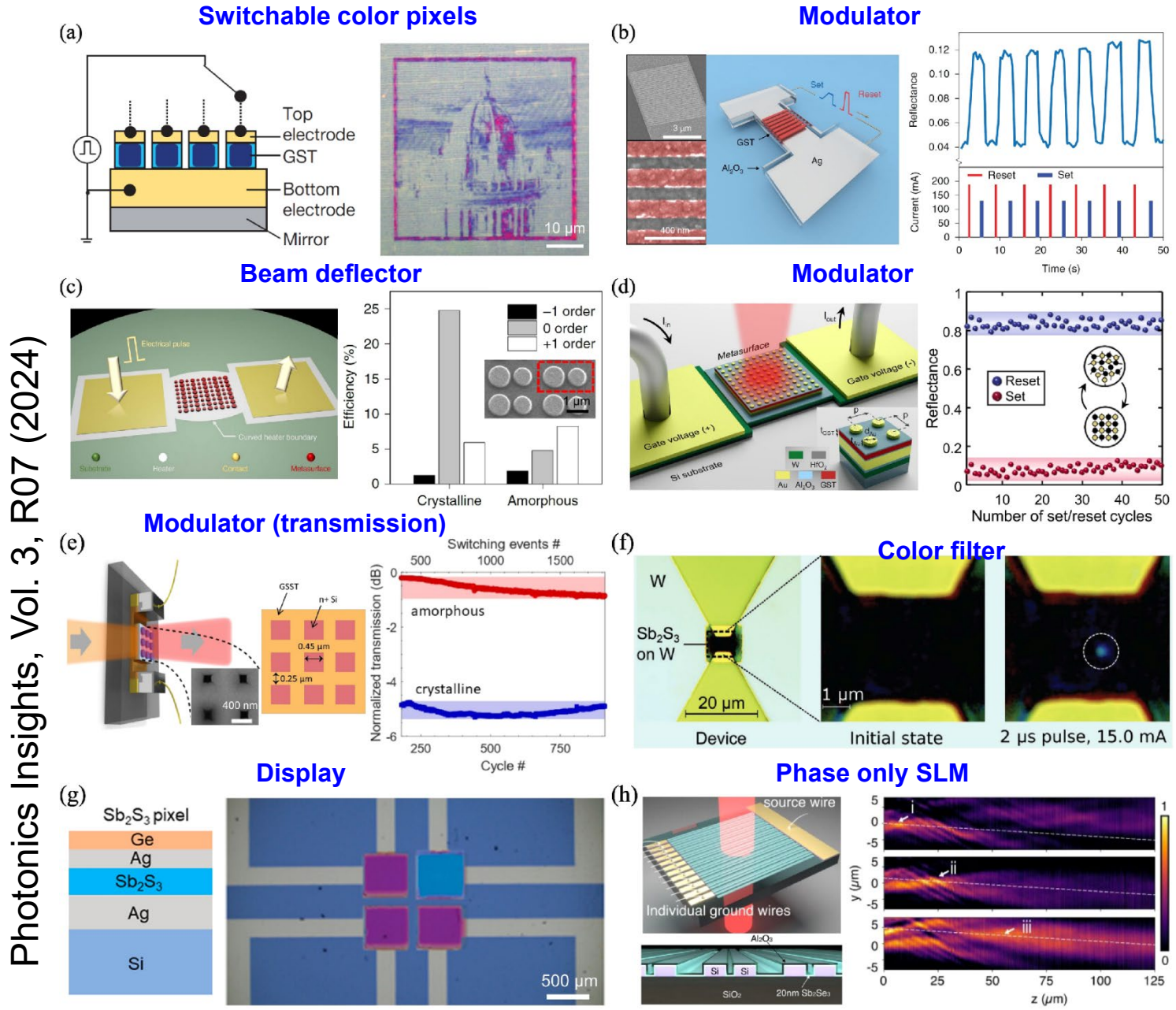


Photonics Insights, Vol. 3, R07 (2024)

Olivier J.F. Martin

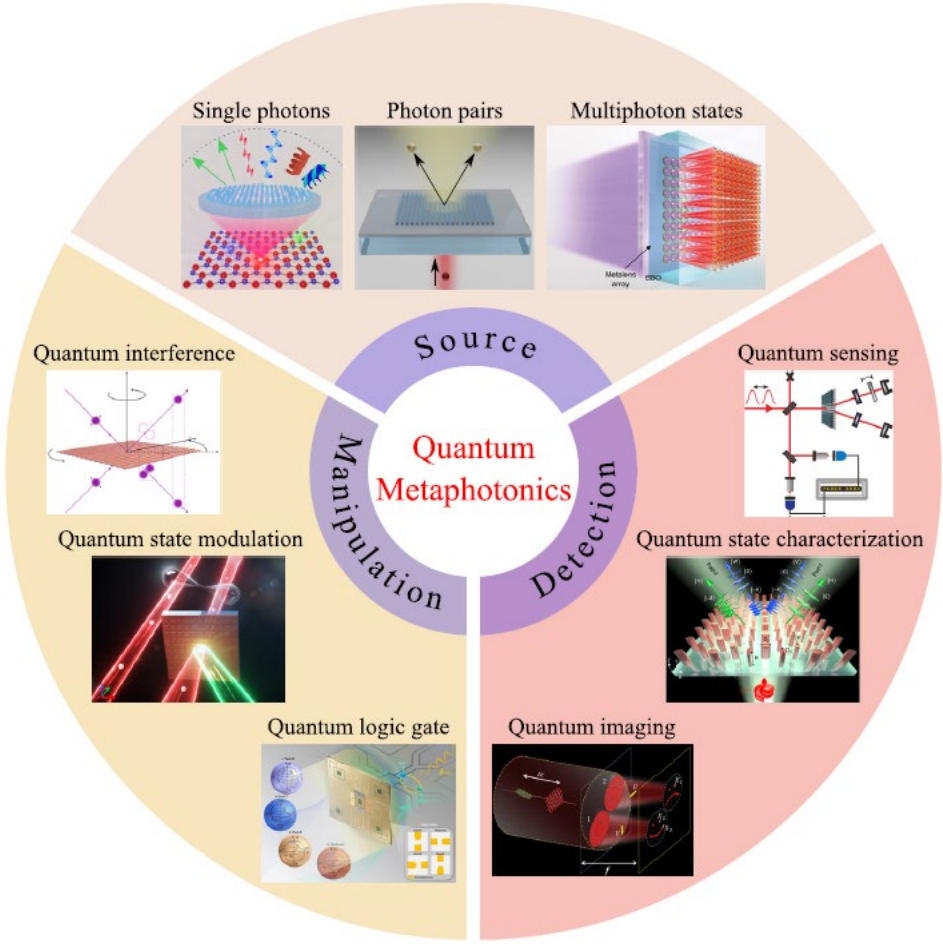
Electrically tunable metasurfaces

- Combination with Chalcogenides



Metasurfaces for quantum applications

- Metsurfaces can find their place in the different components required for quantum photonics



APL Quantum, vol. 1, p. 020902 (2024)

Selected Topics in Advanced Optics

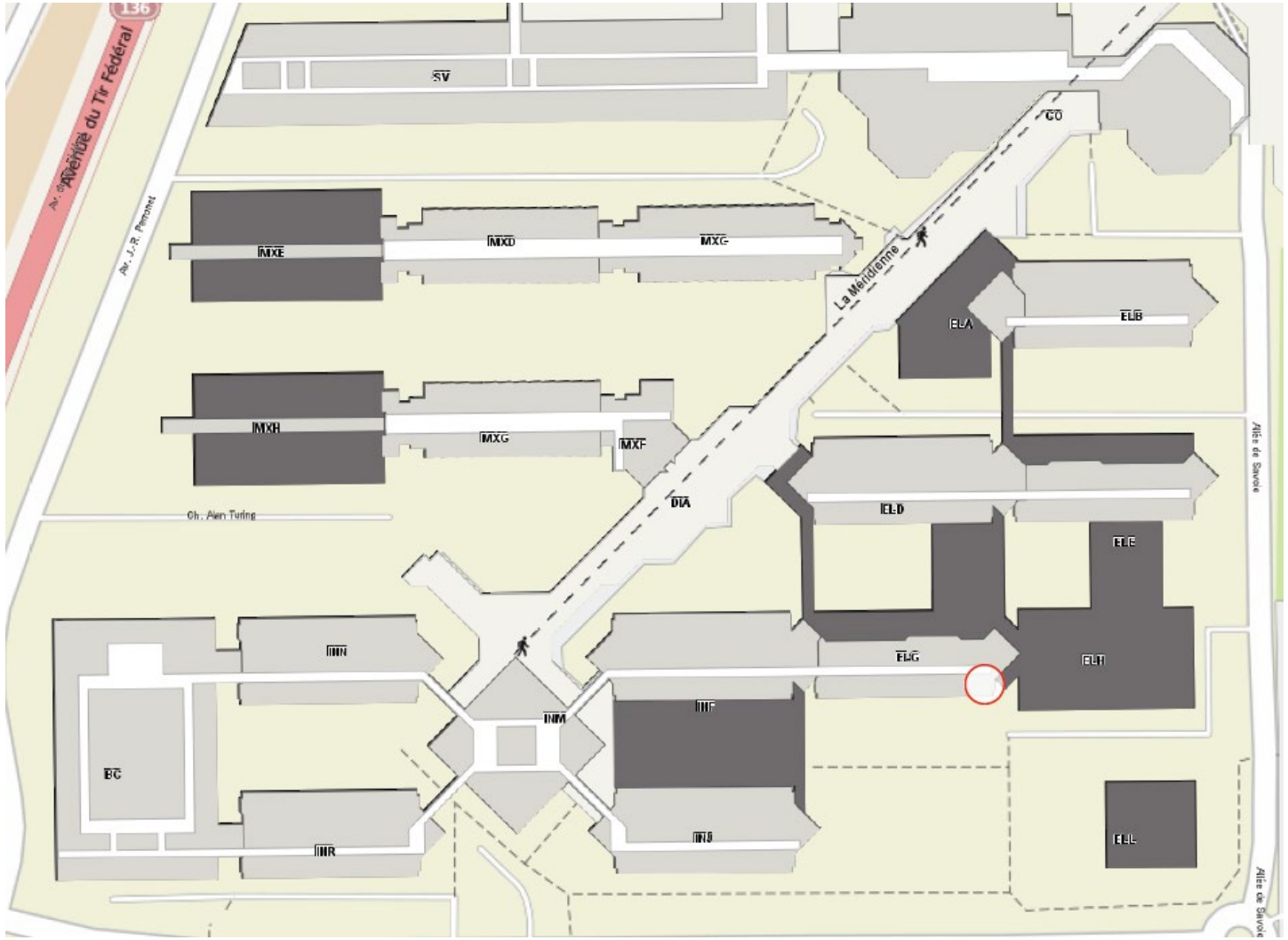
Week 13 – part 4

Olivier J.F. Martin
Nanophotonics and Metrology Laboratory

EPFL

Lab visit

- Next week, meet us at 9:15 in ELG 240



Advanced Optics – Information for the exam

The examination will be conducted in the following manner:

- The candidate will enter the room, show her/his Camipro card
- The candidate will choose at random one of the following topics:

1) Material properties and optical constants
2) Light scattering
3) Optics of metals & plasmonics
4) Gratings, stratified media & photonic crystals
5) Metamaterials and metasurfaces

- The candidate will then have about 20 minutes to prepare the topic with all possible documents (course, lecture notes, books, etc...)
- After this preparation time, the student will present for about 20 minutes the topic on the blackboard and answer questions. The entire material seen during the course and the exercises can be tested during the examination

Please select your time slot for the exam on moodle!