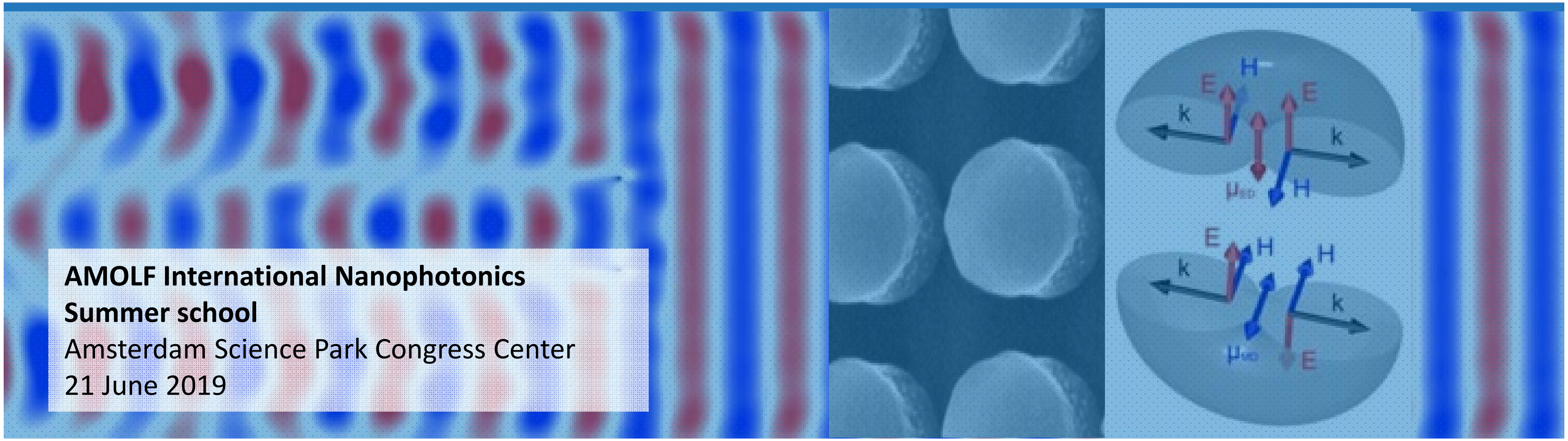
Abbe Center of Photonics | JENA
Friedrich-Schiller-Universität

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Metasurfaces and Mie-resonant nanophotonics

Isabelle Staude

Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-University Jena,
07743 Jena, Germany



AMOLF International Nanophotonics Summer school
Amsterdam Science Park Congress Center
21 June 2019

…a Team Effort

@ Friedrich Schiller University Jena:

Dr Falk Eilenberger

Dr Frank Setzpfandt

Prof. Andrey Turchanin

Prof Thomas Pertsch

@Australian National University:

Prof Dr Dragomir Neshev

Prof Yuri Kivshar

@ Sandia National Laboratories:

Dr Igal Brener

@ Lomonosov Moscow State University

Dr Maxim R. Shcherbakov

Prof Andrey A. Fedyanin

@ Karlsruhe Institute of Technology:

Prof Carsten Rockstuhl

@ Norfolk State University:

Prof Mikhail Noginov

Prof Natalia Noginova

@JCM Wave

Dr Sven Burger

@ National Academy of Sciences of Belarus

Dr Alexander Muravsky

@AMOLF

Prof Femius Koenderink

Dr Radoslav Kolkowski

My Current Institution

Abbe Center of Photonics | JENA
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Jena, Thuringia

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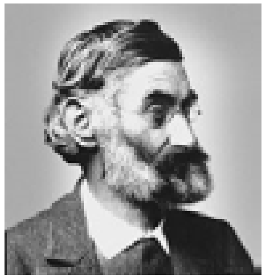
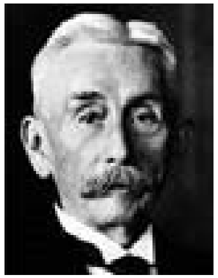
Friedrich-Schiller-Universität Jena



Ernst Abbe
(1840-1905)



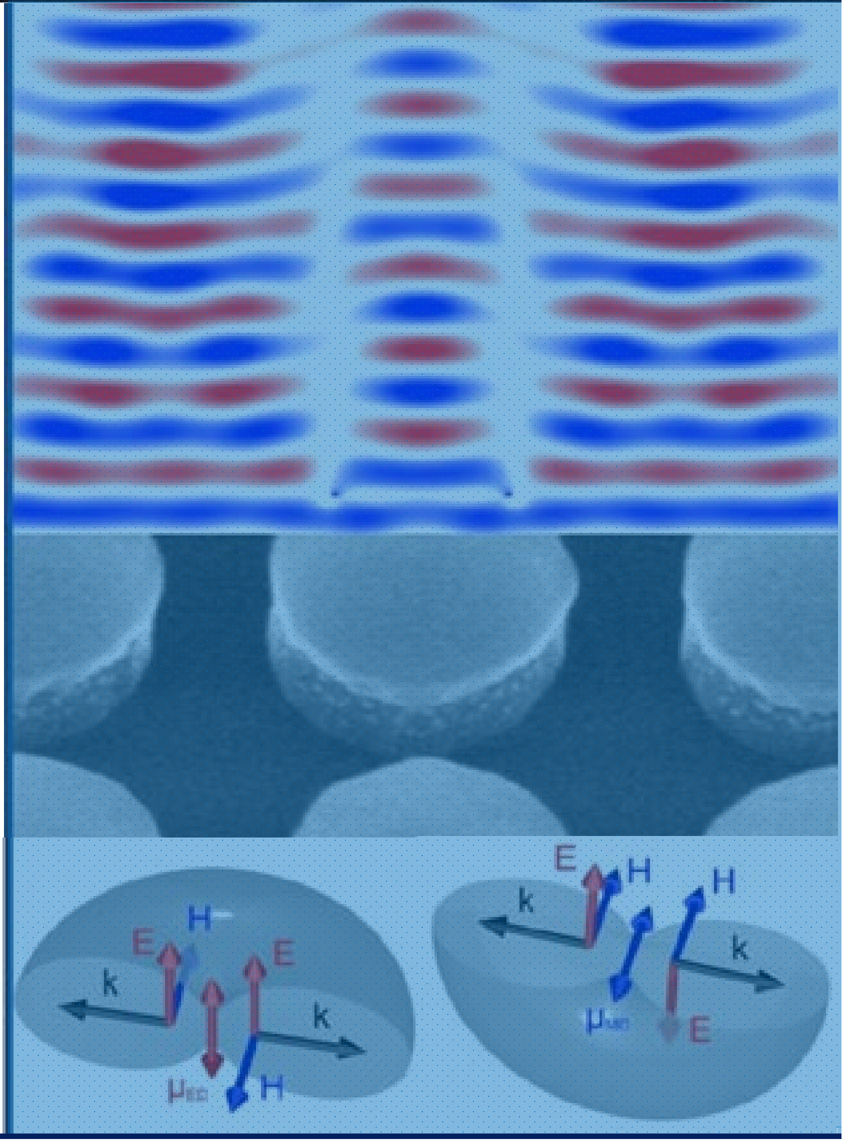
Otto Schott
(1851-1935)

Carl Zeiss
(1816-1888)

Outline

- Motivation
- Optical properties of high-index dielectric nanoparticles
- Dielectric Huygens' metasurfaces

- Highlight talk
  - Active control of dielectric metasurfaces
  - Light emission from dielectric metasurfaces



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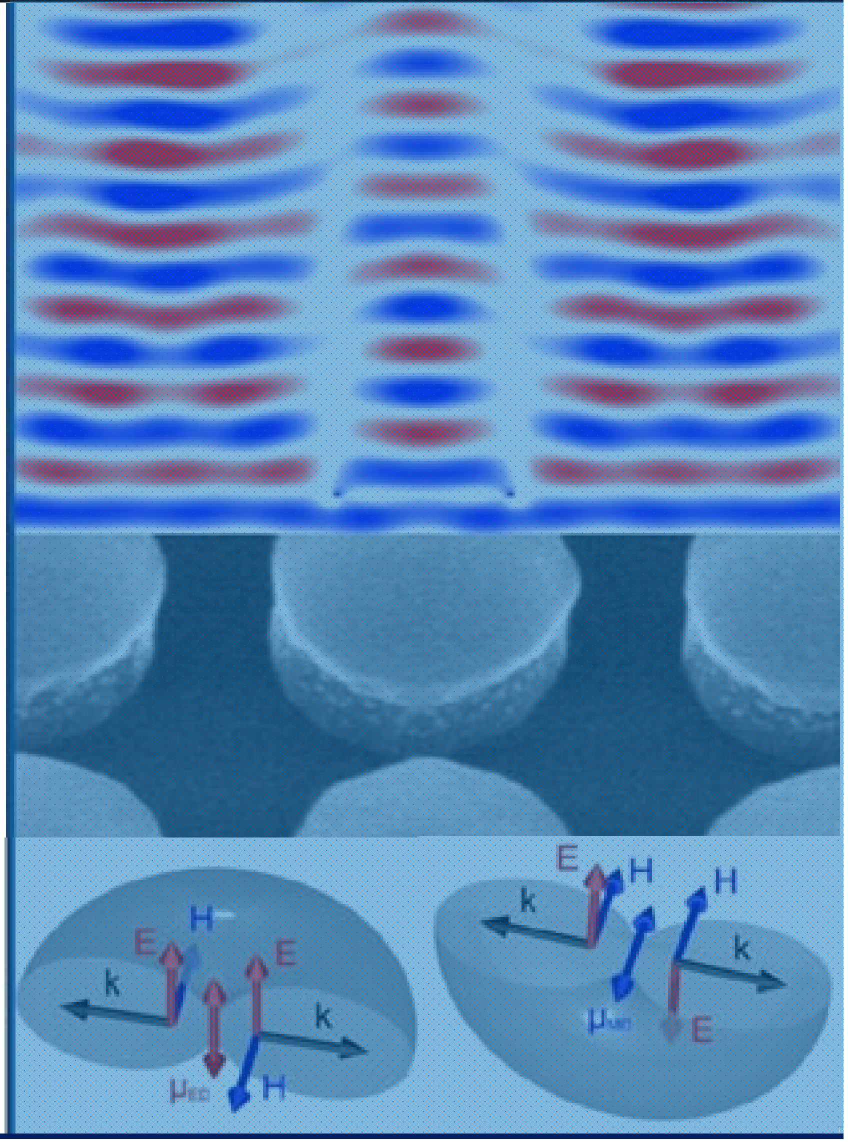
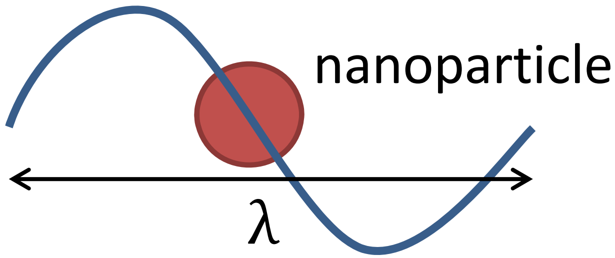
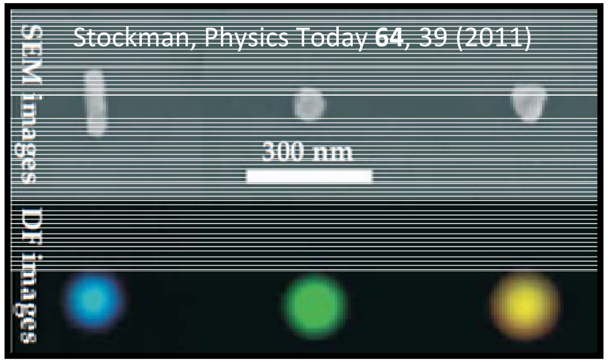


Optical Response of Nanoscale Particles



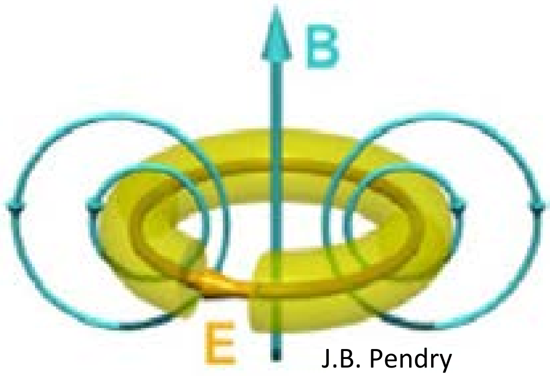
λ: wavelength of light

strong
resonant response



Stockman, Physics Today **64**, 39 (2011)

magnetic response
@ optical frequencies



J.B. Pendry

sub-wavelength
field confinement

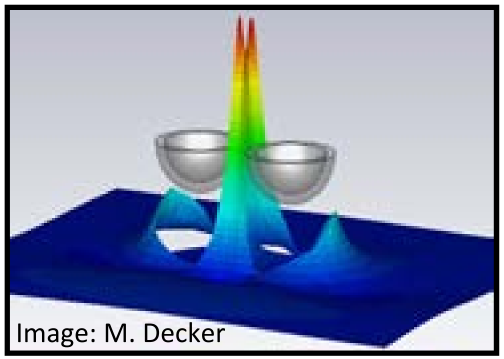


Image: M. Decker

Key Concepts in Nanophotonics

Optical Nanoantennas

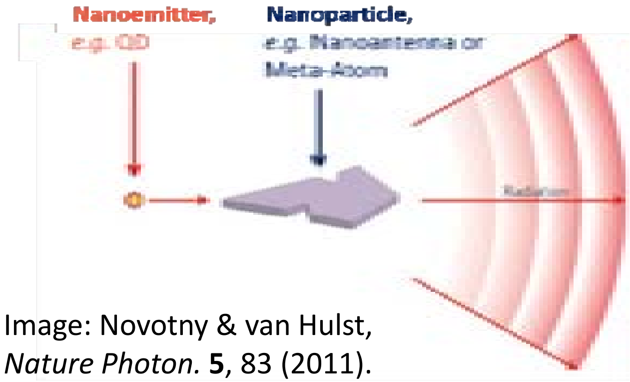
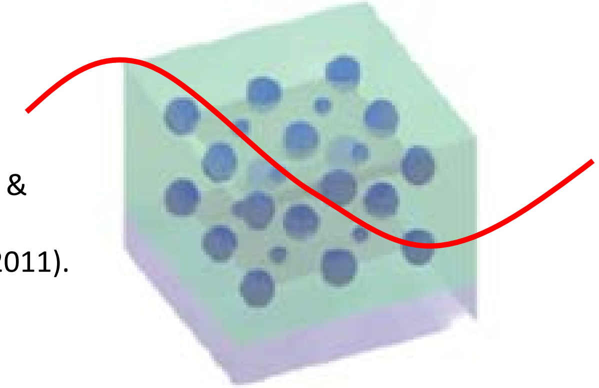


Image: Novotny & van Hulst,
Nature Photon. **5**, 83 (2011).

Optical Metamaterials

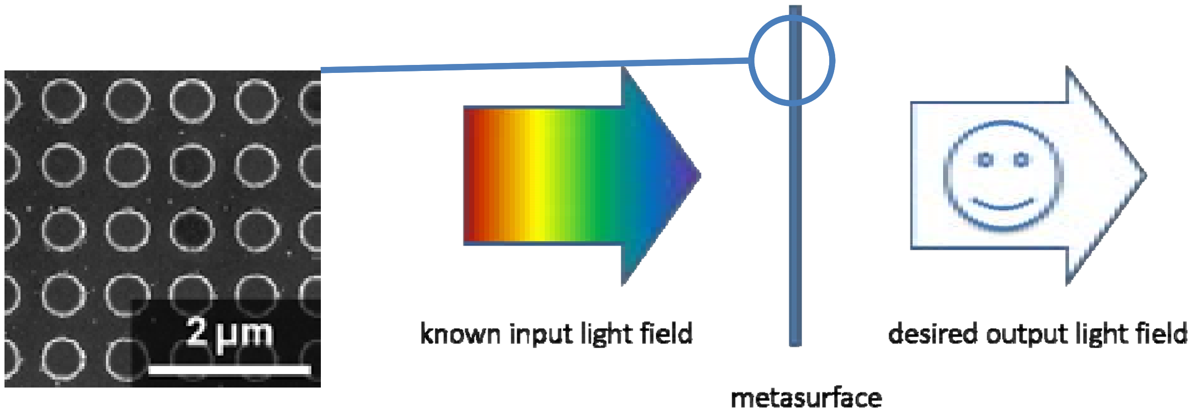
Image: Soukoulis & Wegener, Nature Photon. 5, 523 (2011).



2D array of nanoantennas

Optical Metasurfaces

2D counterpart of metamaterials

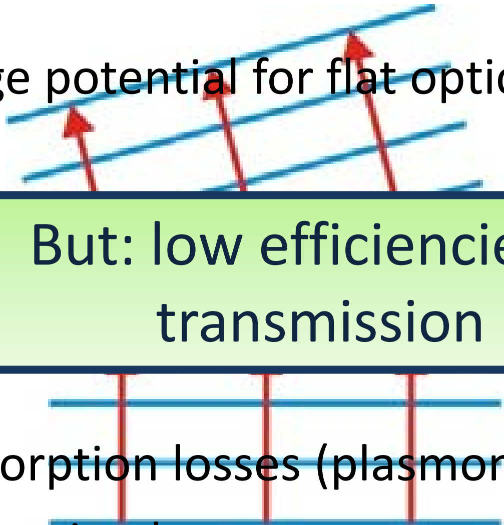


2D subwavelength arrangement of designed nanoscale building blocks

Graded Optical Metasurfaces

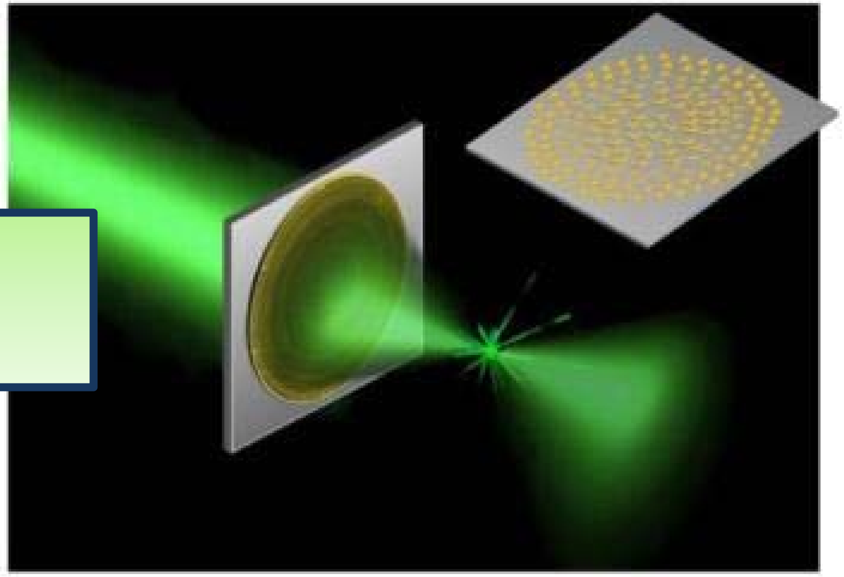
- Metasurfaces for wavefront manipulation enabled by designed subwavelength building blocks imposing a position dependent phase shift onto an incident light field

- Huge potential for flat optical de



But: low efficiencies in transmission

- Absorption losses (plasmonics!)
- Reflection losses
- Limited polarization conversion efficiencies



F. Aieta *et al.*, *Nano Lett.* **12**, 4932 (2012).

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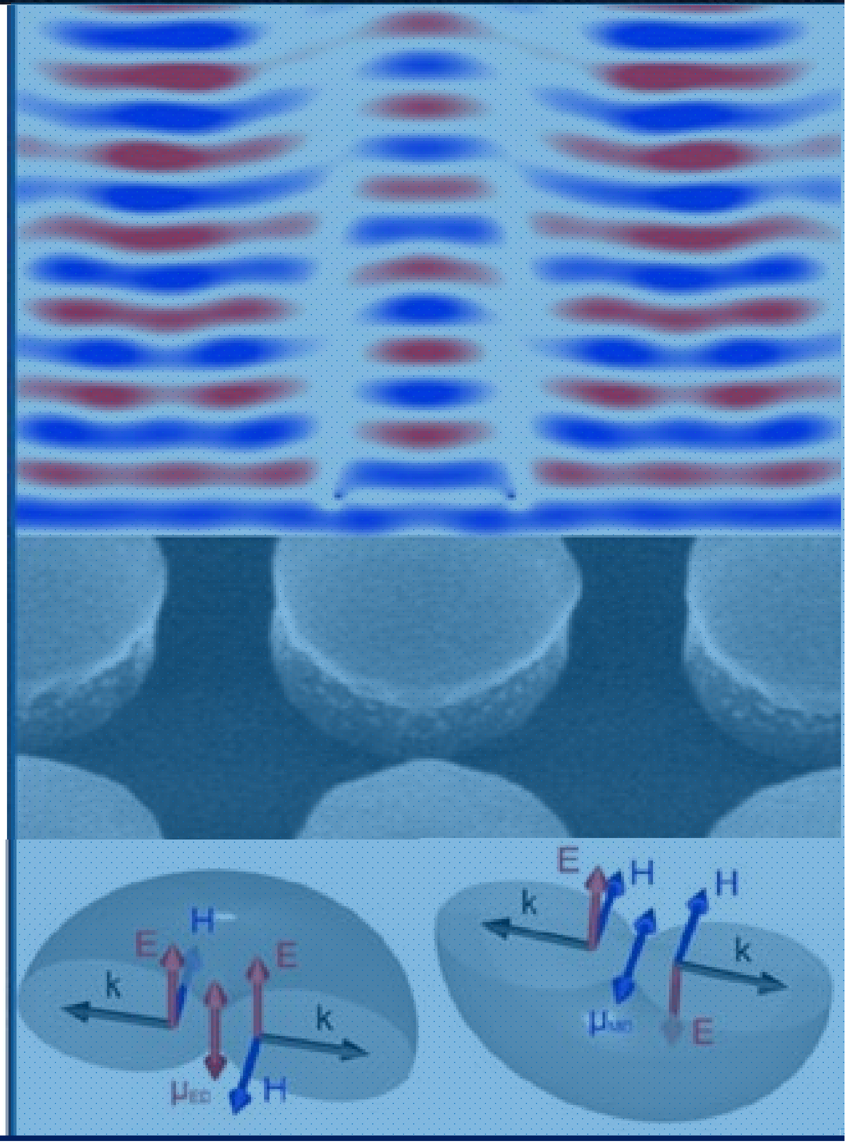
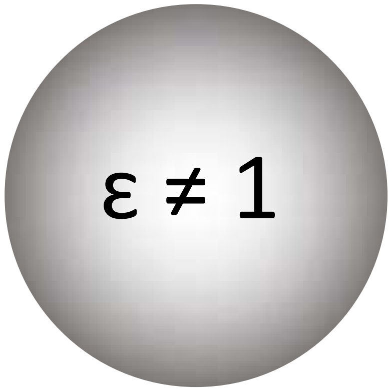


All-Dielectric Nanoparticles

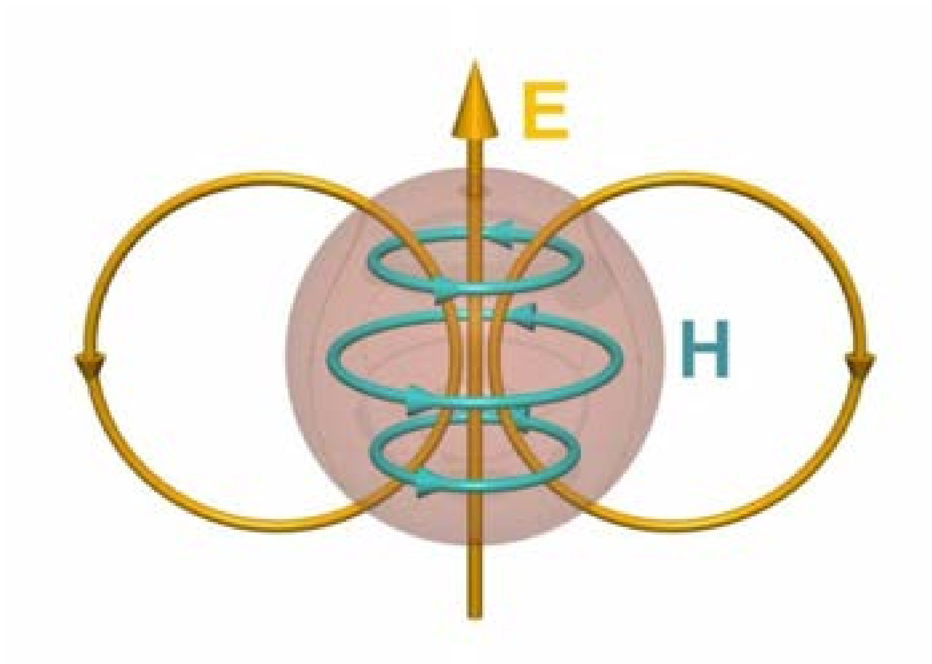
Electric

Magnetic



Images: A. Miroshnichenko

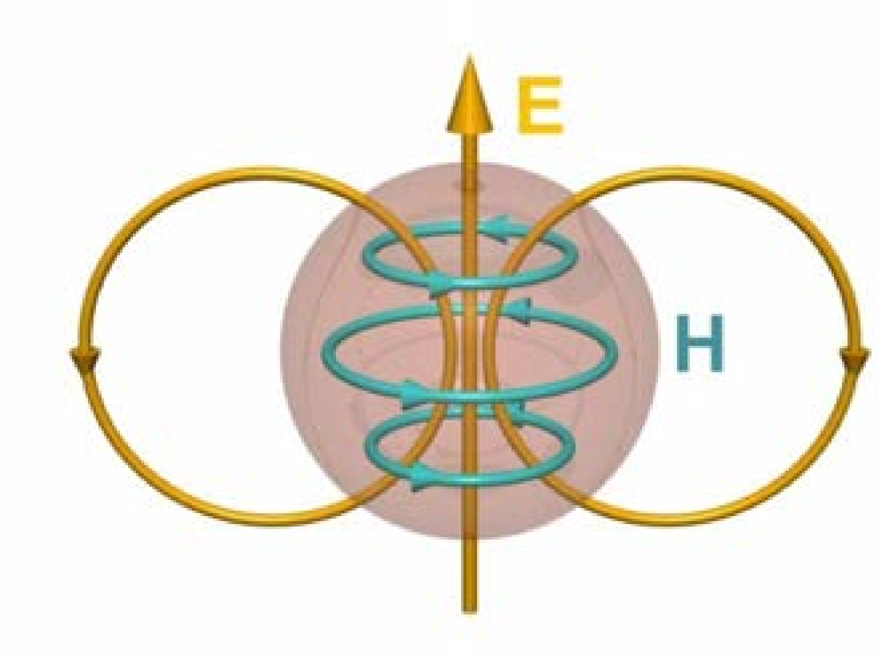
Electric

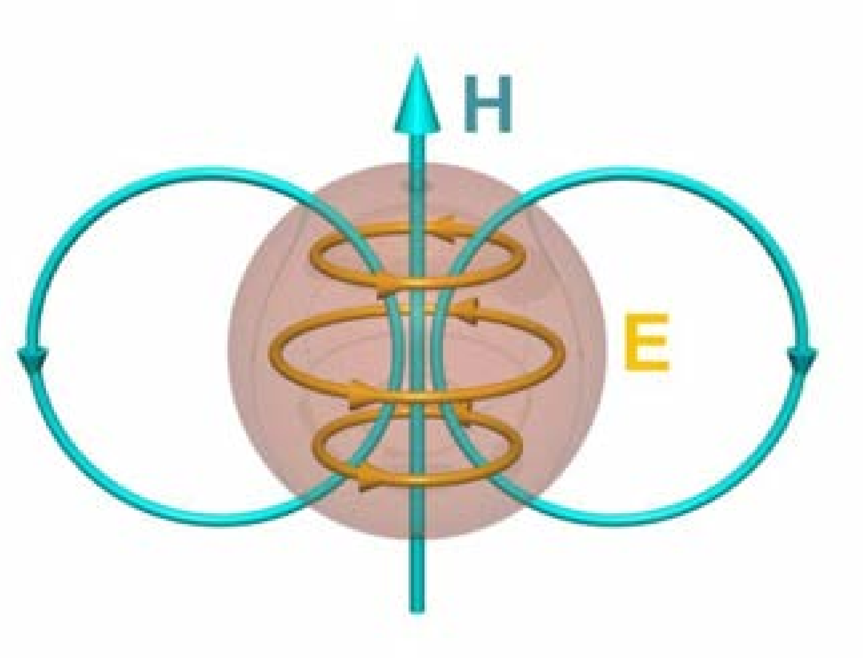


Magnetic

Images: A. Miroshnichenko

Electric **Magnetic**

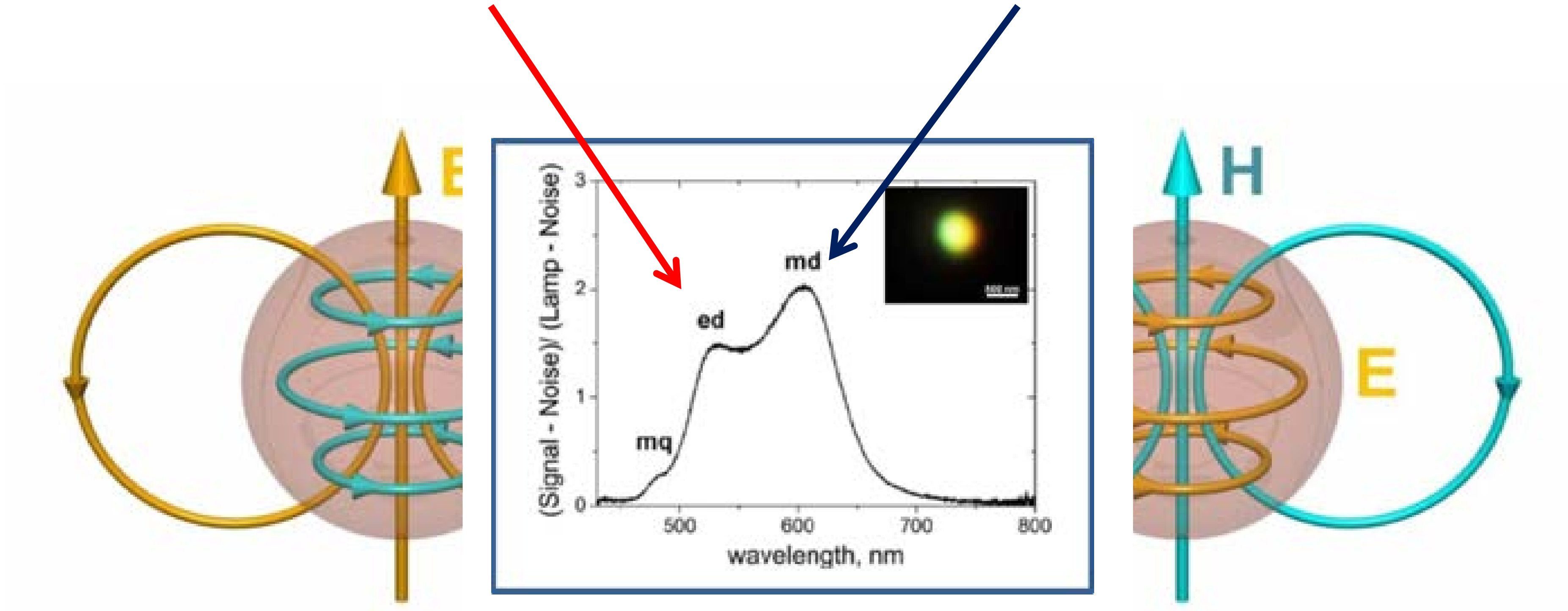




Images: A. Miroshnichenko

All-Dielectric Nanoparticles

Electric **Magnetic**



A. Kutznetsov *et al.*, Sci. Rep. **2**, 492 (2012).

Gustav Mie, Ann. Phys. **25**, 377-445 (1908).

Images: A. Miroshnichenko

Mie-Theorie in a Nutshell

The scattered field of a single isolated dielectric sphere with radius a, size parameter $x = k_0 a$ and relative refractive index $n = n_p / n_m$ can be decomposed into a multipole series with the 2^m-pole term of the scattered electric field proportional to:

$$a_m = \frac{n\Psi_m(nx)\Psi'_m(x) - \Psi_m(x)\Psi'_m(nx)}{n\Psi_m(nx)\Xi'_m(x) - \Xi_m(x)\Psi'_m(nx)}$$

And of the scattered magnetic field proportional to:

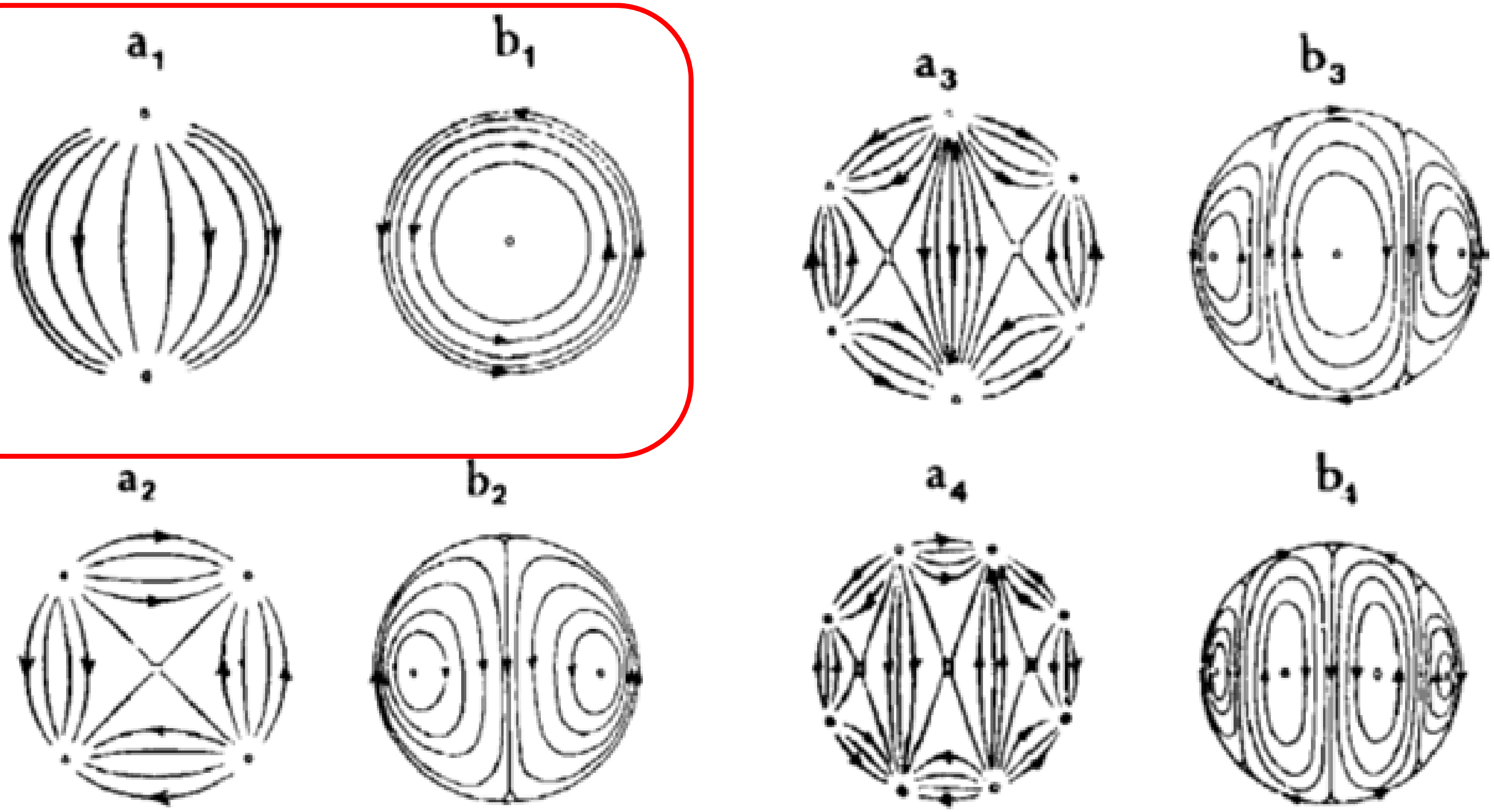
$$b_m = \frac{\Psi_m(nx)\Psi'_m(x) - n\Psi_m(x)\Psi'_m(nx)}{\Psi_m(nx)\Xi'_m(x) - n\Xi_m(x)\Psi'_m(nx)}$$

$\Psi_m(\rho)$, $\Xi_m(\rho)$: Riccati-Bessel functions

Bohren & Hoffmann: Absorption & scattering of light by small particles

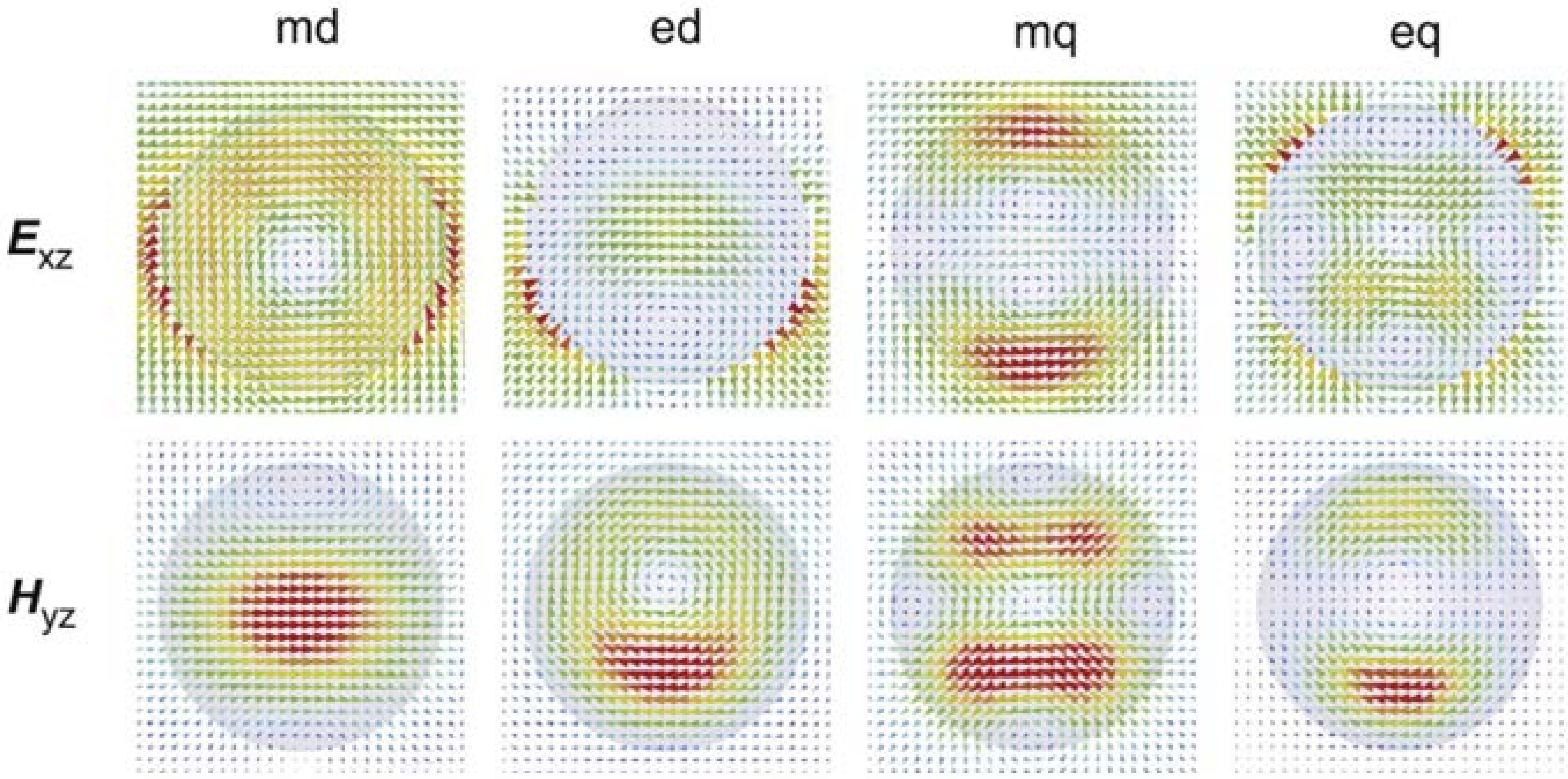
Mode Profiles

Gustav Mie, Ann. Phys. **25**, 377-445 (1908).



Electric field lines (transverse components) shown on the surface of an imaginary sphere concentric with but at a distance from the particle

Near-Field Profiles

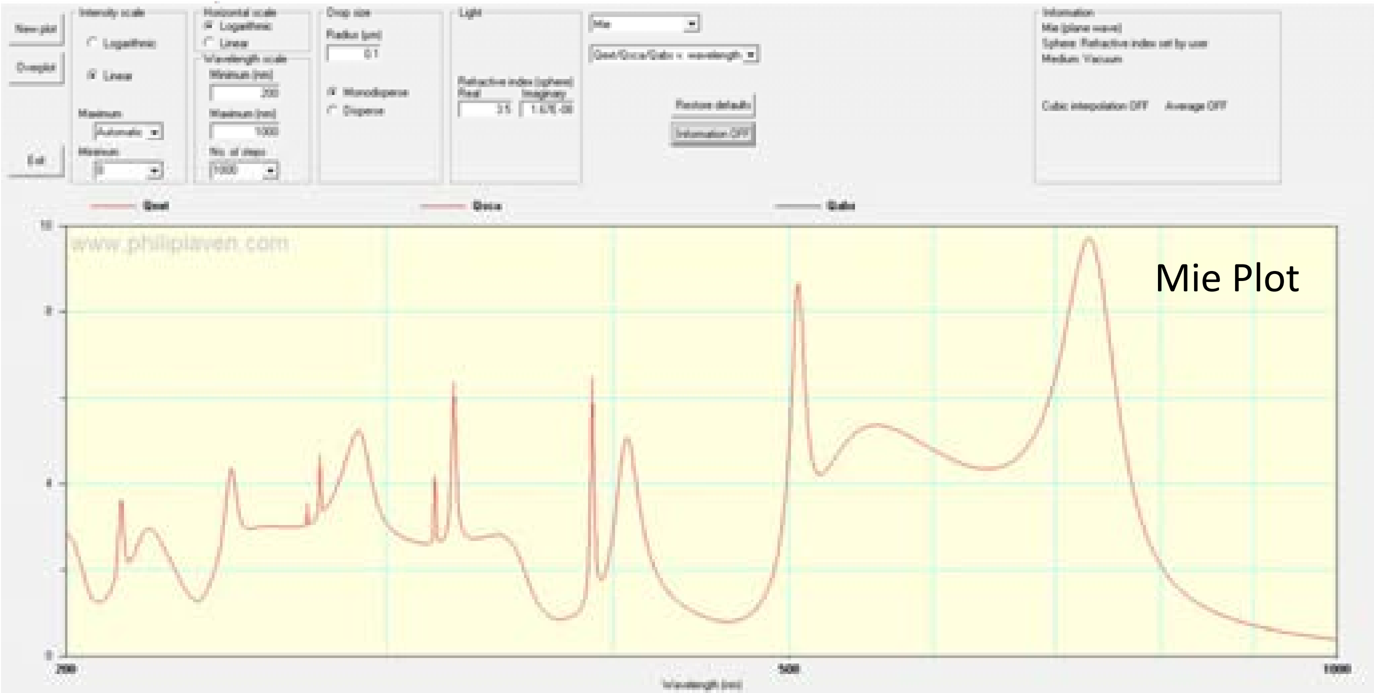


First four Mie-modes excited by an x-polarized plane wave

Extinction Cross Section

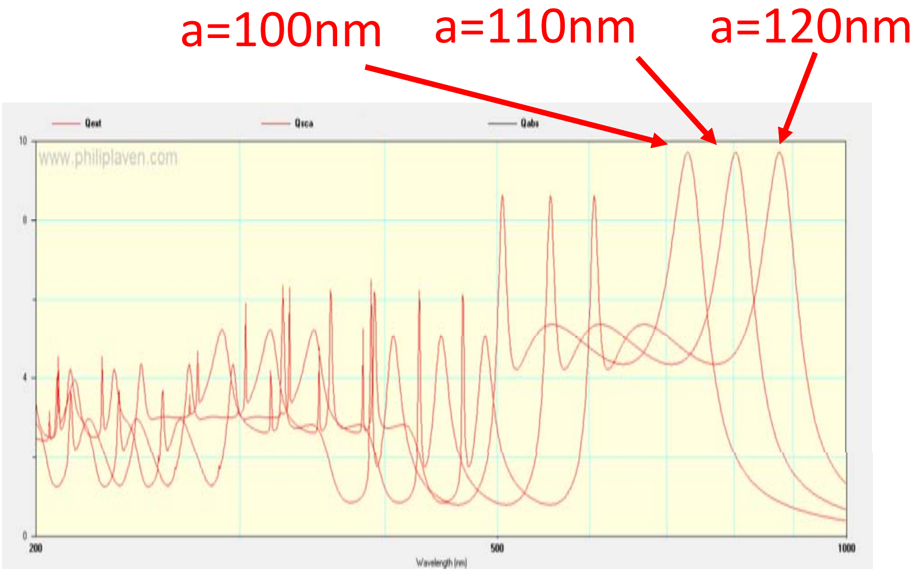
- Connect to an observable quantity, the extinction cross section σ_{ext}
- For non-absorbing nanoparticles:

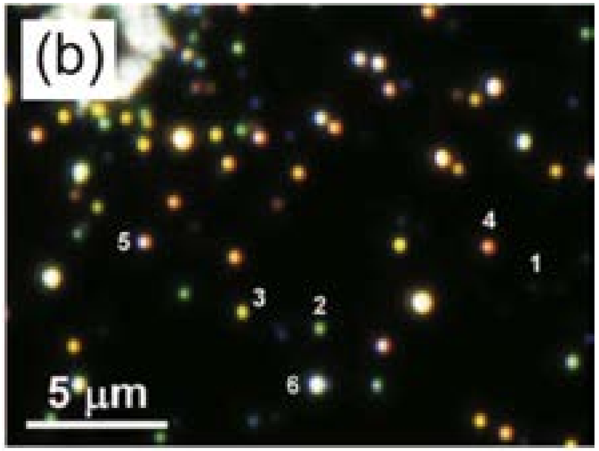
$$\sigma_{ext} = \sigma_S = \frac{2\pi}{k^2} \sum_{m=1}^{\infty} (2m+1)(|a_m|^2 + |b_m|^2)$$



Bohren & Hoffmann: Absorption & scattering of light by small particles

Influence of the Nanoparticle Size





A. Kutznetsov *et al.*, Sci. Rep. **2**, 492 (2012).

Small particle – high-refractive-index limit, in air: Lowest order resonance of a particle at

$$\lambda = 2na$$

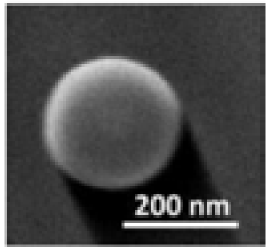
Corresponds to magnetic dipole term b_1

Scaling law: Scattering response will not change as $\frac{\lambda}{na}$ is kept constant

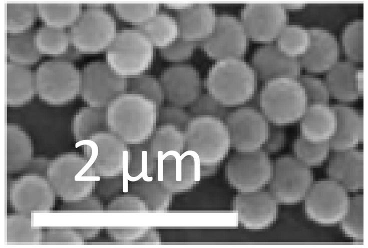
→ useful insight for performing experiments at different frequency ranges

A Few Words on Technology

Spherical nanoparticles:
- Laser printing
- Trisilane decomposition



ACS Phot. 2 913 (2015)



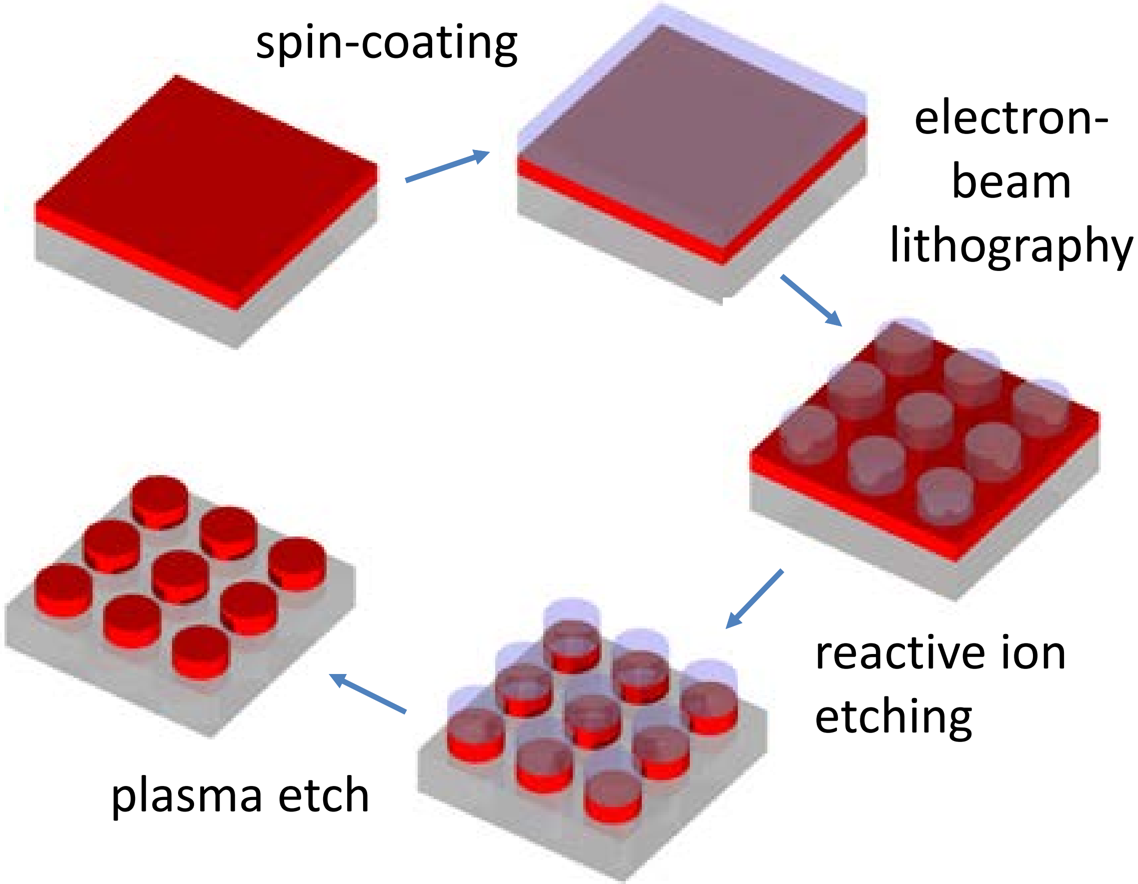
Nat. Commun. 4, 1904 (2013).

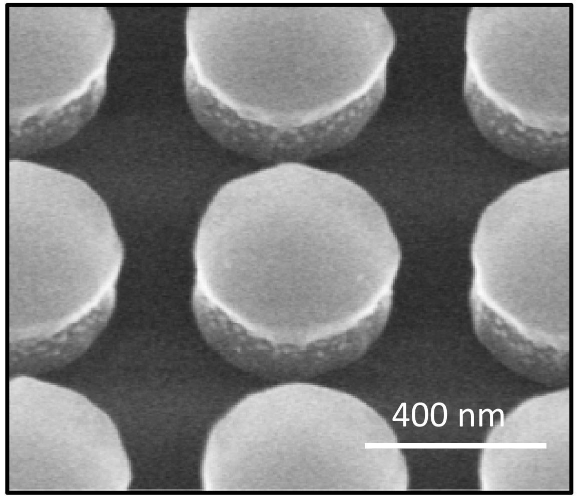
Other shapes:
- Lithographic approaches
  - electron-beam lithography
  - UV lithography
  - interference lithography
  - nanosphere lithography

Typically with reactive ion etching, but low-cost wet etch & atomic layer deposition were also demonstrated

- Focused ion beam milling
- Electron-beam deposition
- Dewetting schemes

Standard 2D Silicon Nanofabrication

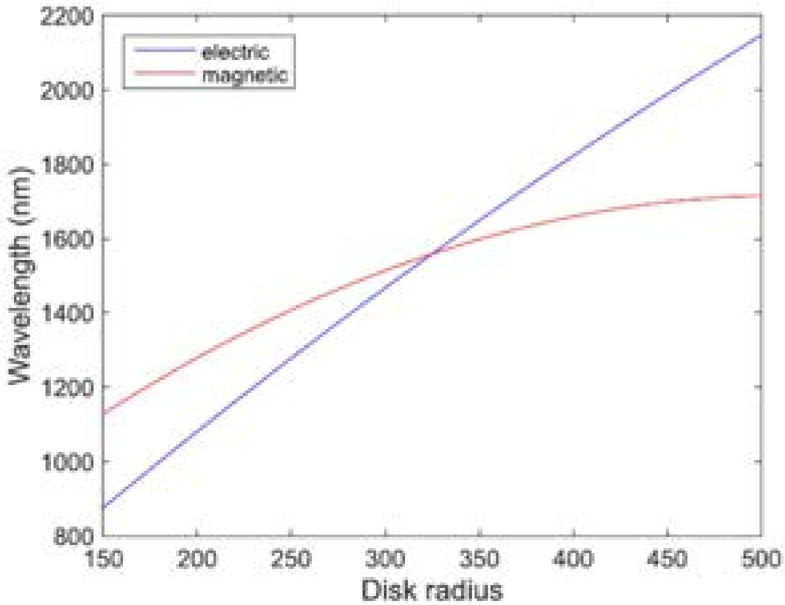




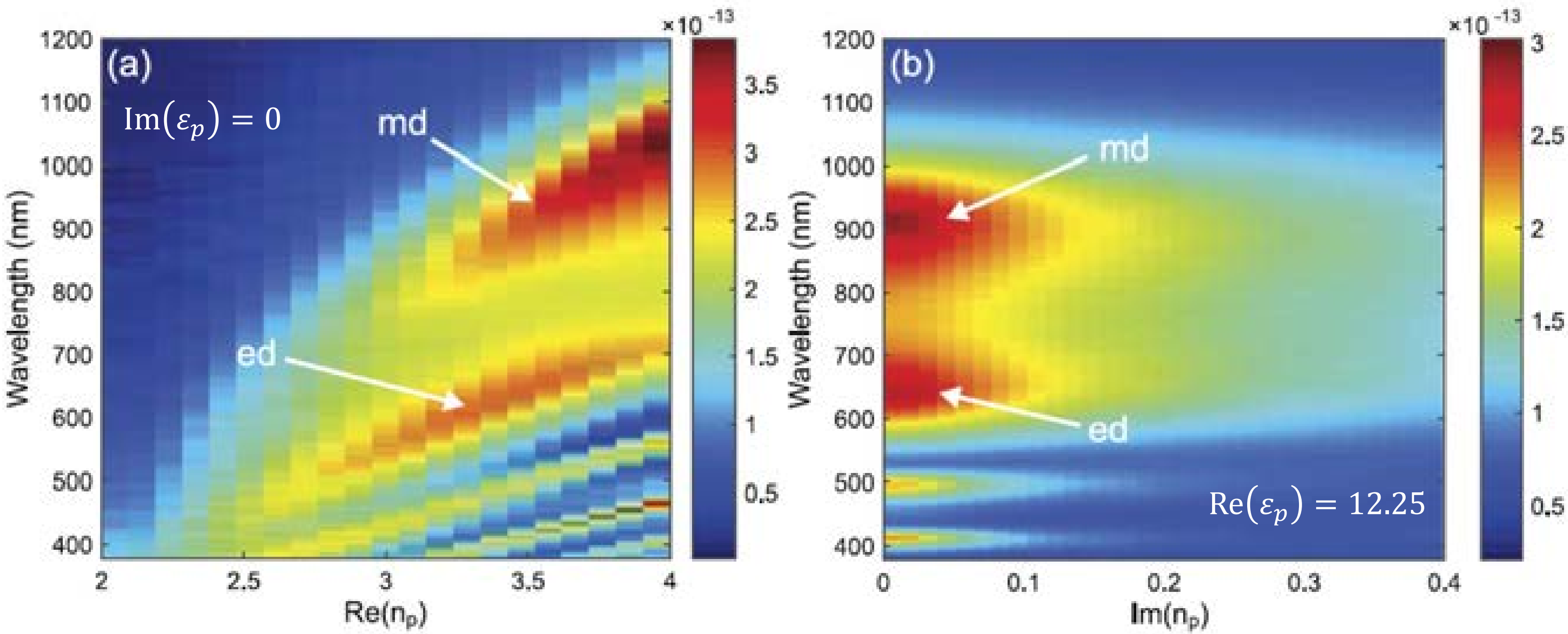
Influence of the Nanoparticle Shape

- Mie theory formulated for spheres.
- Similar resonances ("Mie-type") are also found in particles having other shapes (cubes, cylinders…)
- Calculation using numerical techniques (FDTD, FEM,…)
- Opportunity to tailor the resonances by geometry

Example: resonance positions of the electric and magnetic dipole mode of individual silicon nanocylinders ($h = 220\ \mathrm{nm}$, $n_p = 3.5$, $n_m = 1.5$)

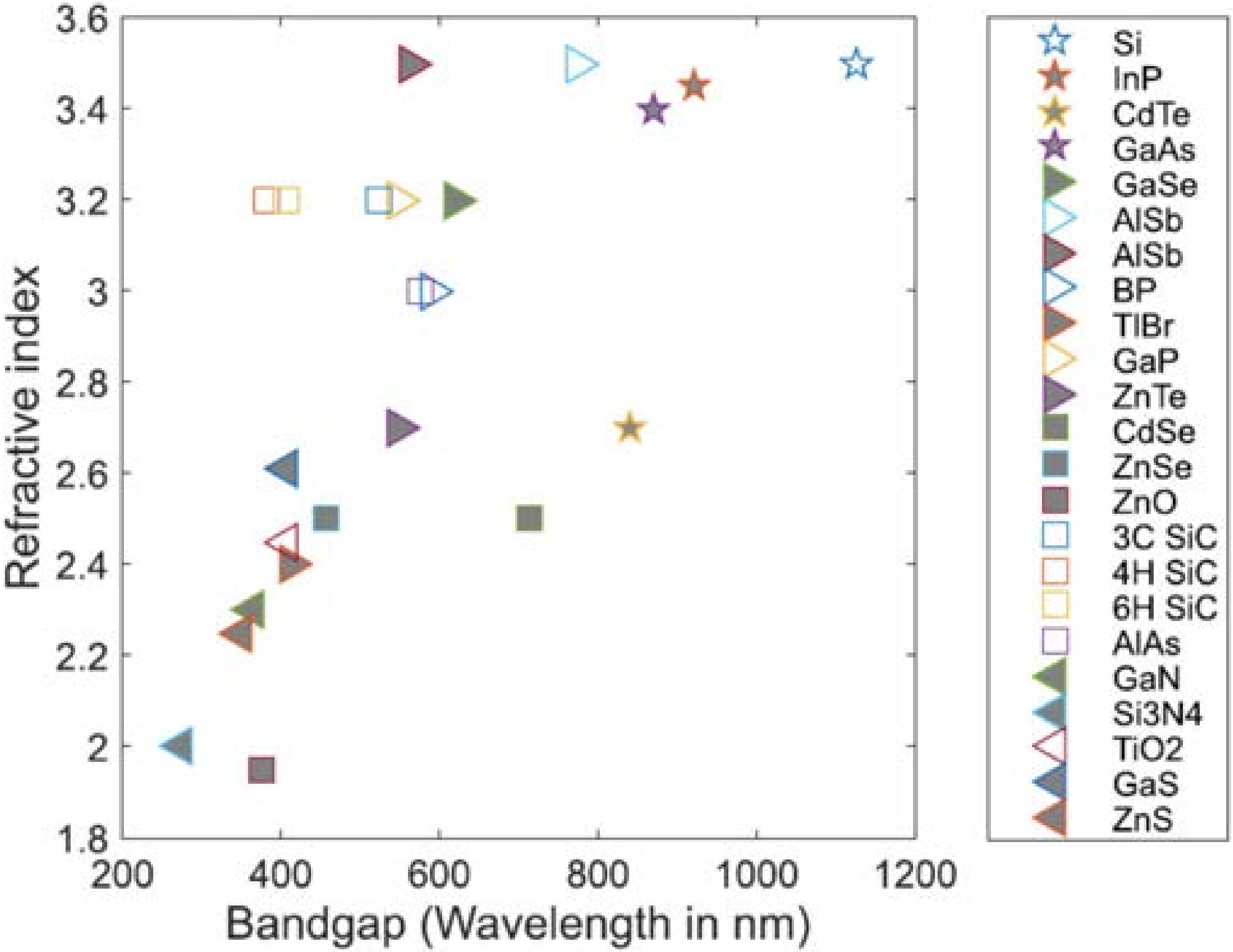


Refractive Index Dependence



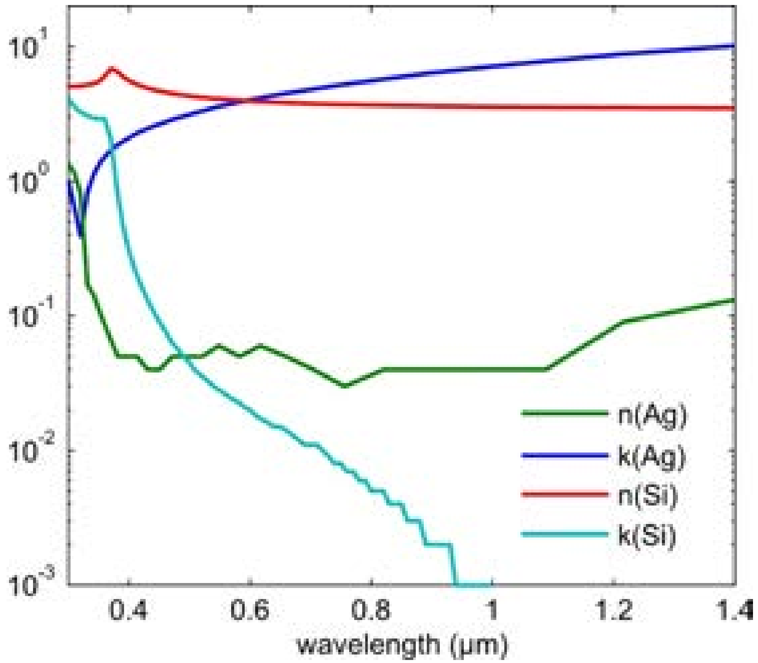
Numerically calculated scattering cross section (in units of m^2) of an individual nanodisk (height $h = 220$ nm, diameter $d = 220$ nm, incident wave vector oriented along the rotational symmetry axis of the nanodisk) in $n_m = 1.5$ material

Suitable Materials

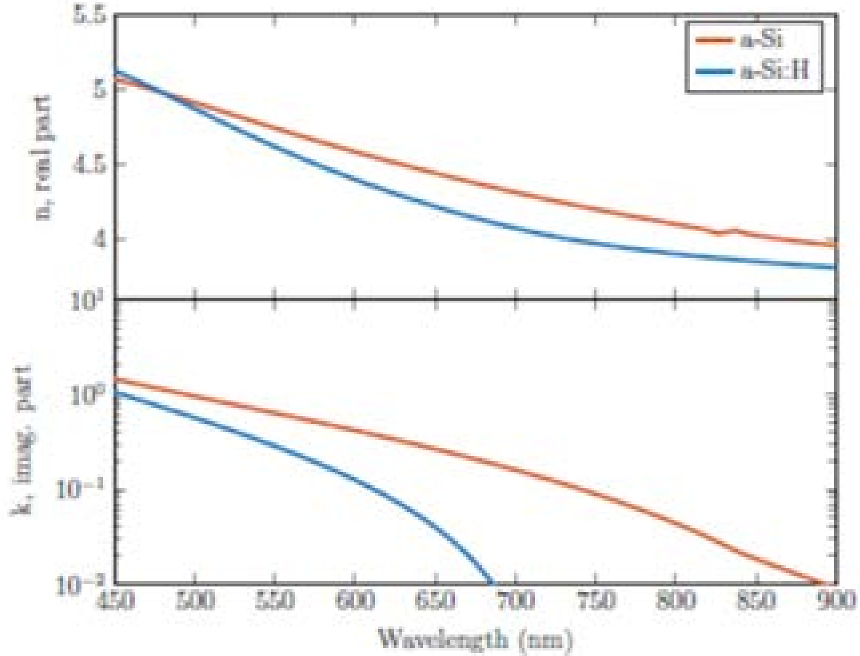


Optical Properties of Silicon

Crystalline silicon
vs. silver

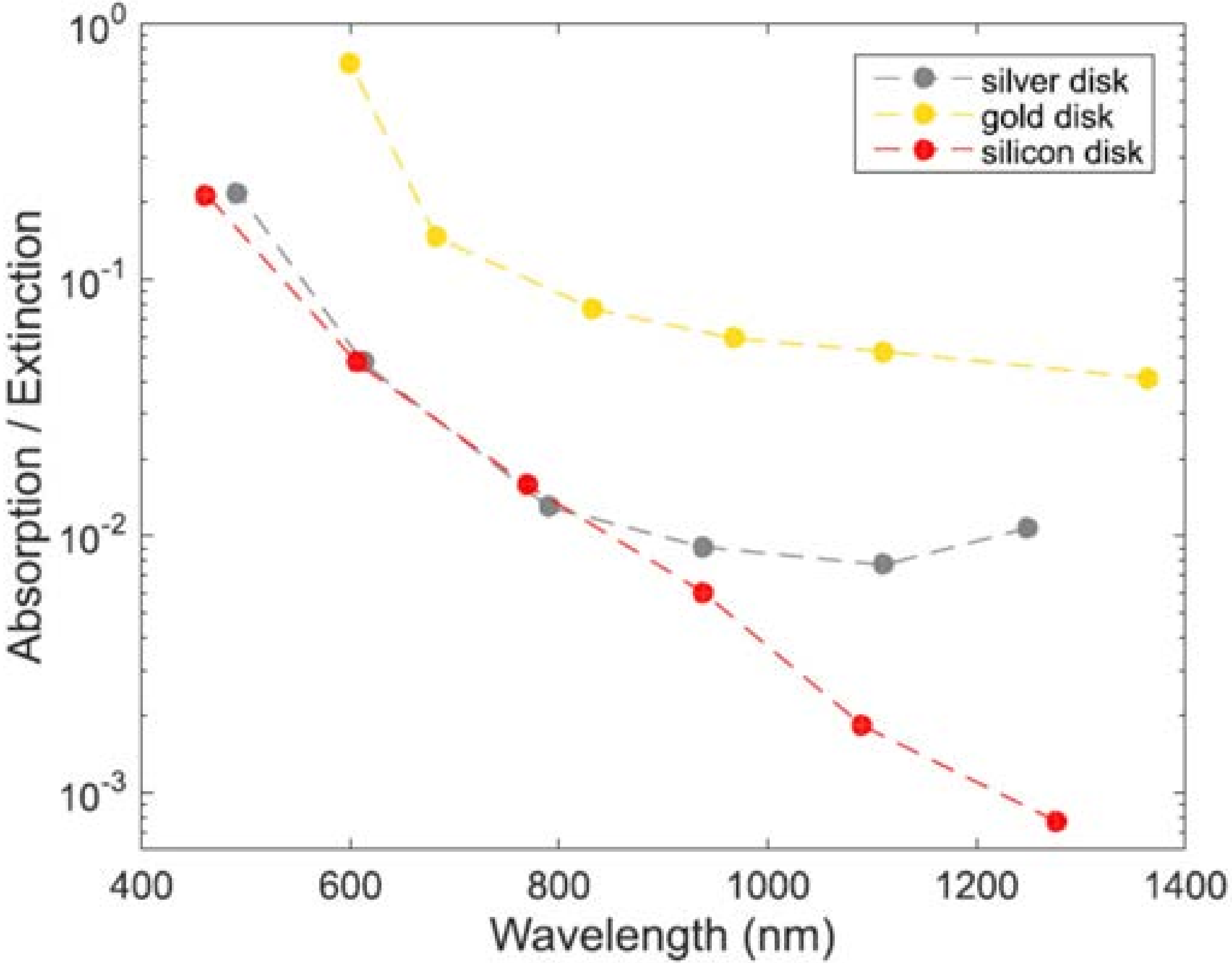


Examples for different
types of silicon



c-Silicon: Green & Keevers, Progress in photovoltaics 3, 189-192 (1995).
Silver: Johnson & Christy, Phys. Rev. B 6, 4370-4379 (1972).

Efficiency at Resonance



Comparison with Nanoplasmonics

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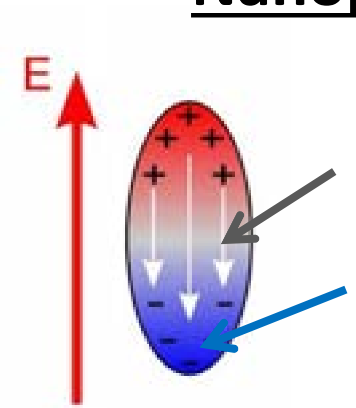
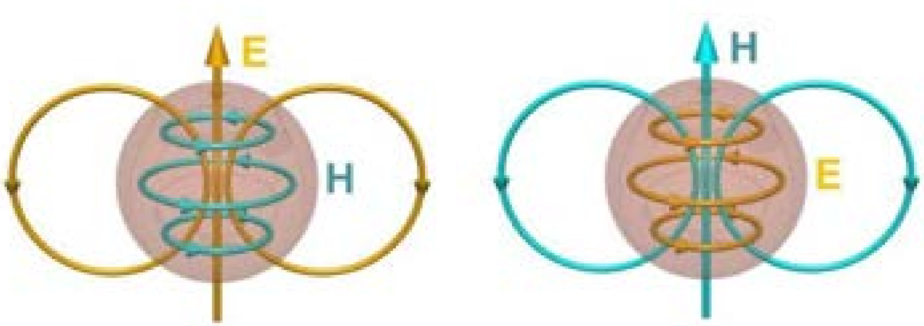
Nanoplasmonics



- Strong resonant response
- Strong field confinement
- Subwavelength dimensions

- Absorption losses
- Magnetic response
  → complex geometries

All-dielectric nanophotonics



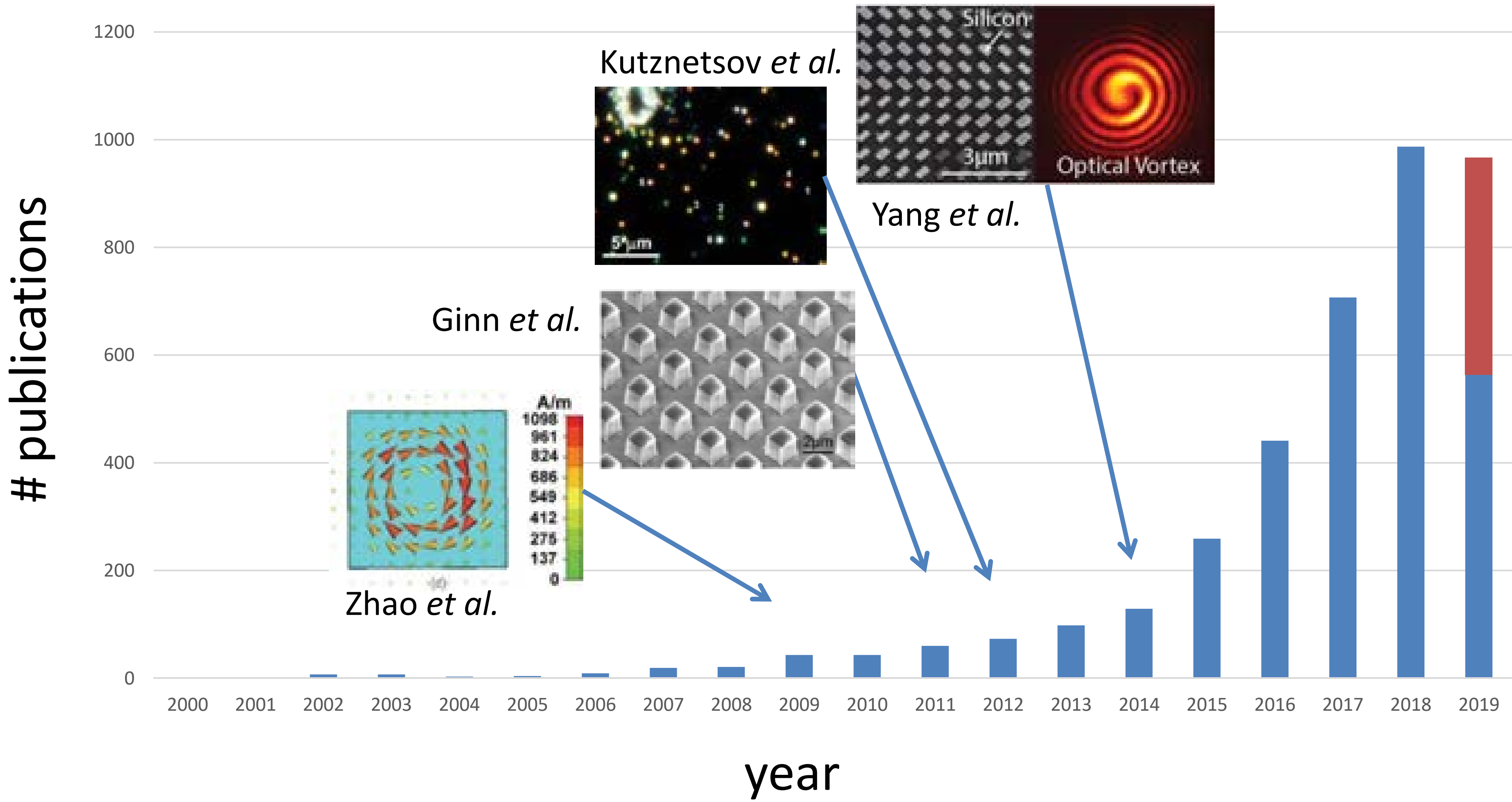
Images: A. Miroshnichenko

- Strong resonant response
- Strong field enhancement
- Negligible absorption losses
- Electric and magnetic multipolar resonances

- Diffraction limit unbroken

Recent Development

Google Scholar search, "dielectric nanoantenna" || "dielectric metamaterial" || "dielectric metasurface“ -"metal-dielectric metamaterial"



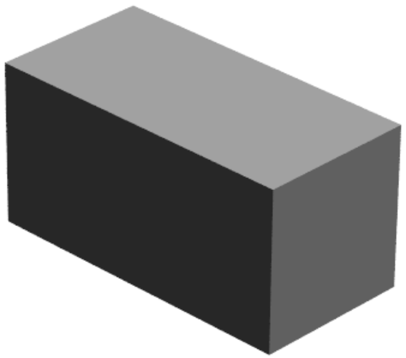
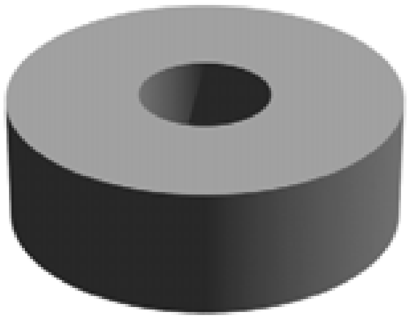
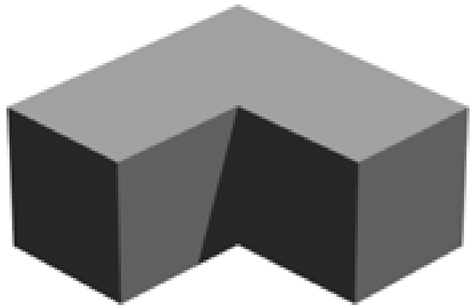
Historical Interlude

- Mie's paper: 1908
- Gans & Happel, Annalen der Physik, 1909, same equation as in Lewin!
- Schaefer & Stallwitz Annalen der Physik, 1916, 2D (rods)
- Lewin 1946
- Sakurai 1949, "Artificial Matter for electromagnetic wave".
- Bell Labs, etc. (artificial dielectrics): 40's-60's
- Early 2000's, late 90's: Kuester & Holloway (RF), Hasman (near IR), Chang-Hasnain, Lalanne, …
- Last ~10 years:
  - Visible&Near IR: Kuznetsov, Luk'yanchuk, Evlyukhin, Polman, Kivshar, Brener, Brongersma, Valentine, etc, etc.
  - IR: Brongersma, Sandia, …
  - RF: Cummer, Gopinath, Lippens, Kuester&Holloway, etc.

Slide by Igal Brener, ibrener@sandia.gov
Many thanks to Ed Kuester, CU Boulder

For a more comprehensive reference list, see Kuester& Holloway, Antennas and Propagation, IEEE Transactions on 51, no. 10 (2003): 2596,PIER B, vol. 33, p. 175 (2011).

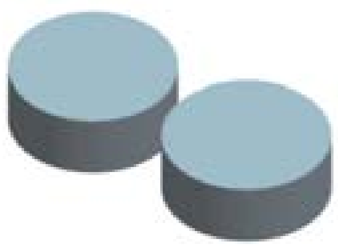
More Complex Nanoparticle Shapes

Anisotropy	Holey structures	Broken symmetries
		
Polarization sensitive response	Resonance engineering, near-field accessability	Resonance coupling, chiral effects

Influence of the Arrangement

- Exploit coupling between nanoparticles
- Many degrees of freedom to tailor nanoparticle response

Dimers



Electric and magnetic field enhancement, mode hybridization

Permyakov *et al., Nano Lett.*15, 2137 (2015).

Chains

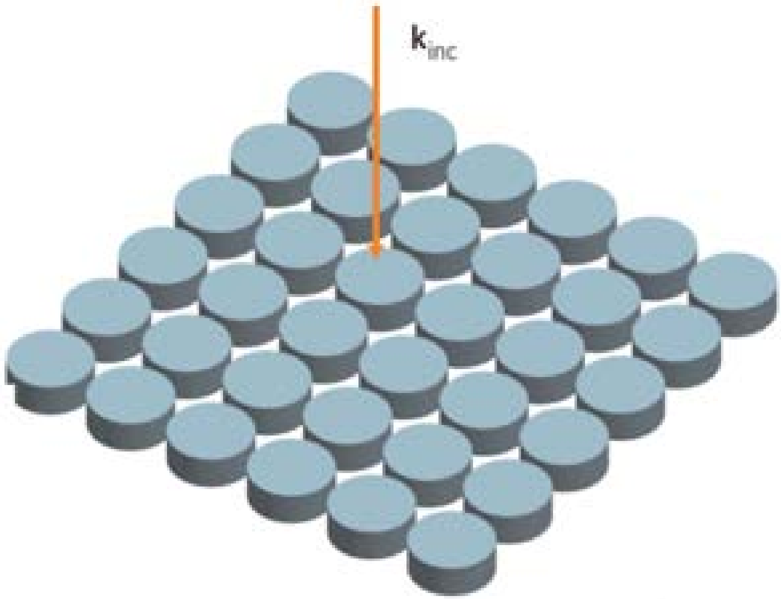
Directional scattering effects (Dielectric Yagi-Uda nanoantennas)

Krasnok *et al.*, *Opt. Exp.* 20, 20599 (2012).

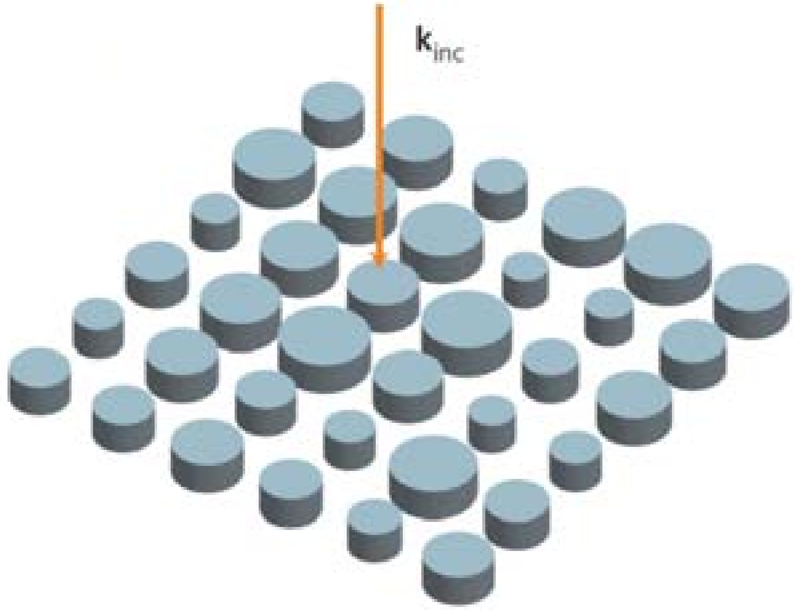
Oligomers

Fano resonances (narrow linewidths useful for sensing)

Chong *et al.*, *Small* 10, 1985 (2014).



Spatially homogeneous metasurface



Disordered metasurface

Subwavelength Arrangement

Goal: we want to work in a non-diffractive regime, where only the zeroth diffraction order is propagating.

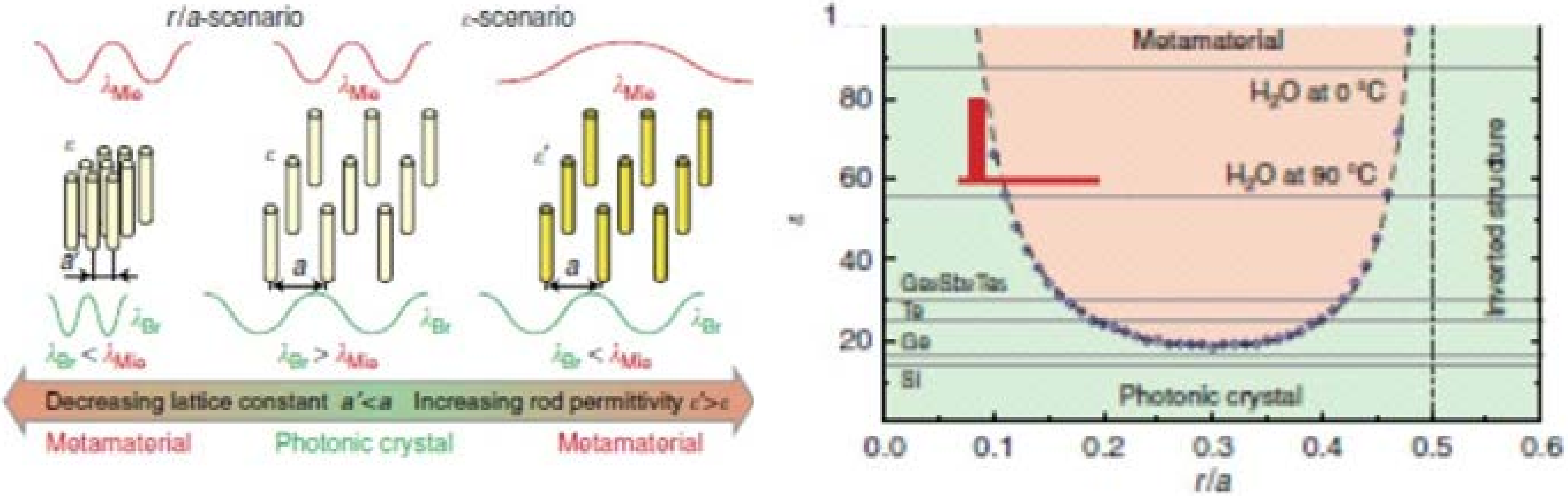
For a square lattice, lattice constant b, the first diffraction order at normal incidence appears at $\lambda_{\mathrm{D}} = n_m b$

Mie resonance at $\lambda_{\mathrm{Mie}} \approx 2n_p a = n_p d_p$ (in vacuum)

Condition: $\lambda_{\mathrm{Mie}} > \lambda_{\mathrm{D}} \rightarrow n_m b < n_p d_p$

→ Another reason for high nanoparticle index!

Mie-Resonant 3D Metamaterials?



Rybin *et al.*, *Nat. Commun.* **6** 10102 (2015).

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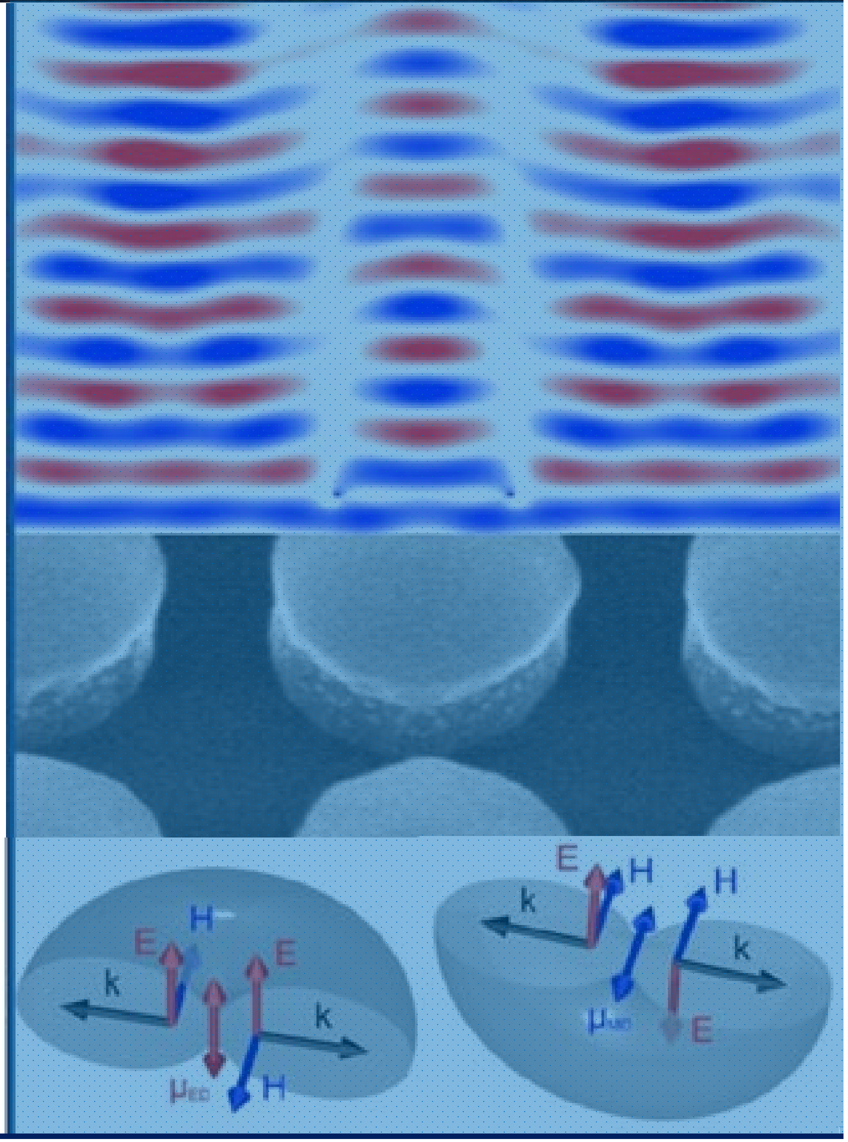
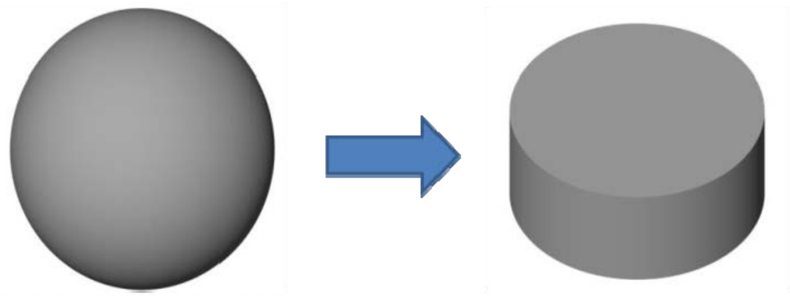
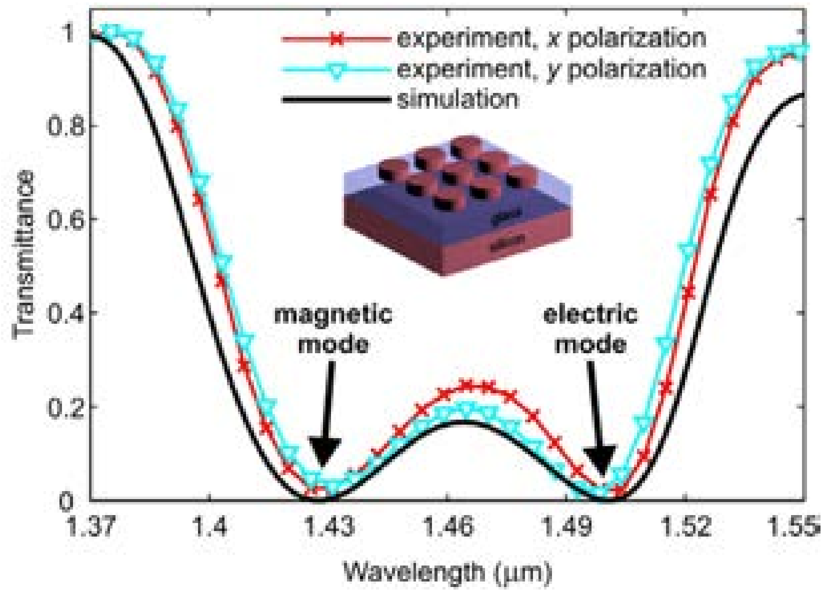
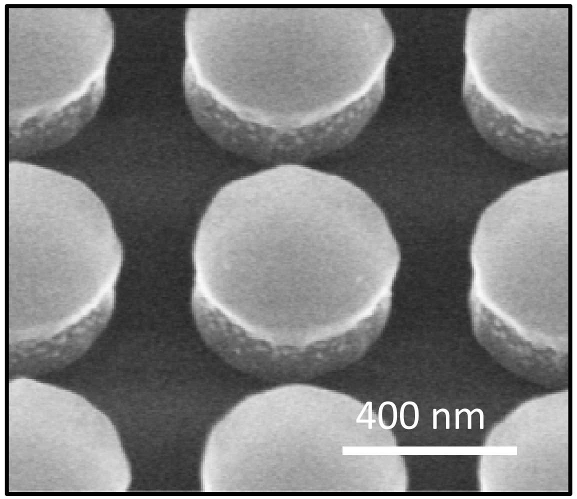
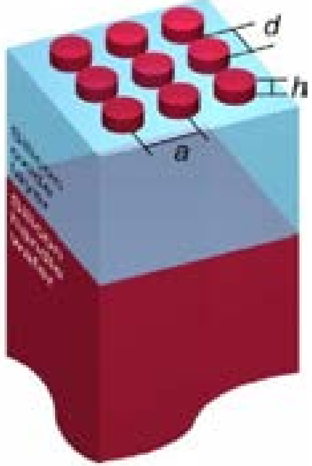


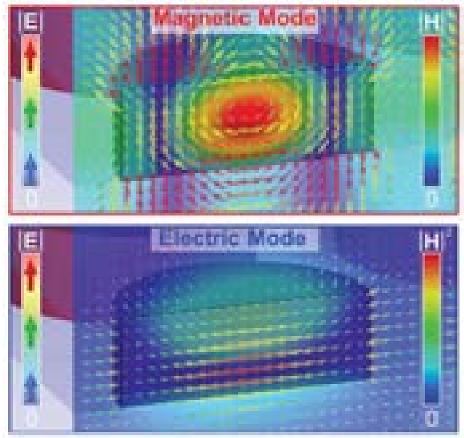
Silicon Nanodisk Array





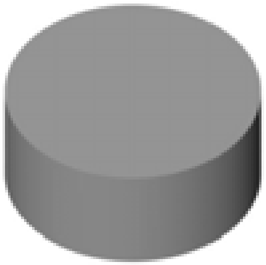




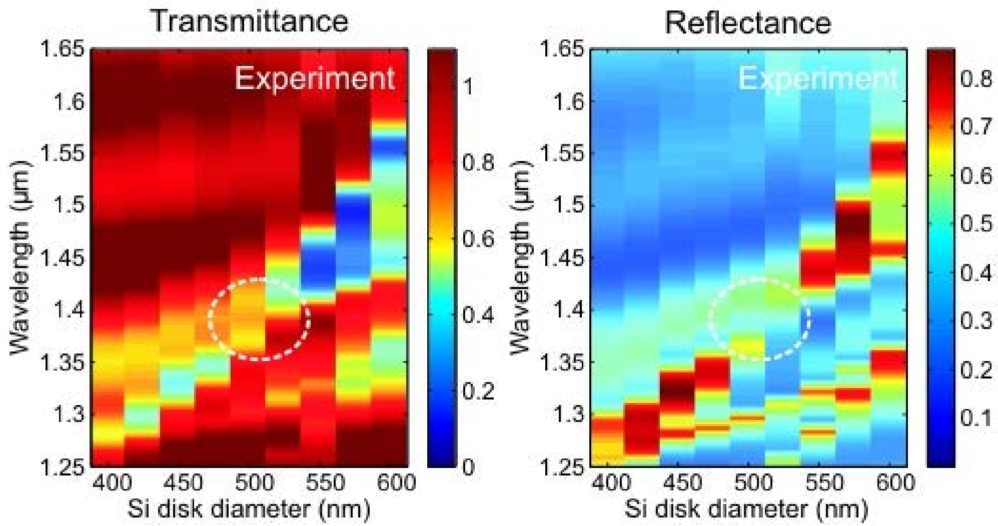


I. Staude *et al.*, *ACS Nano* **7**, 7824 (2013).

Overlapping the ED and MD Resonances



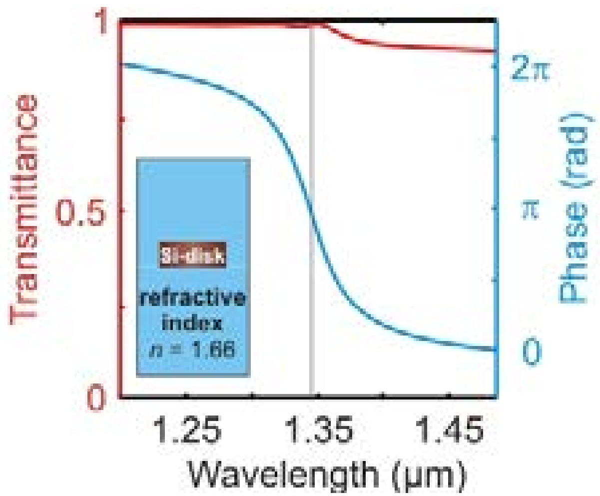
diameter,
height



I. Staude *et al.*, *ACS Nano* **7**, 7824 (2013).

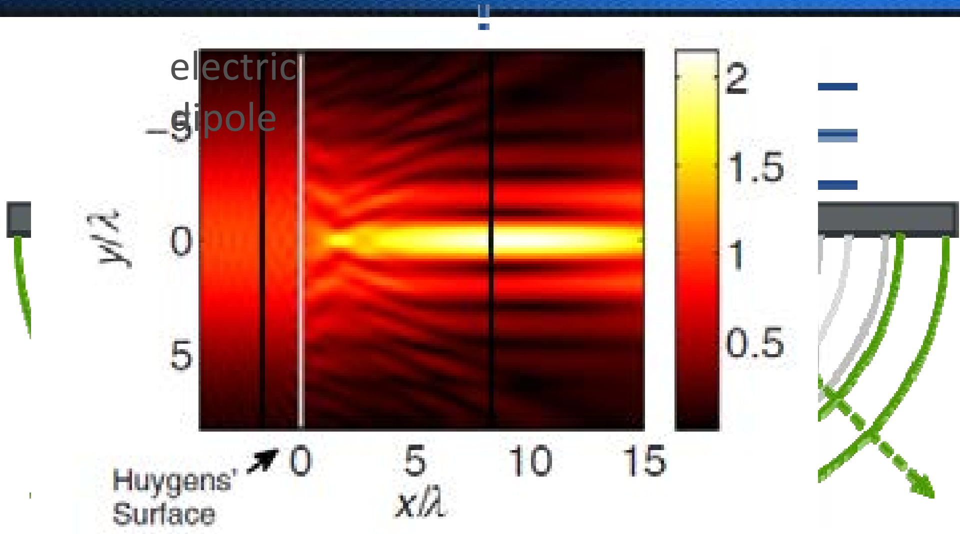
M. Decker, I. Staude *et al.*, *Adv. Opt. Mater.* **3**, 813 (2015).

Numerics

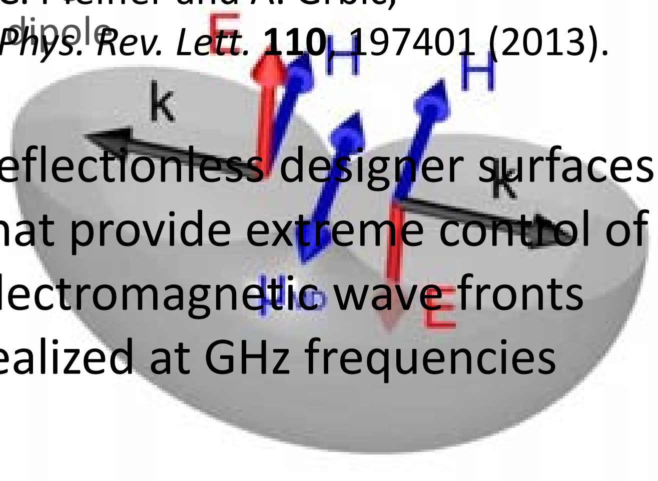


- Manipulate the phase of a light wave at will, with full phase coverage
- Maintain high – ideally unity – transmittance

Huygens' Metasurfaces



C. Pfeiffer and A. Grbic,
Phys. Rev. Lett. **110**, 197401 (2013).



Reflectionless designer surfaces that provide extreme control of electromagnetic wave fronts realized at GHz frequencies

Images adapted from R. Zia

- **Huygens' principle:** each point on a wave front acts as a secondary source of outgoing waves
- **Huygens' source:** source radiating the far-fields of a crossed electric and magnetic dipole

References

C. Huygens, Traité de la Lumiére, (1690).

A. E. H. Love, *Phil. Trans. R. Soc. Lond. A* **197**, 1-45 (1901).

A. D. Yaghjian, *European Conf. Antennas Propagat. (EuCap)*, 856-860 (2009).

F. Monticone, *et al., Phys. Rev. Lett.* **110**, 203903 (2013).

Superposition of E & M Dipoles

Array of electric dipoles

Array of magnetic dipoles

Array of superimposed electric and magnetic dipoles

Movies: M. Decker

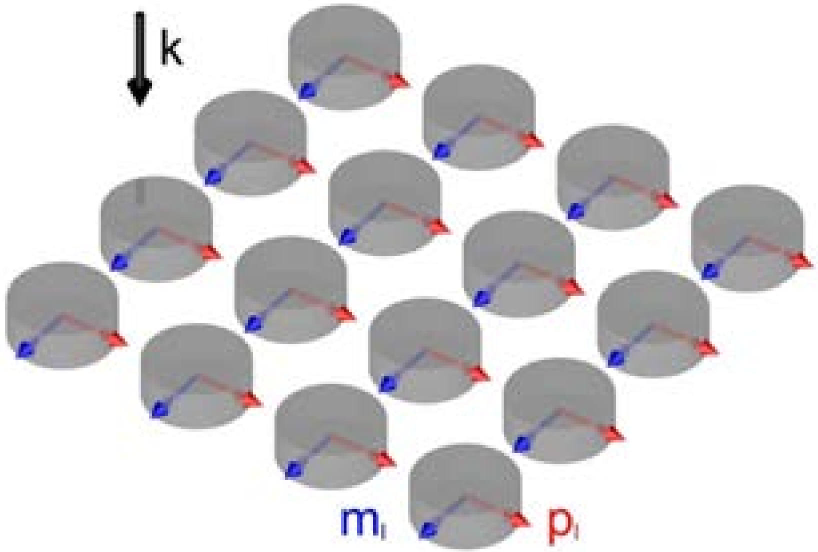
Theoretical Model

Understanding the full complex response of the nanodisk metasurface: Coupled electric and magnetic dipole model

Coupled-dipole equations:

$$\mathbf{p}_l = \alpha^E \left[\mathbf{E}_l^0 + \frac{k_0^2}{\varepsilon_0} \sum_{j \neq l}^{N} \left(\hat{G}_{lj} \mathbf{p}_j + \frac{i}{c k_0} [\mathbf{g}_{lj} \times \mathbf{m}_j] \right) \right]$$

$$\mathbf{m}_l = \alpha^M \left[\mathbf{H}_l^0 + k_0^2 \sum_{j \neq l}^{N} \left(\varepsilon_d \hat{G}_{lj} \mathbf{m}_j - \frac{ic}{k_0} [\mathbf{g}_{lj} \times \mathbf{p}_j] \right) \right]$$



A. B. Evlyukhin *et al.,* Phys. Rev. B **82**, 045404 (2010).

Theoretical Model

- For lattice constants smaller than the wavelength of the incident light: capture influence of the array by defining effective electric and magnetic polarizabilities α_{eff}^{e} and α_{eff}^{m}
- Field transmittance coefficient of the metasurface

$$t = 1 + \frac{ik_d}{2A}(\alpha_{\text{eff}}^{e} + \alpha_{\text{eff}}^{m}); \qquad k_d = n_d \omega / c_0$$

- Assume Lorentzian line shapes for the dispersion of α_{eff}^{e} and α_{eff}^{m}:

$$\alpha_{\text{eff}}^{e} = \frac{\alpha_0^e}{\omega_{e,0}^2 - \omega^2 - 2i\gamma_e\omega}\ ; \qquad \alpha_{\text{eff}}^{m} = \frac{\alpha_0^m}{\omega_{m,0}^2 - \omega^2 - 2i\gamma_m\omega}$$

- Determine amplitudes of the effective polarizability:

$$T = \left|t(\omega_{e,m})\right|^2 = 0 \quad \rightarrow \quad \alpha_0^{e,m} = \frac{4Ac_0}{n_d}\gamma_{e,m}$$

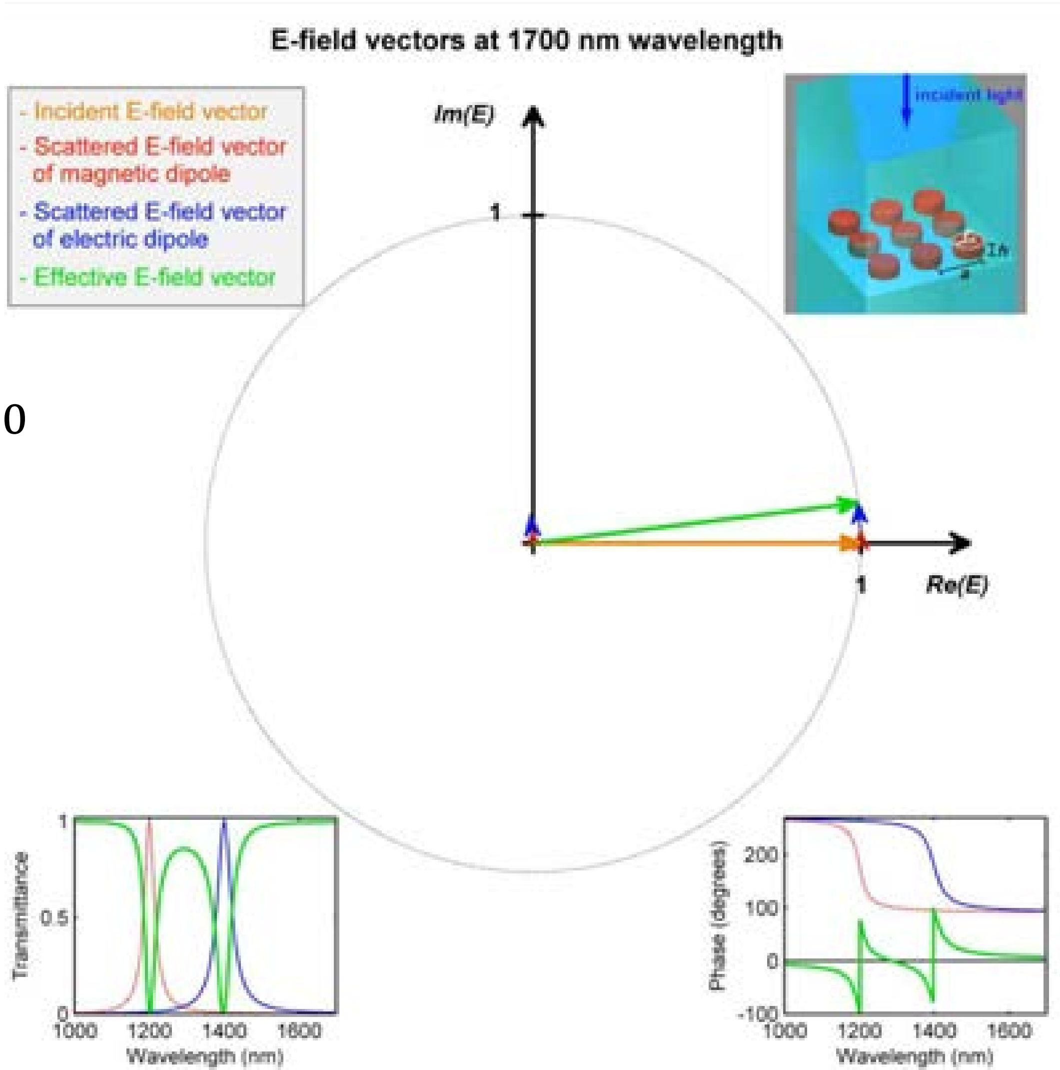
- Field transmittance coefficient of the metasurface:

$$t = 1 + \frac{2i\gamma_e\omega}{\omega_{e,0}^2 - \omega^2 - 2i\gamma_e\omega} + \frac{2i\gamma_m\omega}{\omega_{m,0}^2 - \omega^2 - 2i\gamma_m\omega}$$

Evlyukhin *et al.,* Phys. Rev. B **82**, 045404 (2010), Decker *et al.*, *Adv. Opt. Mater.* **3**, 813 (2015).

Two Individual Dipole Resonances

$$\omega_{e,0} \neq \omega_{m,0}$$
$$\gamma_e = \gamma_m$$

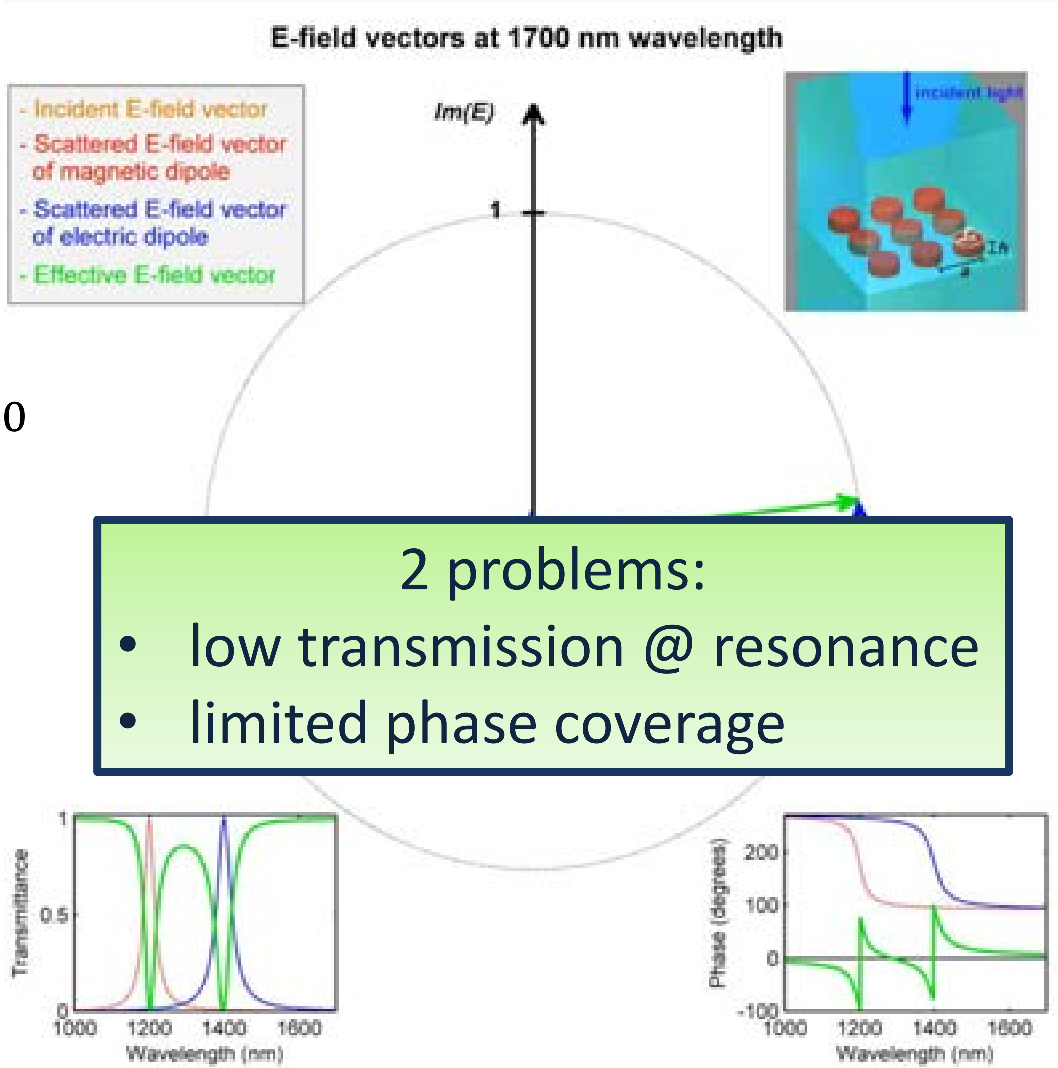


M. Decker, I. Staude *et al.*, *Adv. Opt. Mater.* **3**, 813 (2015).

Two Individual Dipole Resonances

Abbe Center of Photonics | JENA
Friedrich-Schiller-Universität

$$\omega_{e,0} \neq \omega_{m,0}$$
$$\gamma_e = \gamma_m$$



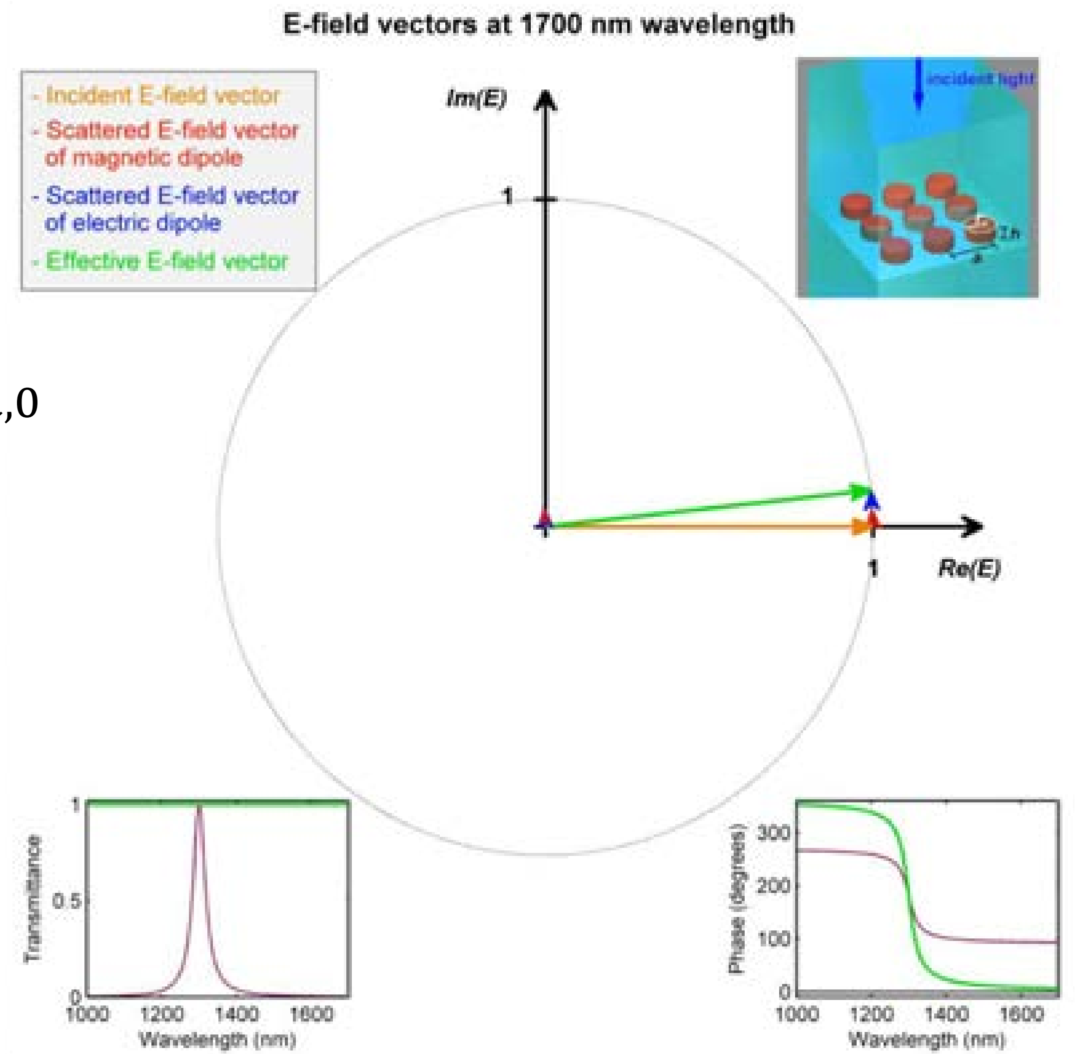
2 problems:

- low transmission @ resonance
- limited phase coverage

M. Decker, I. Staude *et al.*, *Adv. Opt. Mater.* **3**, 813 (2015).

Two Matching Dipole Resonances

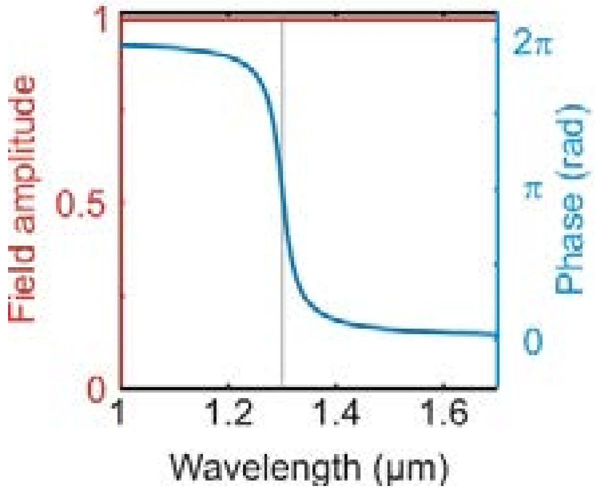
$$\omega_{e,0} = \omega_{m,0}$$
$$\gamma_e = \gamma_m$$



M. Decker, I. Staude *et al.*, *Adv. Opt. Mater.* **3**, 813 (2015).

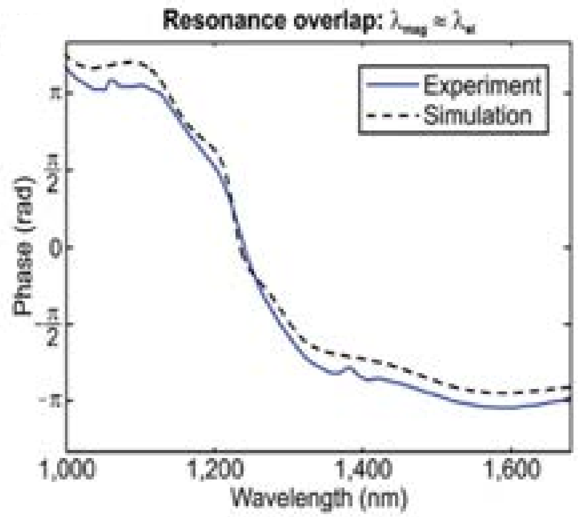
Huygens' Metasurface Transmittance

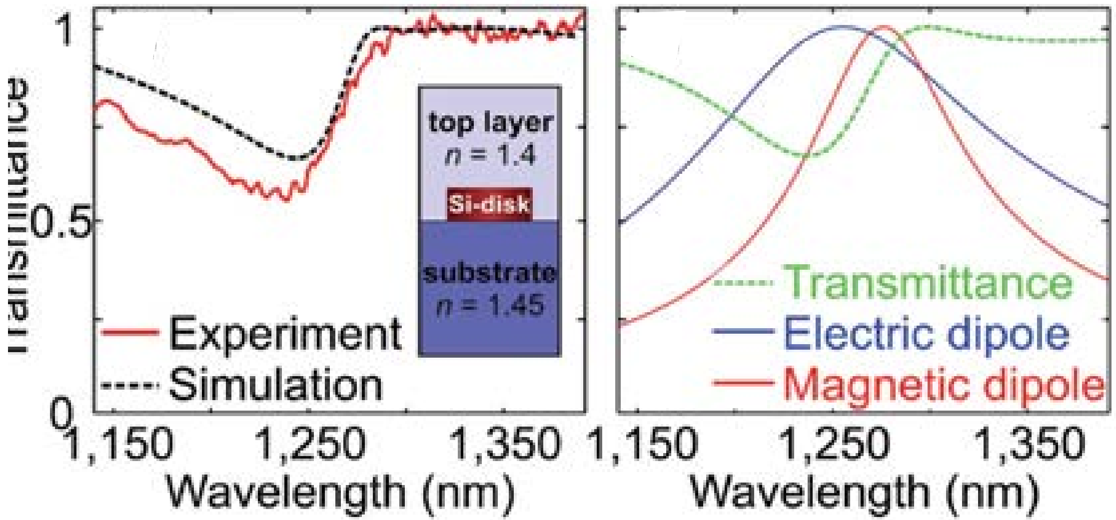
Analytic model



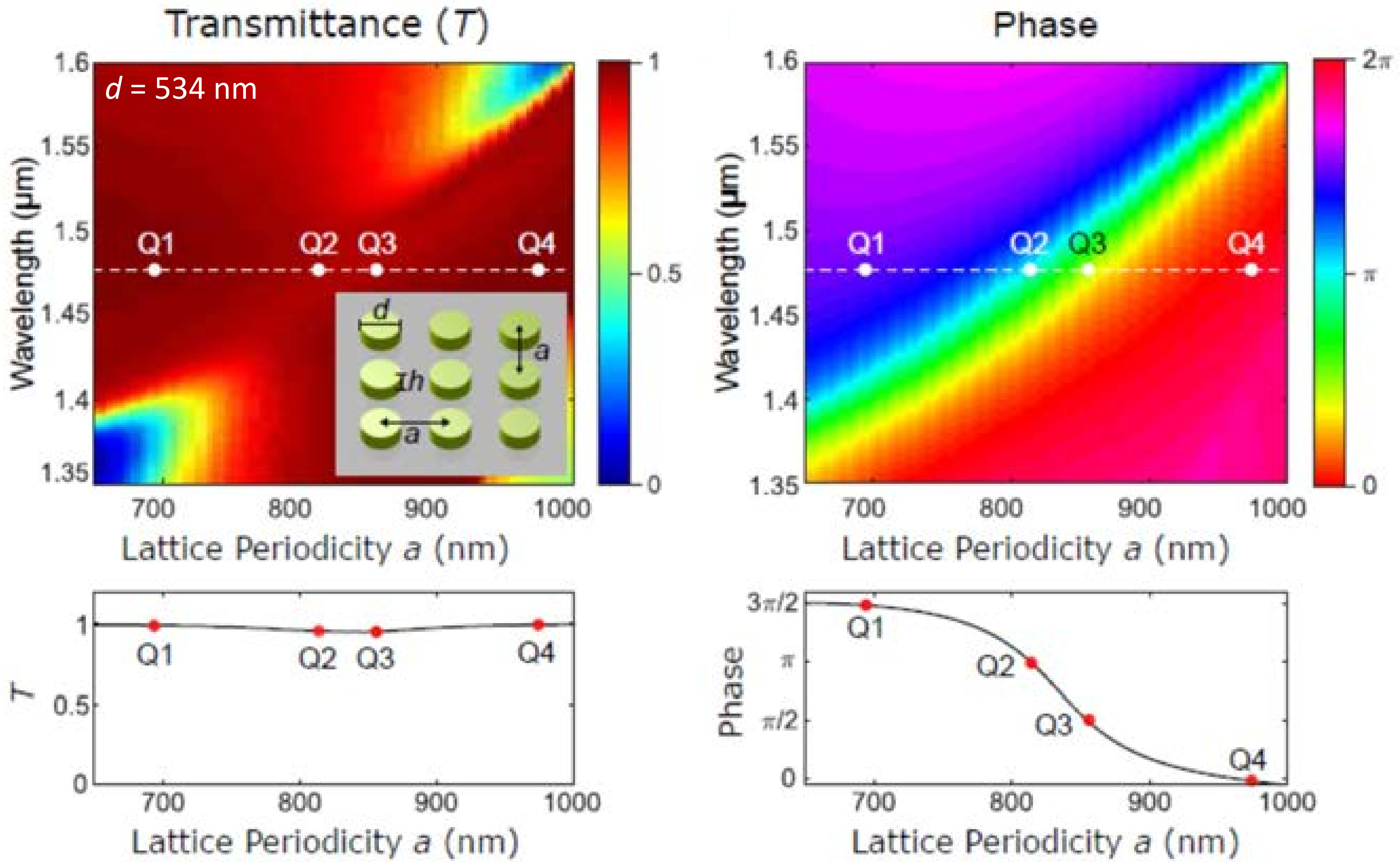
M. Decker, I. Staude *et al.*, *Adv. Opt. Mater.* **3**, 813 (2015).

Next goal: use full phase coverage and high transmittance for wavefront shaping



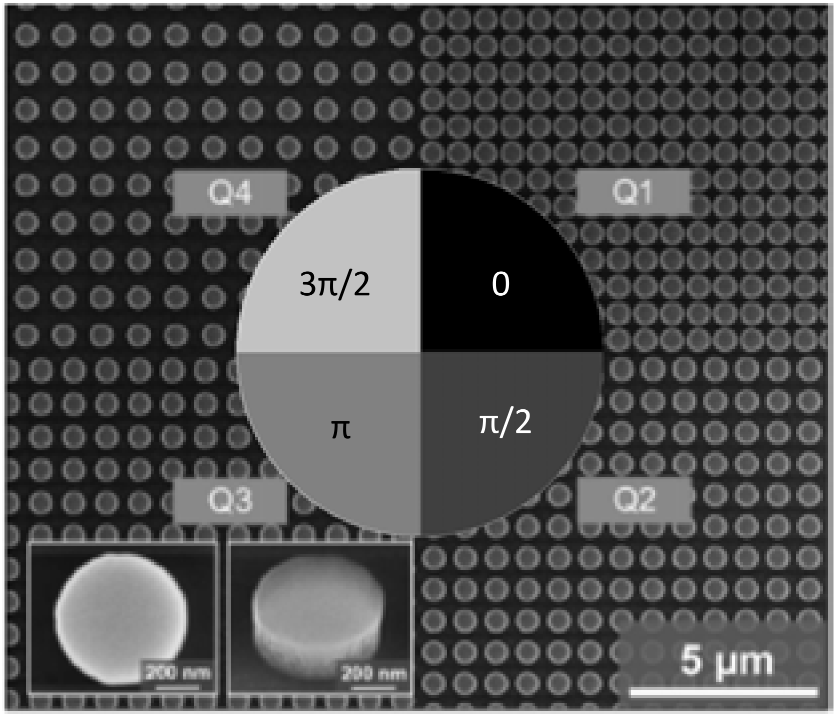


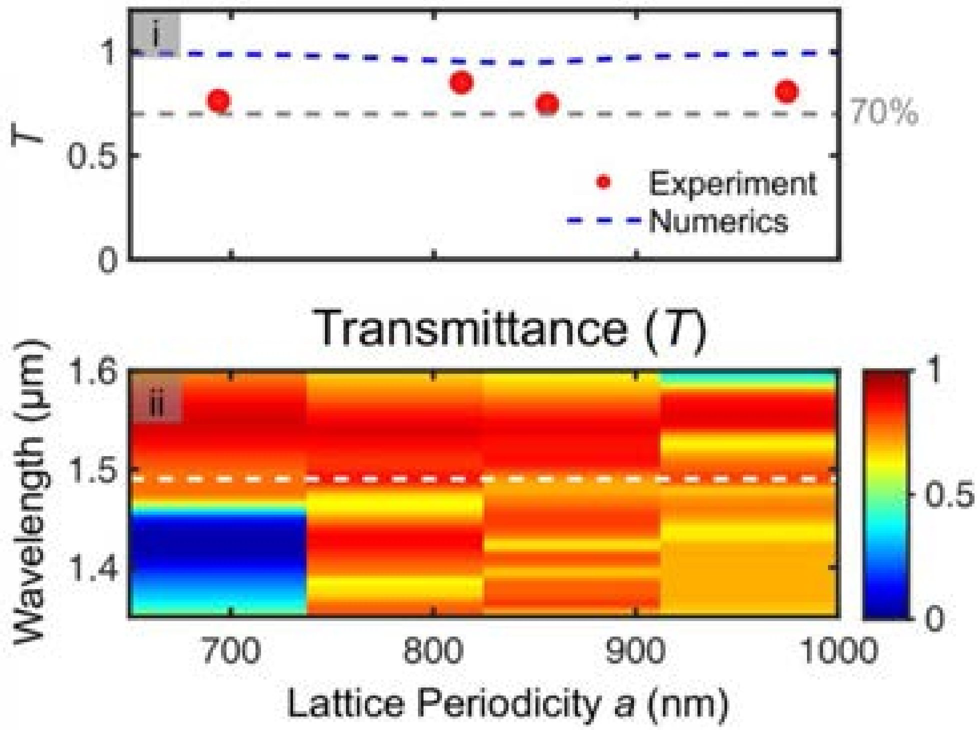
Imprinting Position Dependent Phase



K. Chong, *et al.*, *Nano Lett.* 15, 5369-5374 (2015).

Gaussian-to-Vortex Beam Shaper

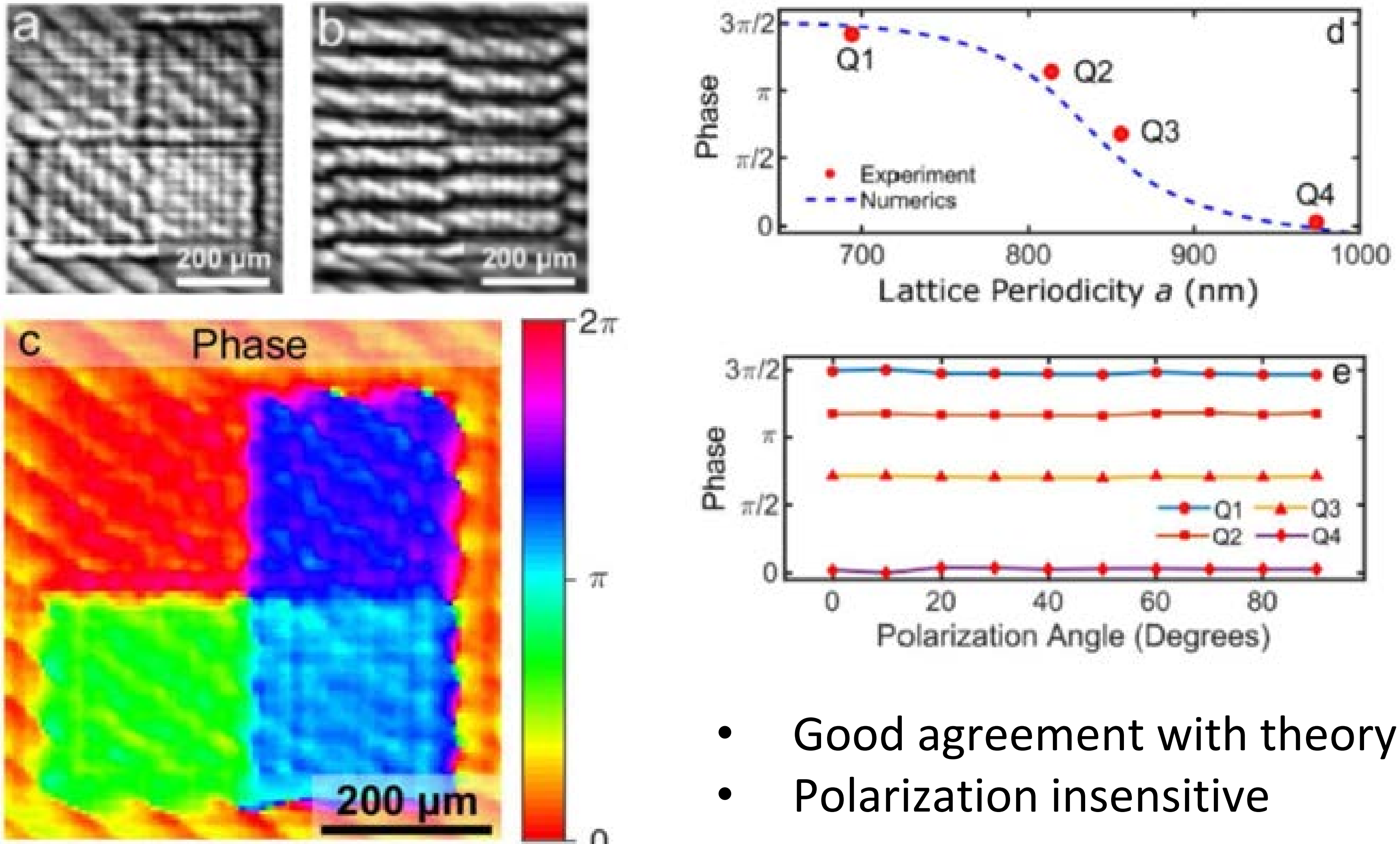




- Approximation of 0 - 2π azimuthal phase gradient by 4 quadrants with equidistant phase differences
- Experimental transmittance efficiency > 70%

K. Chong, *et al.*, *Nano Lett.* 15, 5369-5374 (2015).

Huygens‘ Metasurface Beam Shaper

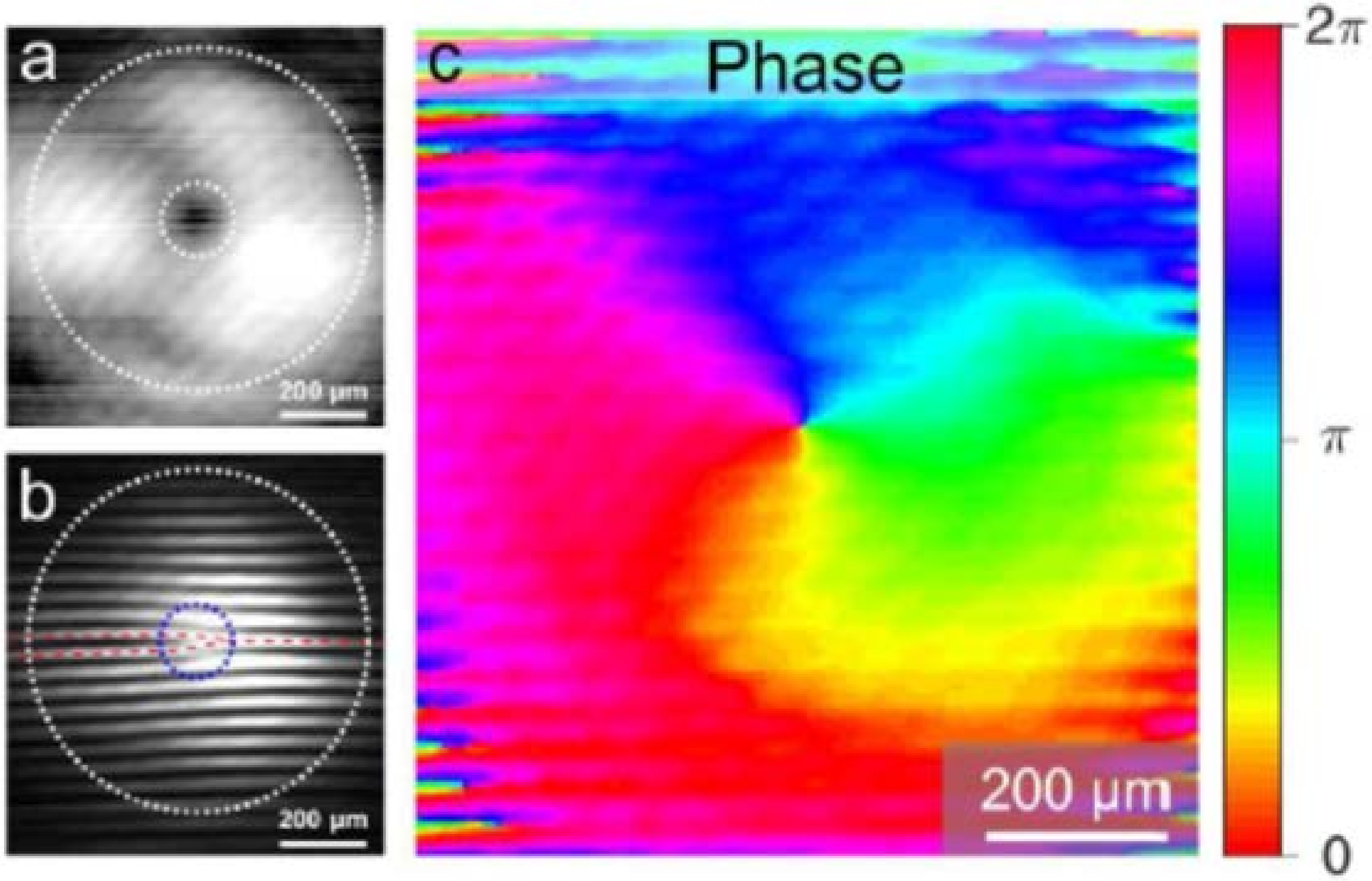


- Good agreement with theory
- Polarization insensitive

K. Chong, *et al.*, *Nano Lett.* 15, 5369-5374 (2015).

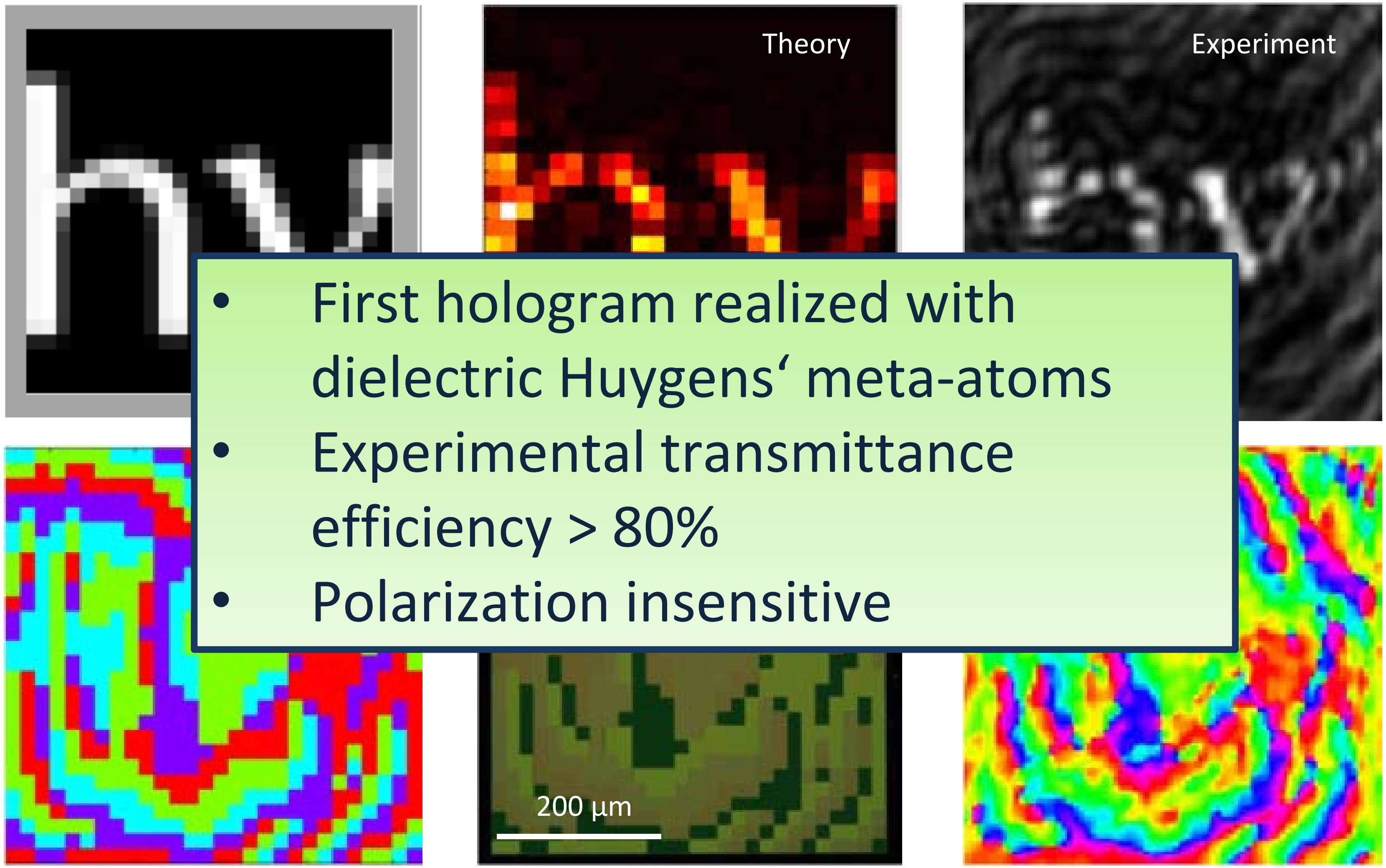
Huygens‘ Metasurface Beam Shaper

Interferometric characterization of the generated beam



K. Chong, *et al.*, *Nano Lett.* 15, 5369-5374 (2015).

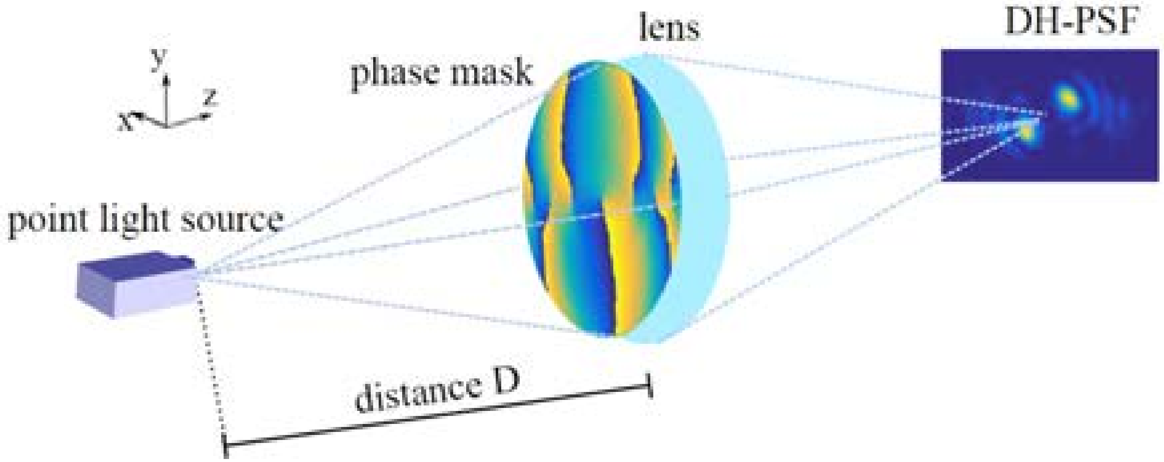
Huygens‘ Metasurface Hologram

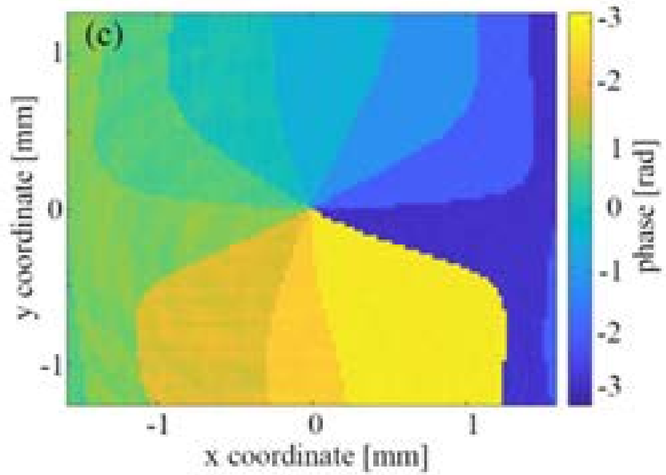


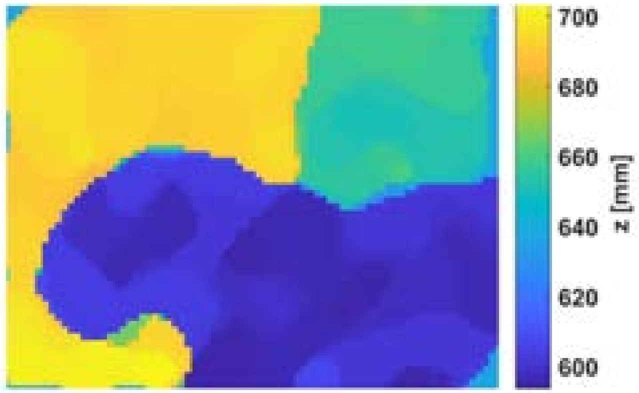
- First hologram realized with dielectric Huygens‘ meta-atoms
- Experimental transmittance efficiency > 80%
- Polarization insensitive

K. Chong, *et al.*, *ACS Photonics* **3**, 514–519 (2016).

Depth Imaging

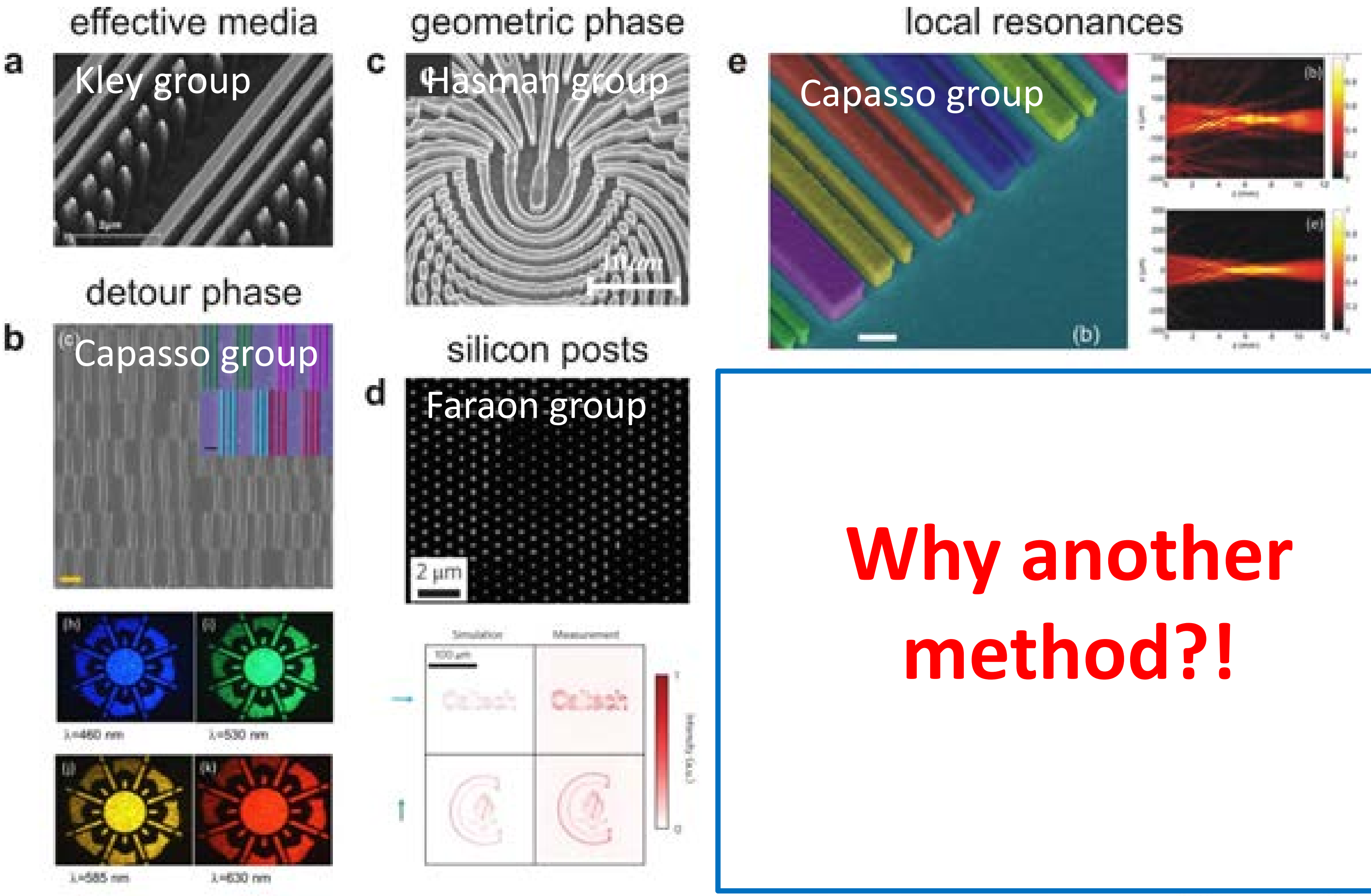






C. Jin et al., *Adv. Photonics* **1**, 6001 (2019).

Different Phase-Control Approaches



Why another method?!

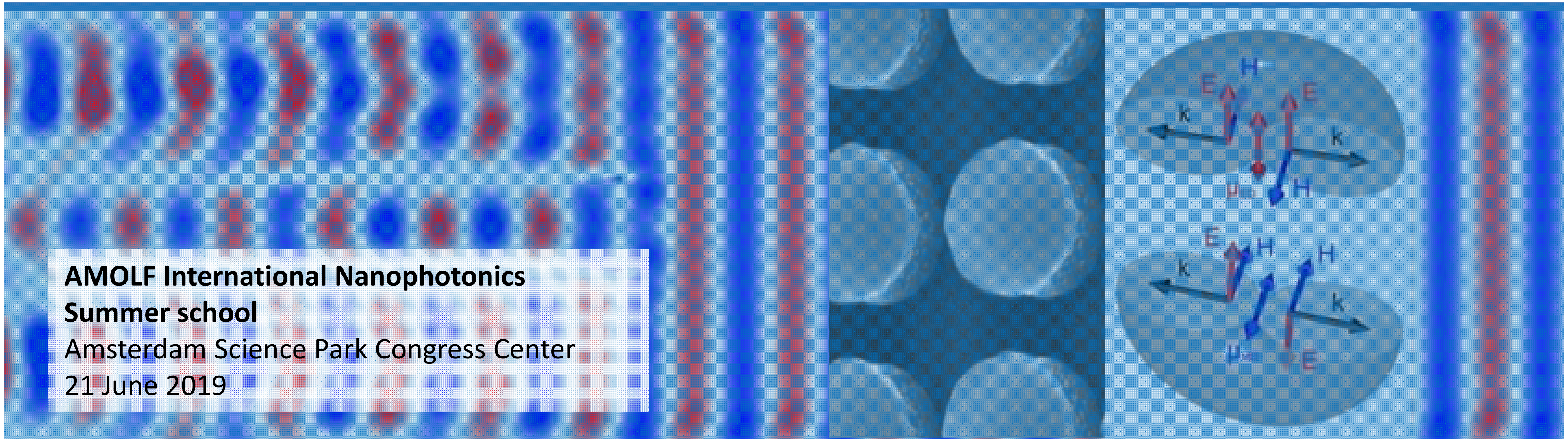
Potential of Resonant Metasurfaces

- Strong spatial and spectral dispersion
  - Opportunity to tailor frequency / angular sensitive optical response
  - Facilitates tuning/switching
- Resonantly enhanced electromagnetic near-fields → enhancement of light-matter interactions
  - Nonlinear optical effects
  - Spontaneous emission

Highlight: Nonlinear, tunable and light-emitting dielectric metasurfaces

Isabelle Staude

Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-University Jena, 07743 Jena, Germany

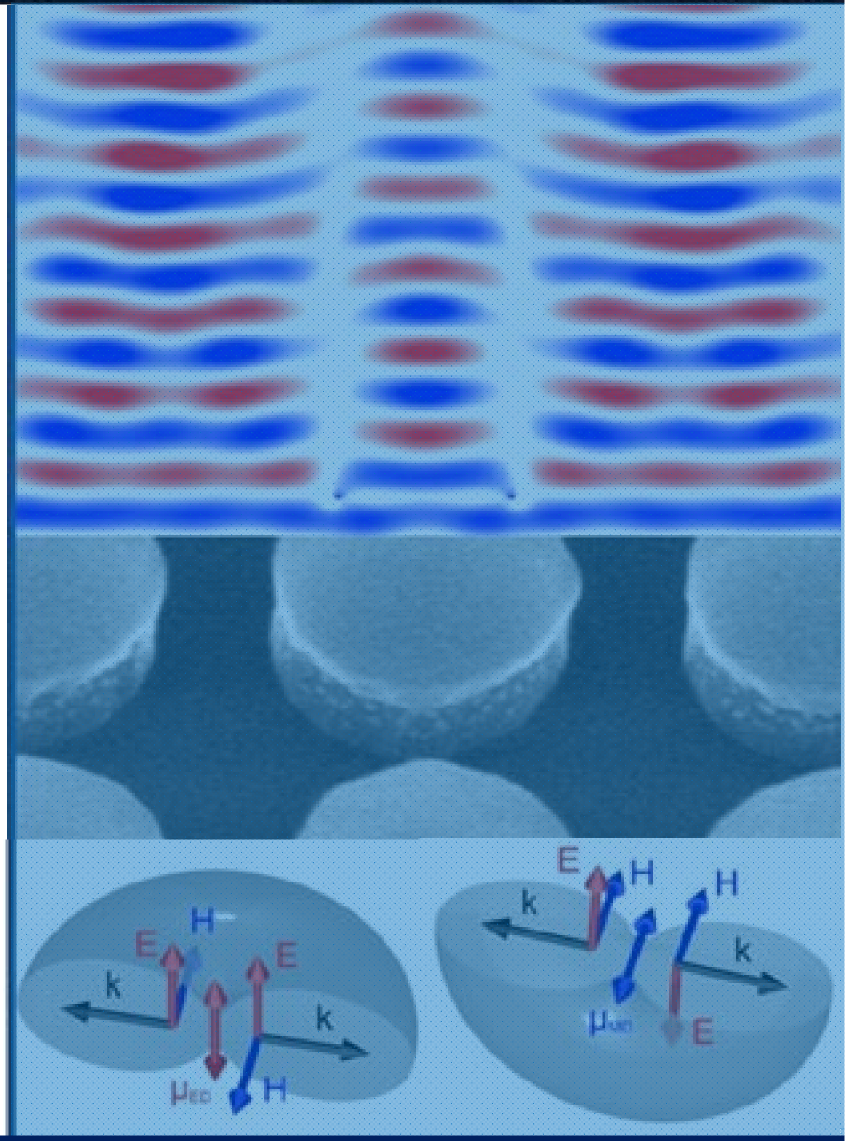


AMOLF International Nanophotonics Summer school
Amsterdam Science Park Congress Center
21 June 2019

Outline

- Motivation
- Optical properties of high-index dielectric nanoparticles
- Dielectric Huygens' metasurfaces

- Highlight talk
  - **Active control of dielectric metasurfaces**
  - Light emission from dielectric metasurfaces



Tuning of Metasurfaces

Tuning approaches:

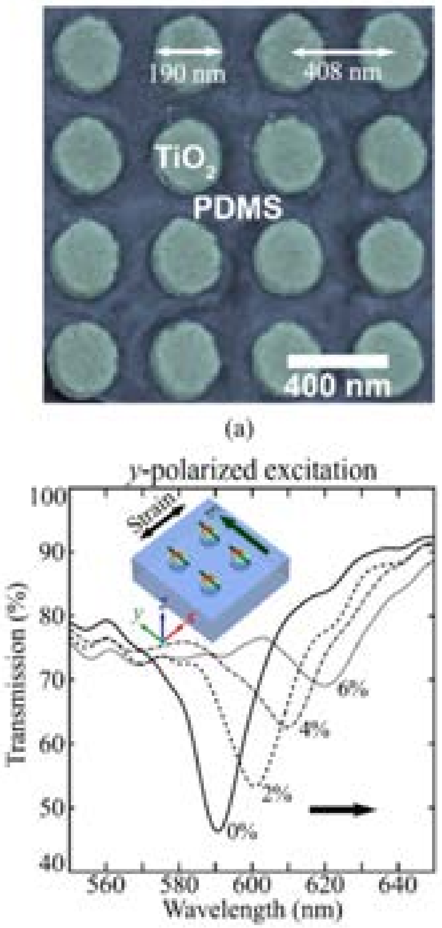
- Change the metasurface geometry
- Change the embedding material properties
- Change the nanoresonator material properties

Tuning performance:

- Resonance shift $\Delta\lambda$
- Relative resonance shifts $\Delta\lambda/\lambda_0$ or $\Delta\lambda/FWHM$
- Absolute changes in transmittance/reflectance ($\Delta T, \Delta R$)
- Relative changes in transmittance/reflectance ($\Delta T/T, \Delta R/R$)

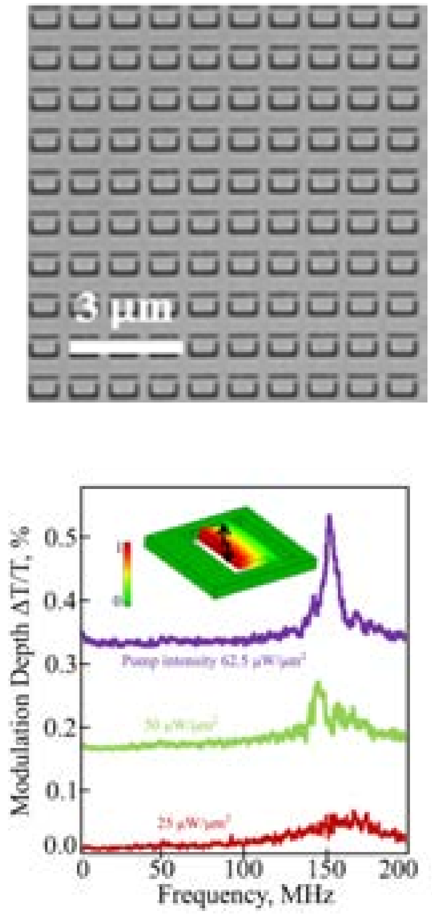
Active Tuning of Dielectric Metasurfaces

Mechanical tuning



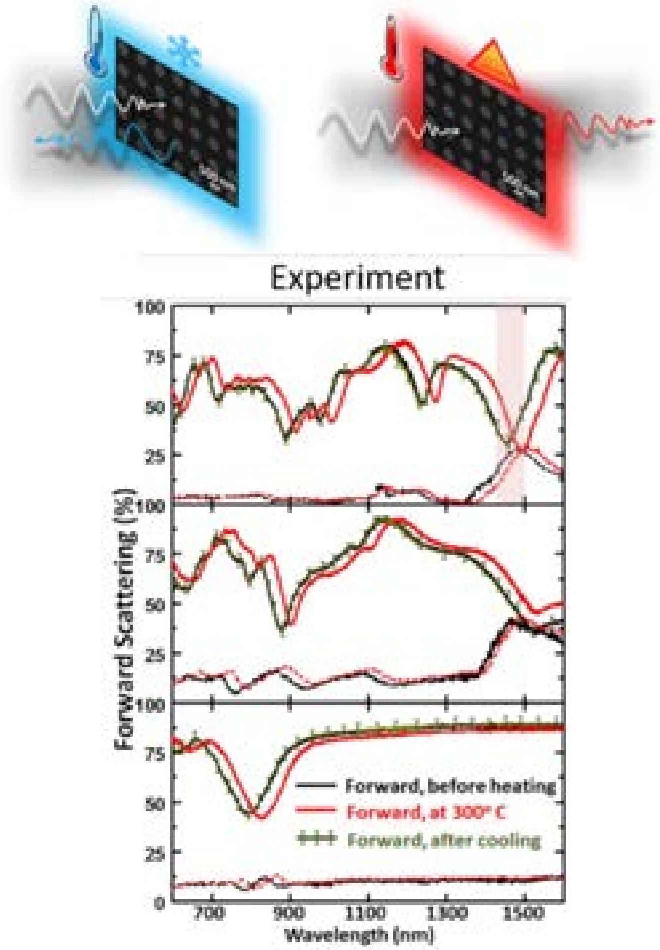
Gutruf *et al.*, *ACS Nano* **10**, 133 (2016).

Optomechanical tuning



Karvounis *et al.*, *Appl. Phys. Lett.* **107**, 191110 (2015).

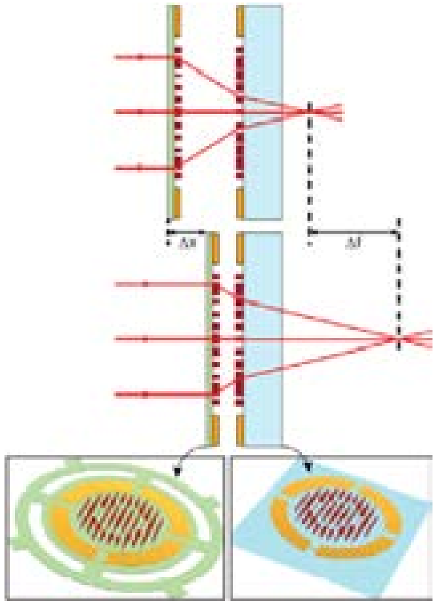
Temperature tuning



Rahmani *et al.*, *Adv. Funct. Mater.* **27**, 1700580 (2017).

Tunable Dielectric Metasurface Devices

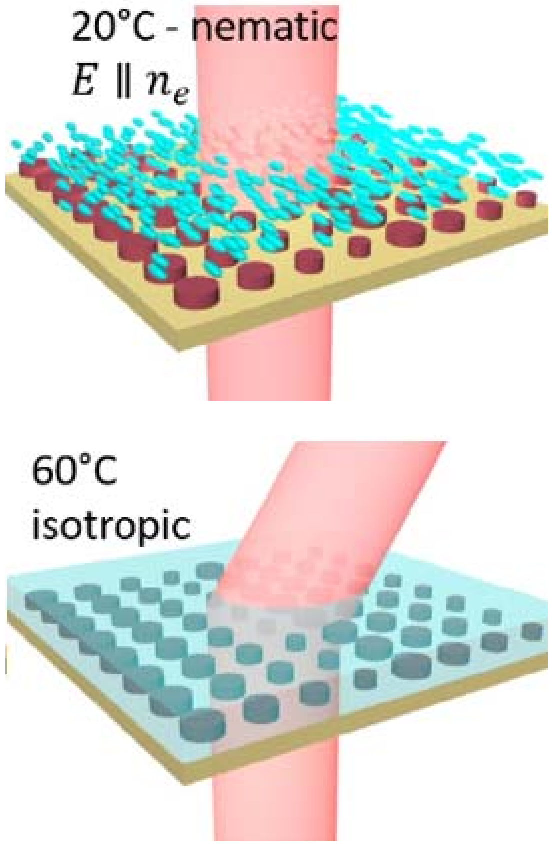
Tunable metalenses



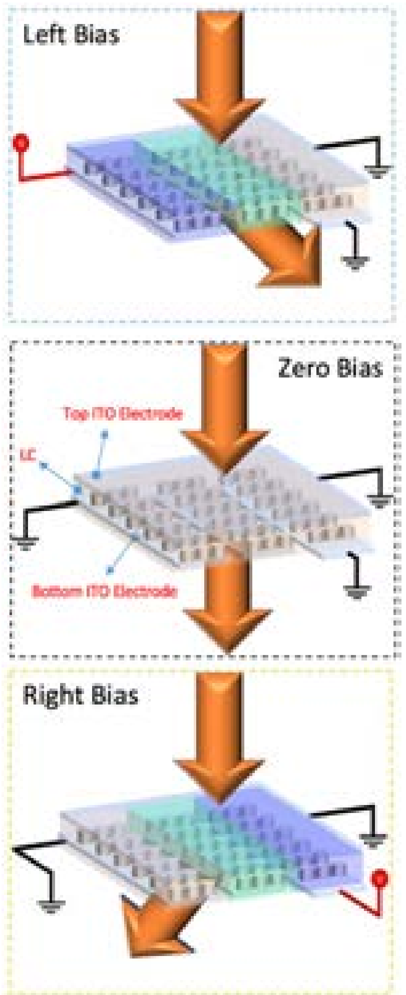
E. Arbabi *et al.*, *Nat. Commun.* **9**, 812, (2018).

A. She *et al.*, *Sci. Adv.* **4**, eaap9957 (2018).

Tunable beam deflectors



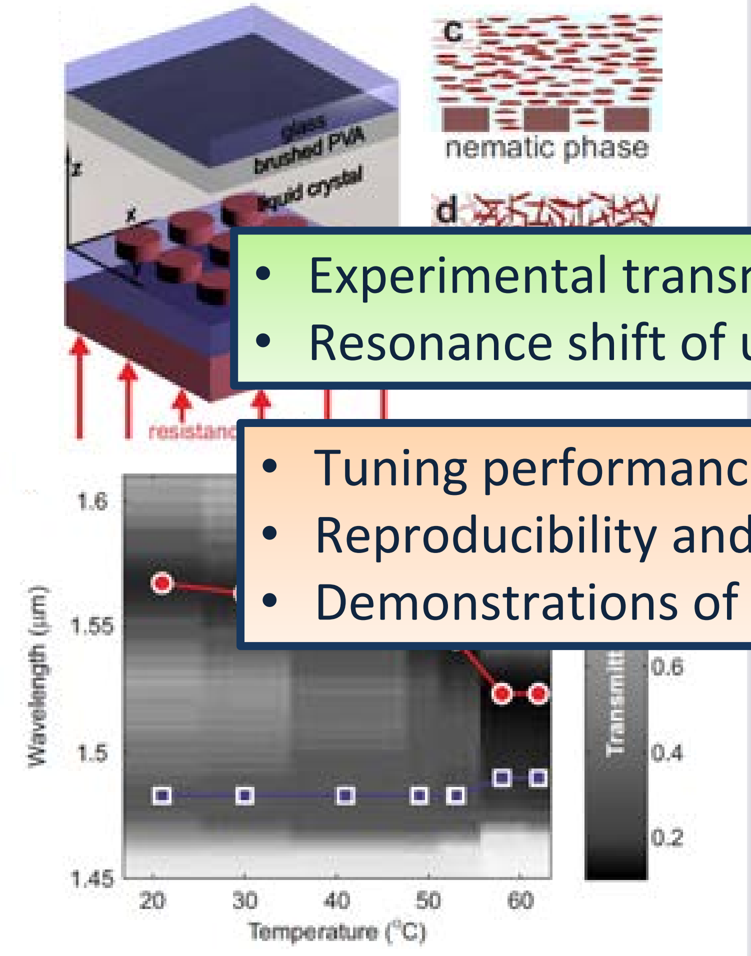
A. Komar *et al.*, *ACS Photon.* **5**, 1742 (2018).



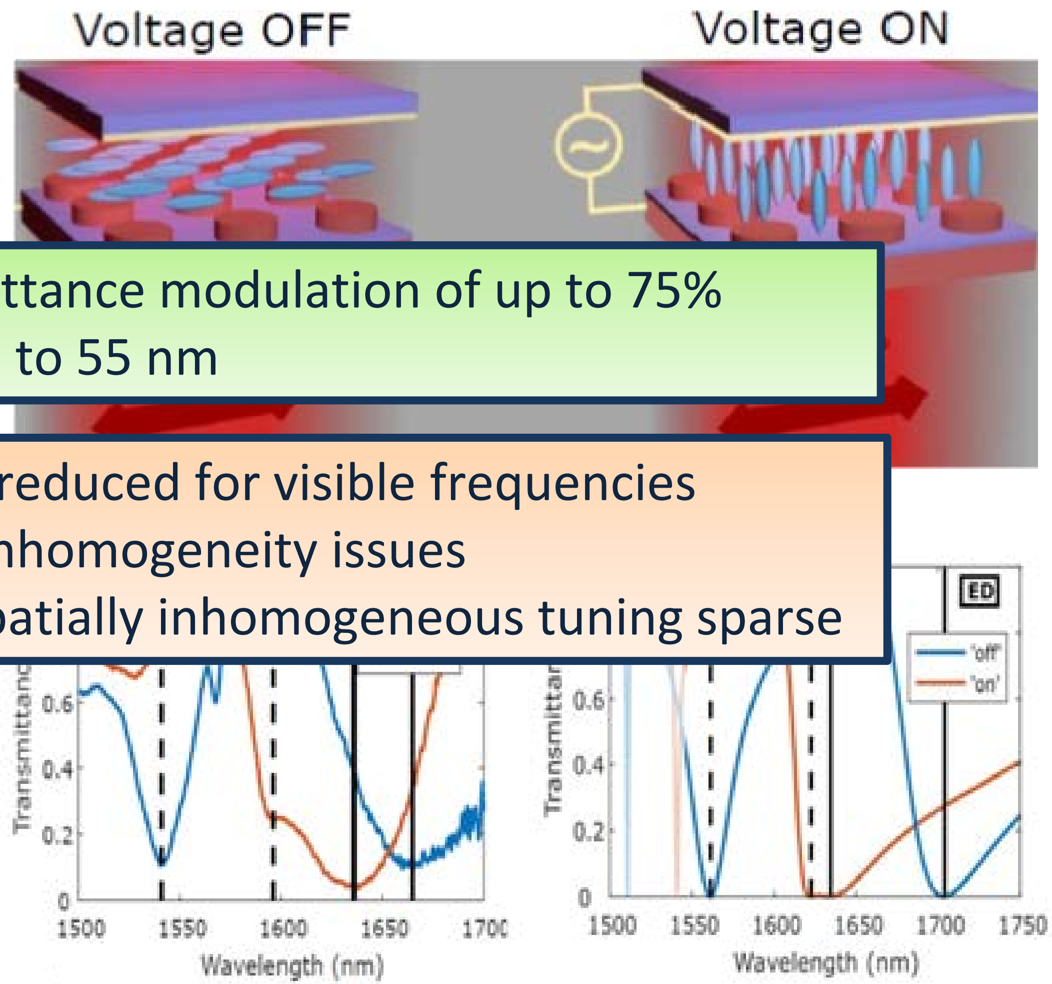
Li *et al.*, arXiv:1901.07742 (2019).

Liquid Crystal Dynamic Control

Temperature Tuning



Voltage Tuning



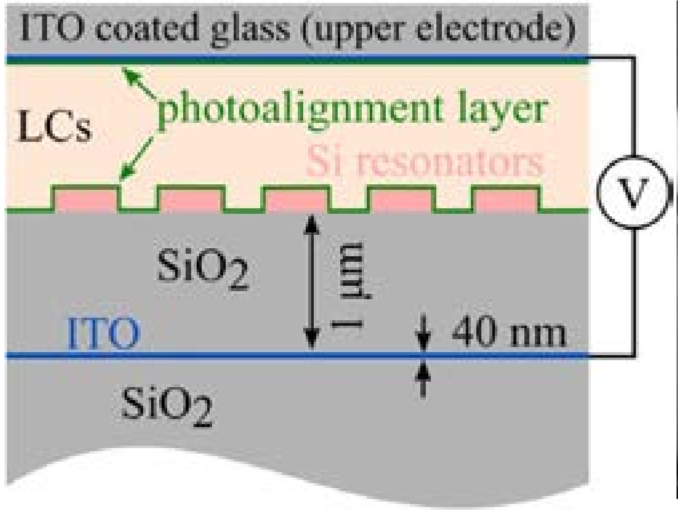
- Experimental transmittance modulation of up to 75%
- Resonance shift of up to 55 nm

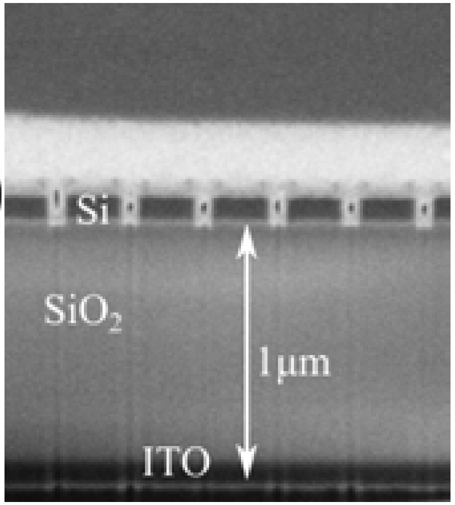
- Tuning performance reduced for visible frequencies
- Reproducibility and inhomogeneity issues
- Demonstrations of spatially inhomogeneous tuning sparse

J. Sautter *et al.*, *ACS Nano* **9**, 4308 (2015).

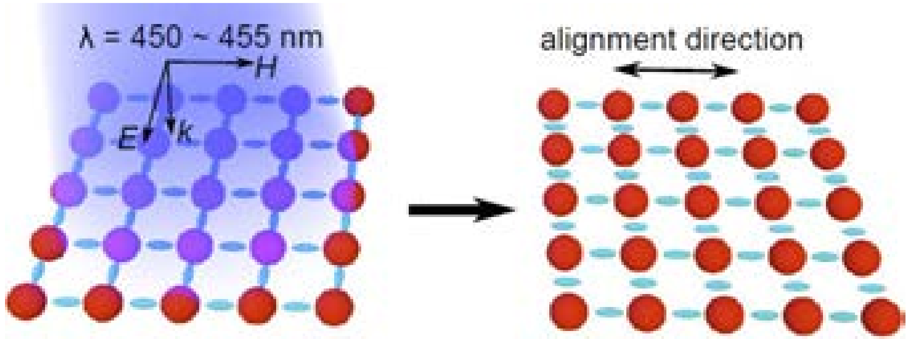
A. Komar *et al.*, *Appl. Phys. Lett.* **110**, 071109 (2017).

LC Cell Design & Assembly



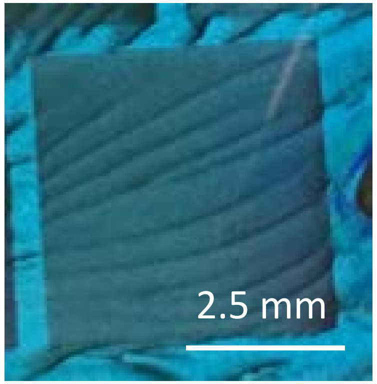


Alignment direction defined by illumination of AtA-2 with polarized light (450 ~455 nm)

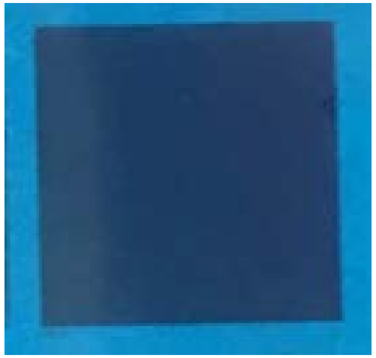


J. Appl. Spectrosc. **83** (1), 115-120, 2016; A. Muravsky, *Next generation of Photoalignment,* VDM Verlag, 2009

Observation through two parallel polarizers



One surface coated

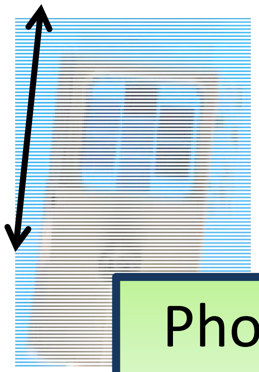


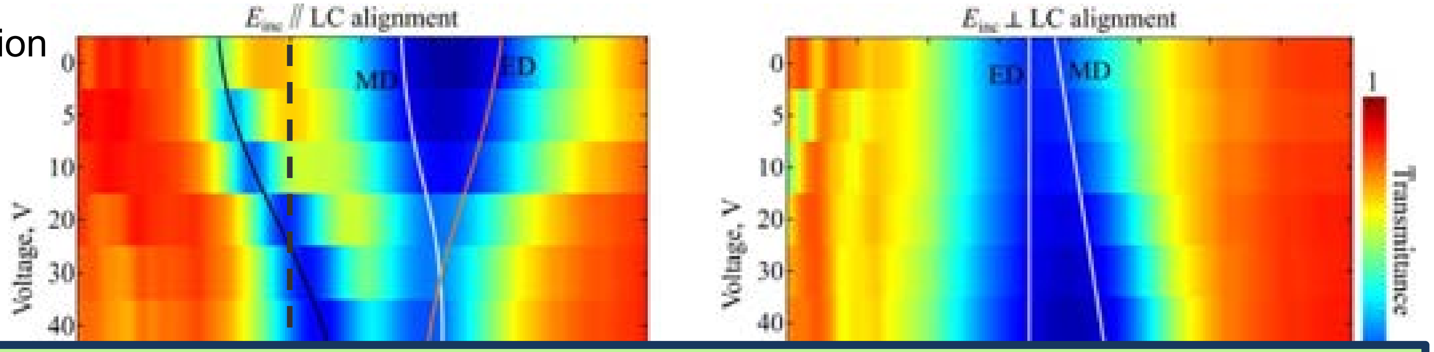
Both surfaces coated

C. Zou *et al.*, *ACS Photonics* **6**, 1533 (2019).

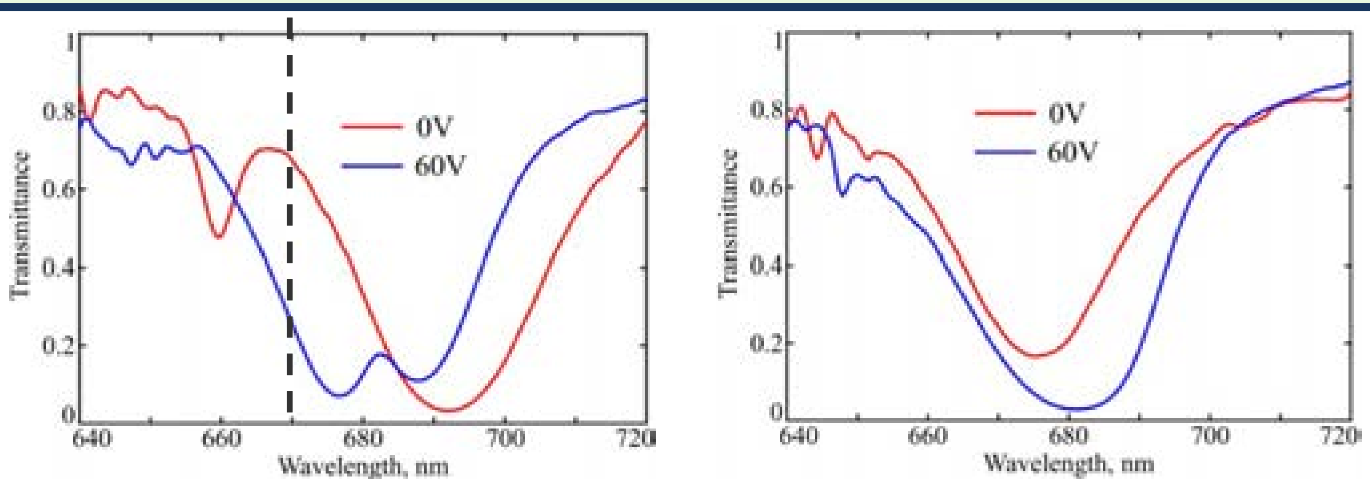
Measured Tuning Performance

LC alignment direction





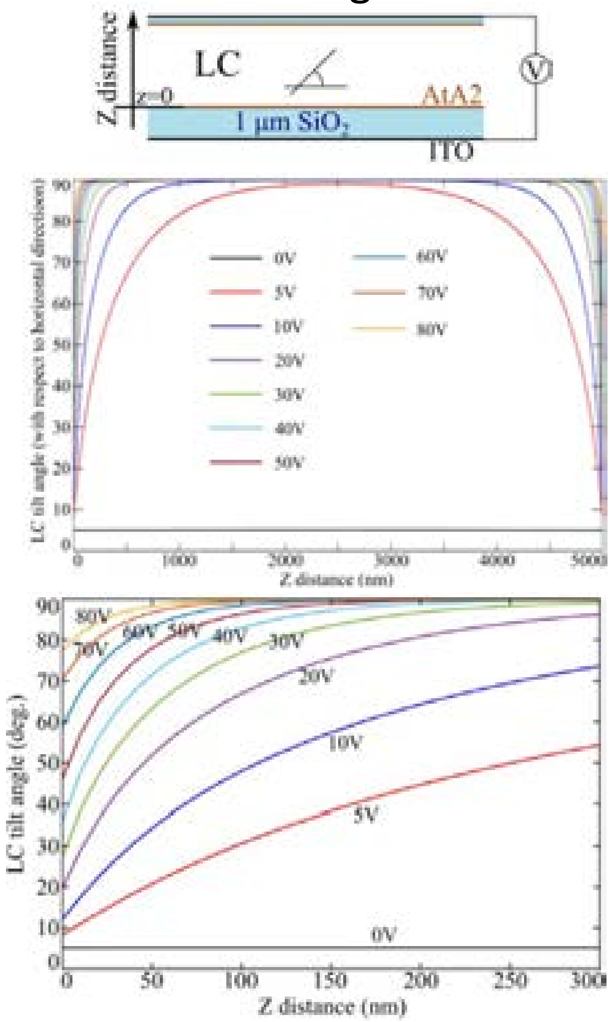
Photoalignment of LCs facilitates the tuning performance, LC alignment accuracy, and sample reproducibility.

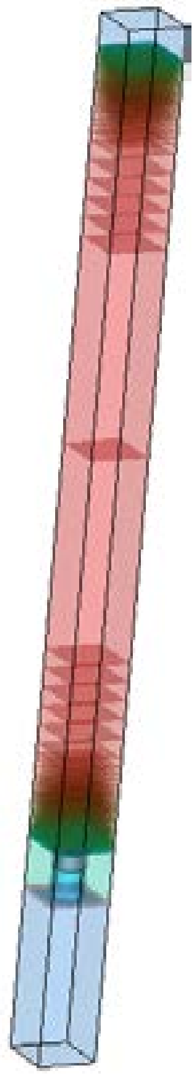


C. Zou *et al.*, *ACS Photonics* **6**, 1533 (2019).

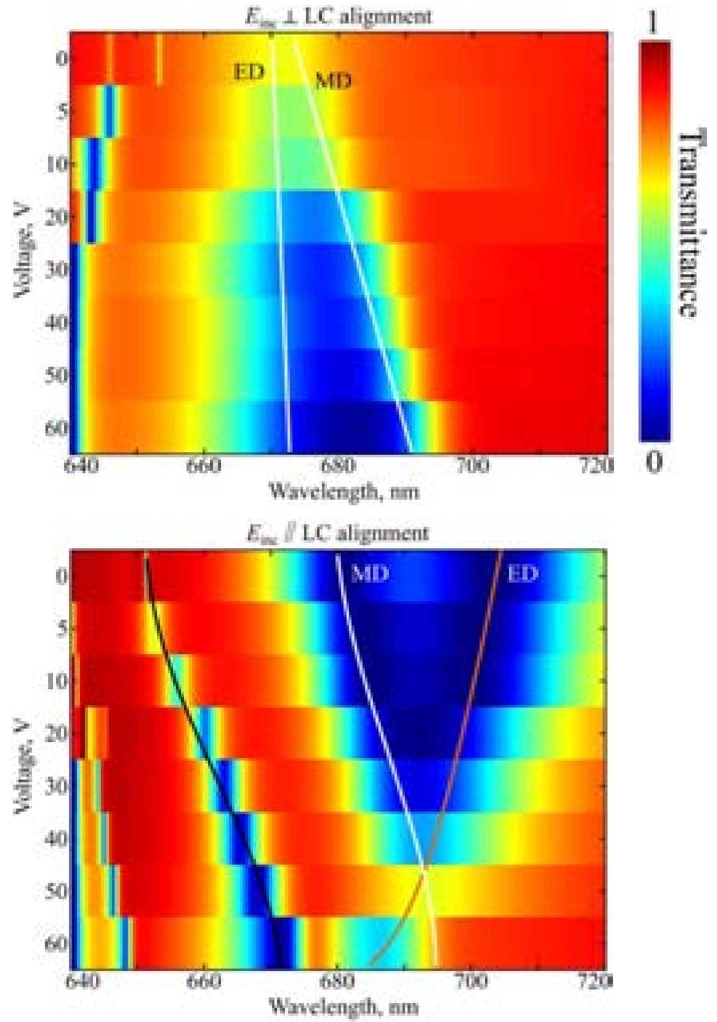
Numerical Simulations

Modelling of LCs



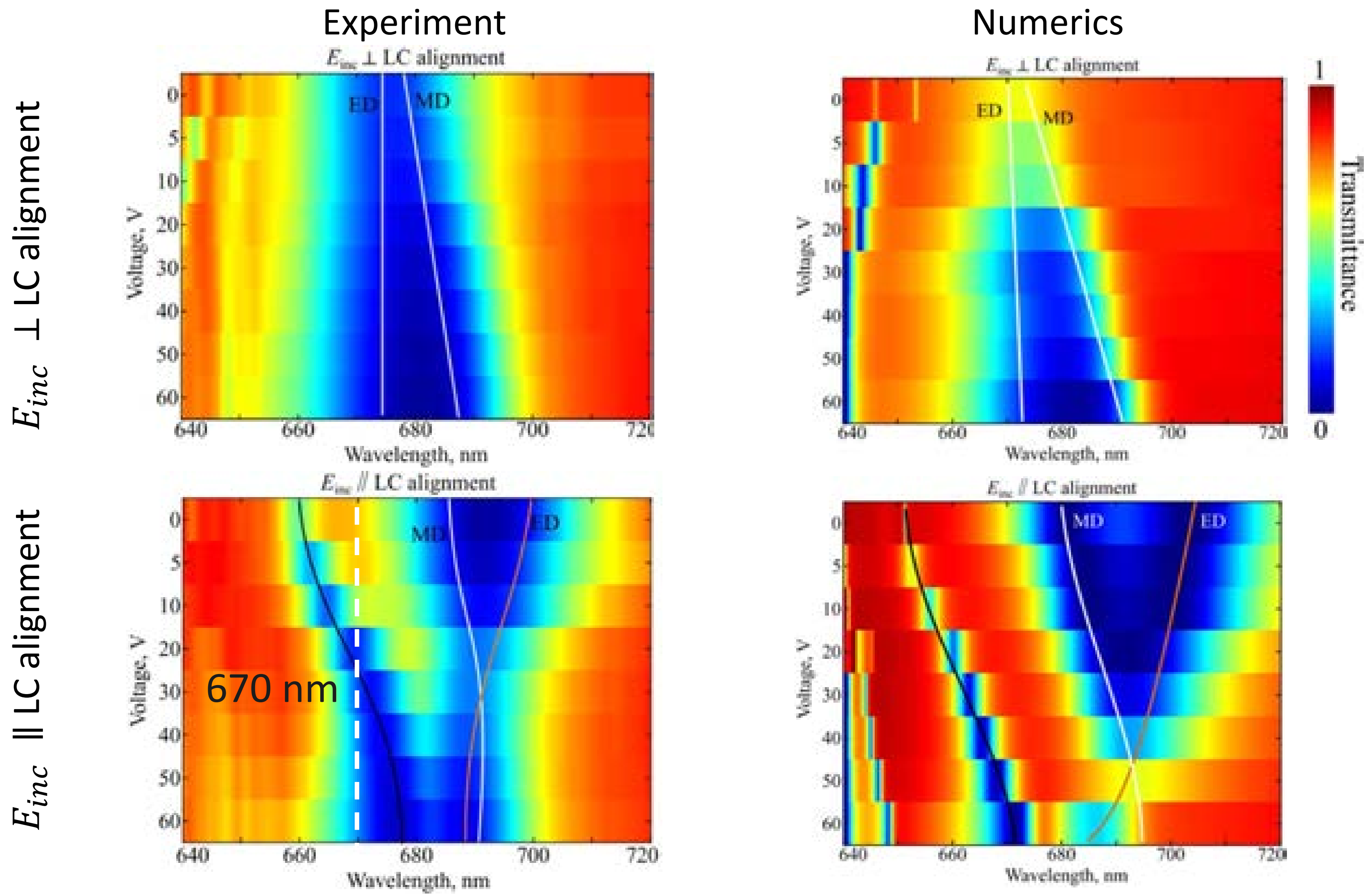


Metasurface with LCs



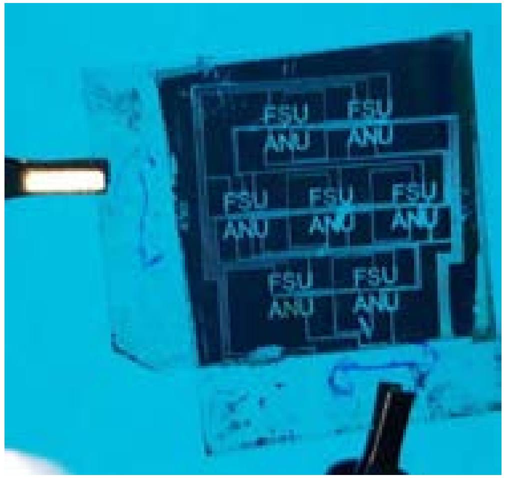
C. Zou *et al.*, *ACS Photonics* **6***,* 1533 (2019).

Comparison with Experiment

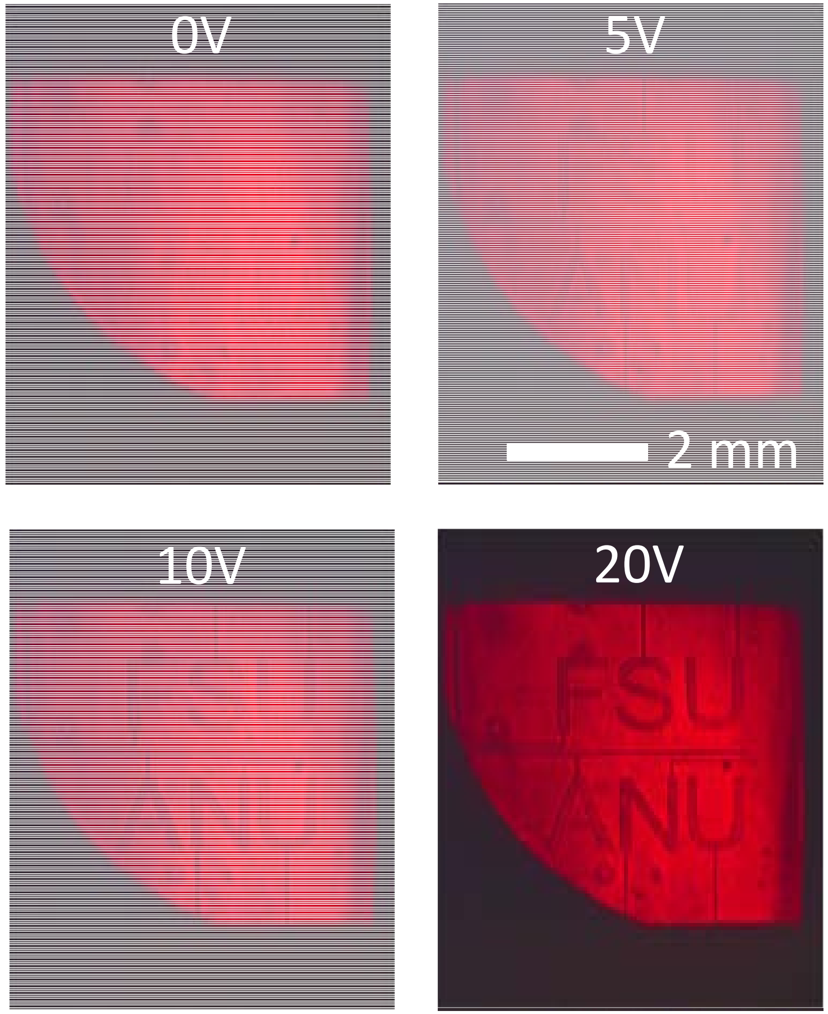


C. Zou *et al.*, *ACS Photonics* **6***,* 1533 (2019).

A Tunable Metasurface Display



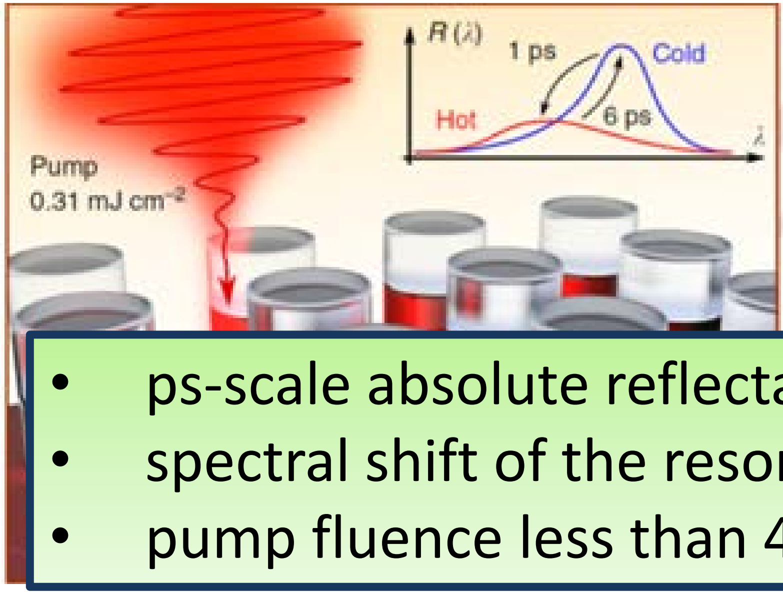
Images taken at 670 nm;
E_{inc} // LC alignment.

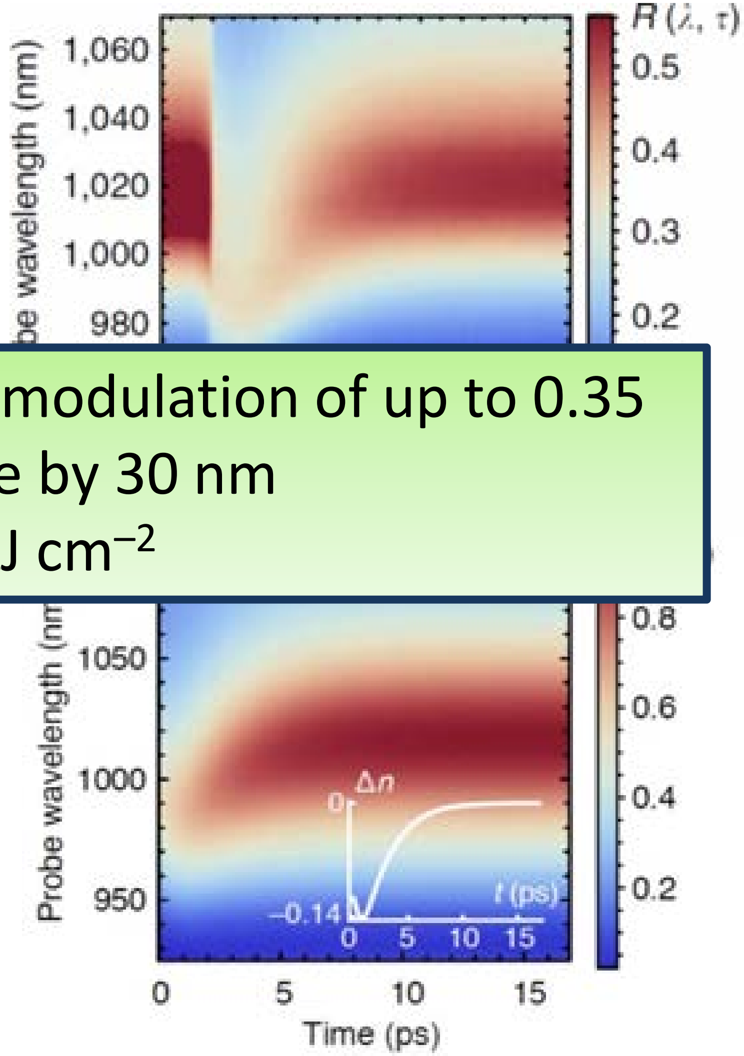


Electrically tunable dielectric metasurface display with ~51% modulation depth in the visible

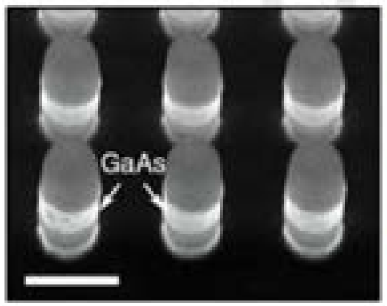
C. Zou *et al.*, *ACS Photonics* **6**, 1533 (2019).

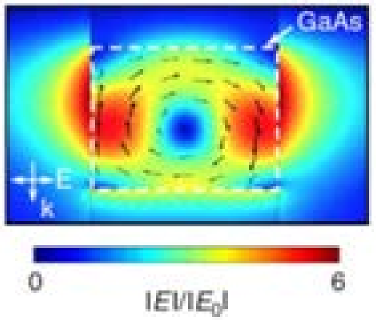
Ultrafast All-Optical Switching in GaAs MS





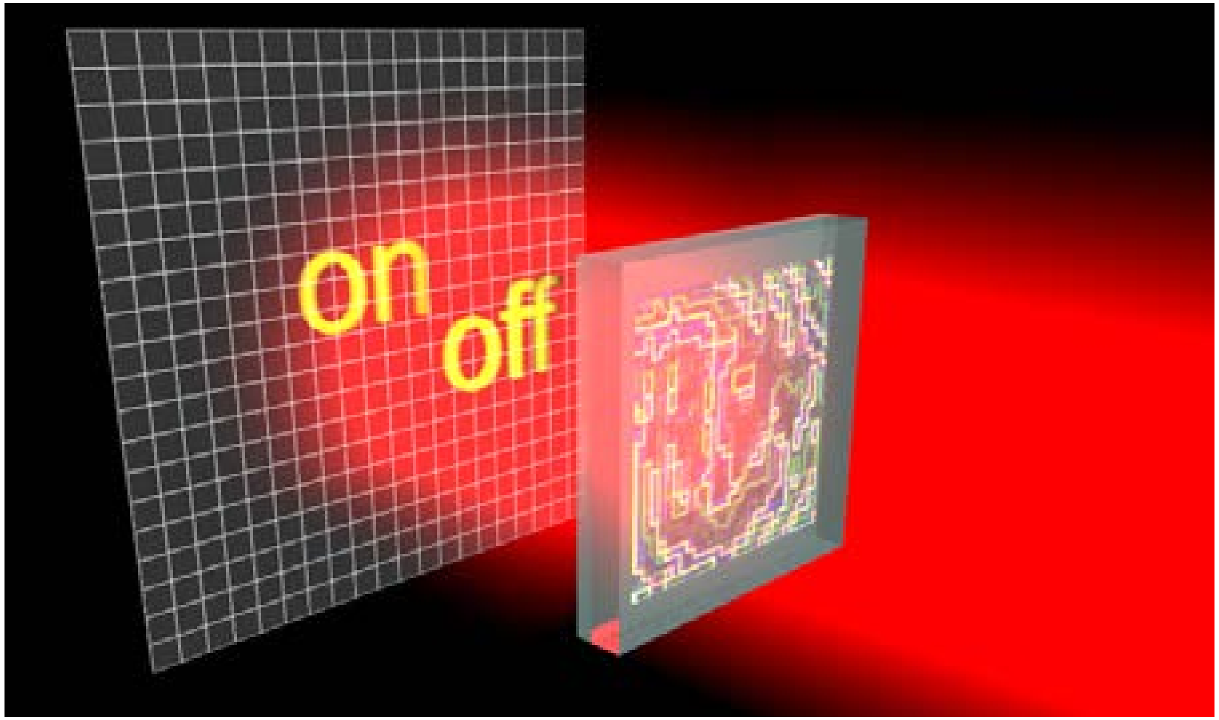
- ps-scale absolute reflectance modulation of up to 0.35
- spectral shift of the resonance by 30 nm
- pump fluence less than 400 μJ cm^{-2}





M. R. Shcherbakov et al., *Nature Commun.* **8**, 17 (2017).

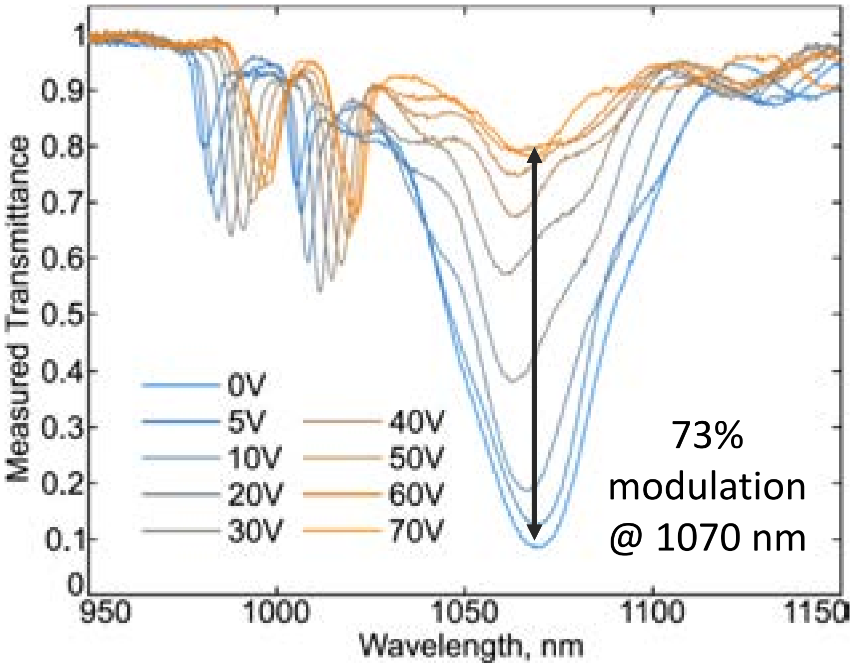
The Road Ahead



- Combine tuning, switching and nonlinear response with spatial phase control
  → nonlinear and (ultrafast) dynamic wavefront control

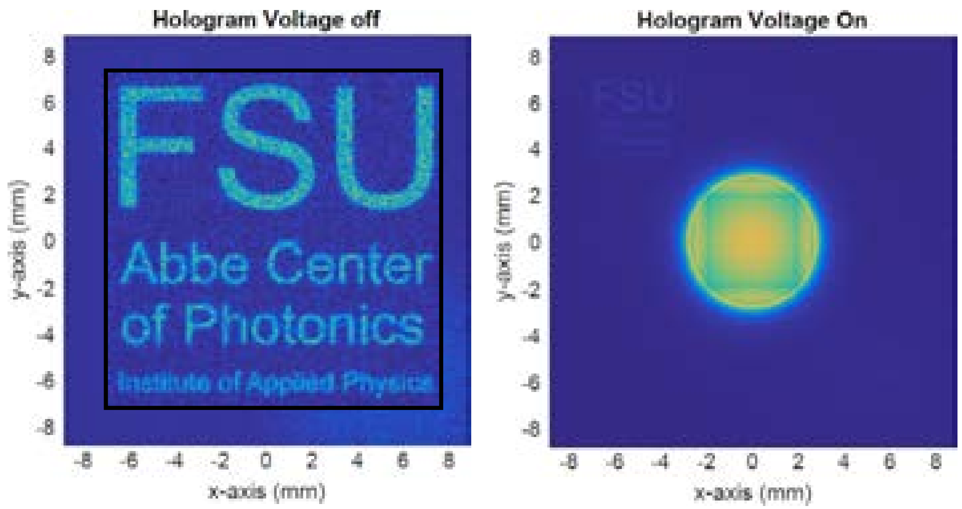
Tuning the Huygens' Regime in the NIR

Polarization ∥ LC alignment direction



1	0.7	0.08/0.81

9.8%	37.9%	52.1%



Metasurface transmission can be switched from almost transparent to almost opaque

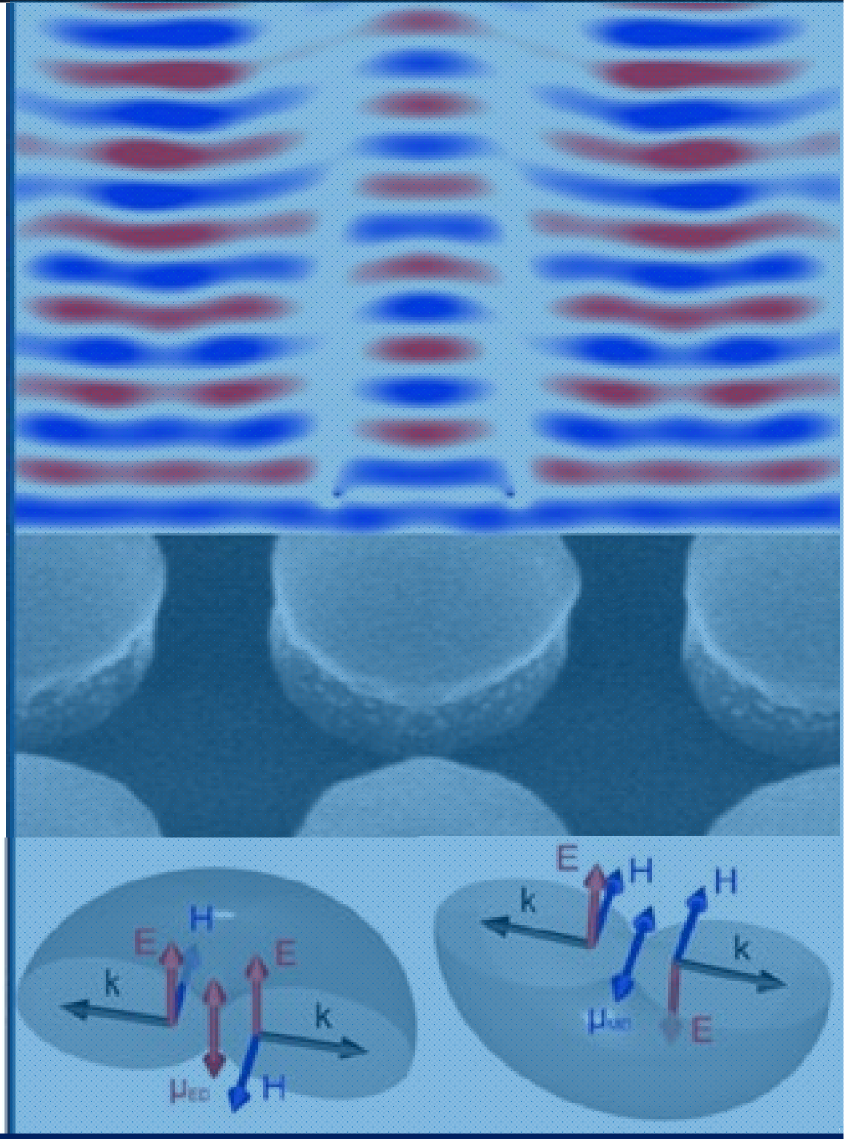
Hologram intensity ratio: $I_{off}/I_{on} = 8.6$.

C. Zou *et al.*, in preparation (2019).

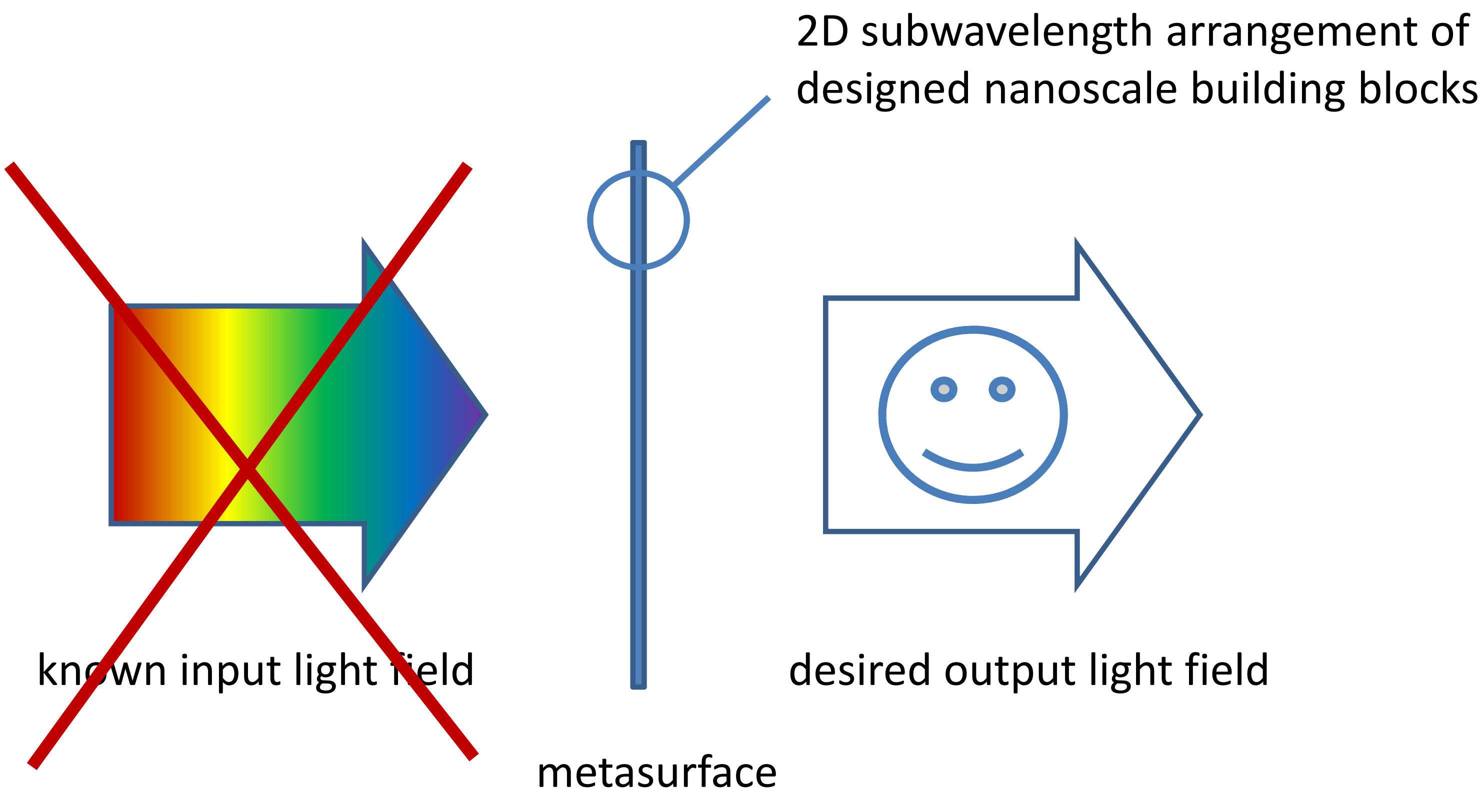
Outline

- Motivation
- Optical properties of high-index dielectric nanoparticles
- Dielectric Huygens' metasurfaces

- Highlight talk
  - Active control of dielectric metasurfaces
  - **Light emission from dielectric metasurfaces**



Light-Emitting Metasurfaces



Consider the metasurface an array of resonant dielectric nanoantennas driven by localized sources

Brightness Enhancement by MS

Abbe Center of Photonics | JENA
Friedrich-Schiller-Universität

Measured fluorescence count rate from a metasurface with a single emitter placed at the position $\boldsymbol{r}_{em}$ on it:

$$I(\boldsymbol{r}_{em}, \omega_{exc}, \omega_{em}) \propto \Gamma_{exc}(\boldsymbol{r}_{em}, \omega_{exc}) \cdot QY(\boldsymbol{r}_{em}, \omega_{em}) \cdot \eta_{ext}(\boldsymbol{r}_{em}, \omega_{em}) \cdot \eta_{coll}(\boldsymbol{r}_{em}, \omega_{em})$$

Excitation enhancement

Quantum yield enhancement

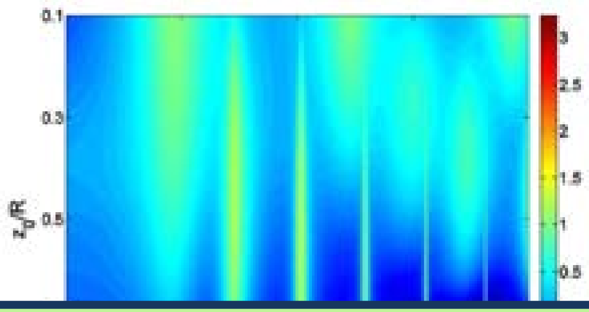
Extraction efficiency

Collection efficiency

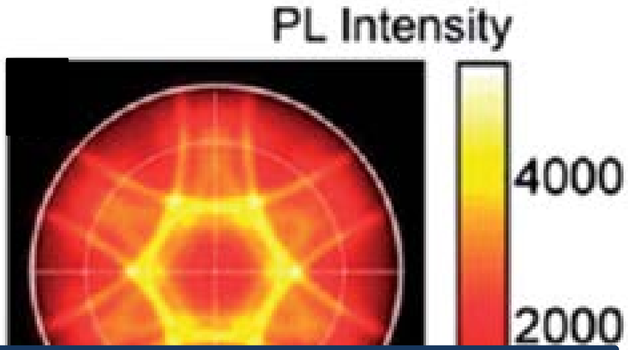
A. Vaskin, **R. Kolkowski, A. F. Koendrink,** and I. Staude, *Nanophotonics*, accepted (2019).

(Dielectric) Light-Emitting Metasurfaces

- Antenna effect from individual meta-atoms: emission enhancement, spectral and directional emission tailoring
  - Dielectric building blocks: moderate Purcell, high radiation efficiency
- Effect of the array/arrangement
- ➢ **Shaping emission patterns: form factor, structure/array factor, momentum distribution of the source**, previously studied in plasmonic metasurfaces (see example)



Purcell factor of an electric dipole emitter inside a silicon nanosphere

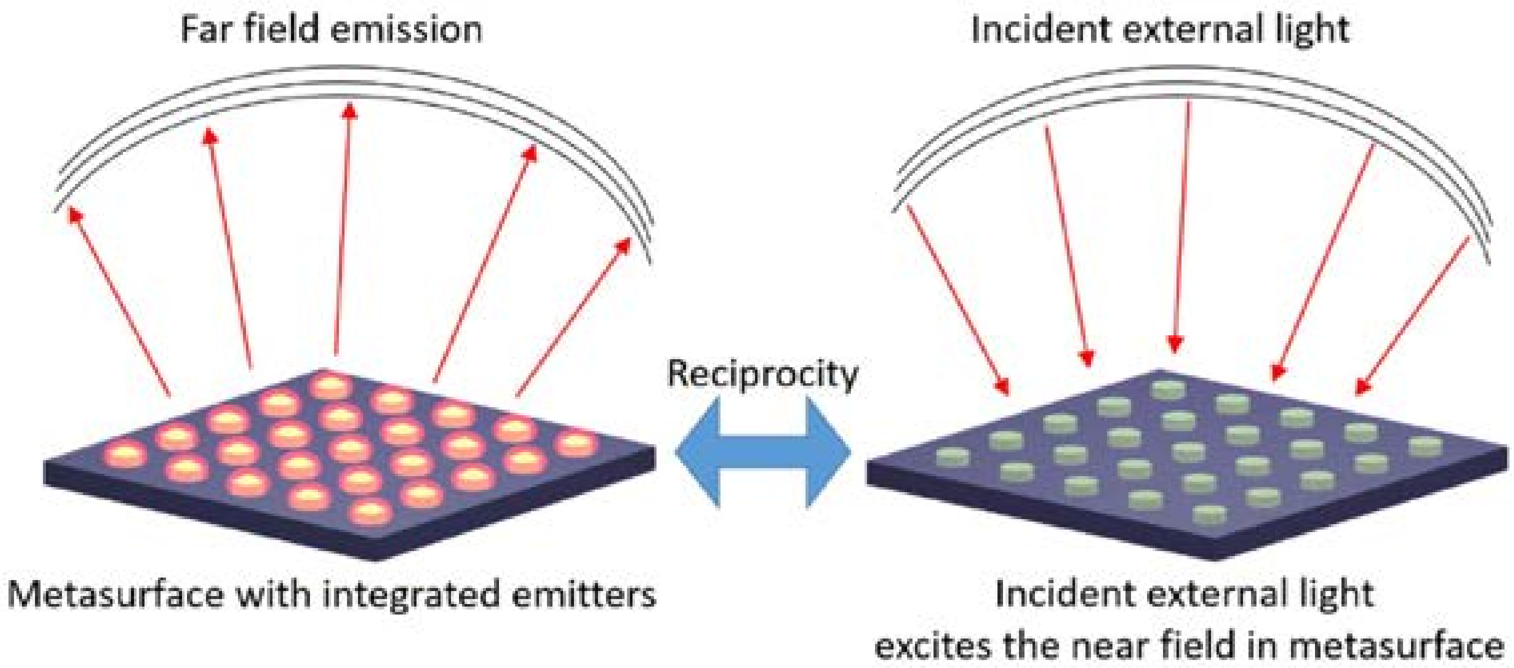


- Interesting platform for study of light-matter interactions
- Potential applications in smart lighting, new display and projector concepts, smart substrates etc.

Zambrana-Puyalto *et al.*, *PRB.* **91,** 195422 (2015). Lozano *et al.*, *Nanoscale* **6**, 9223 (2014).

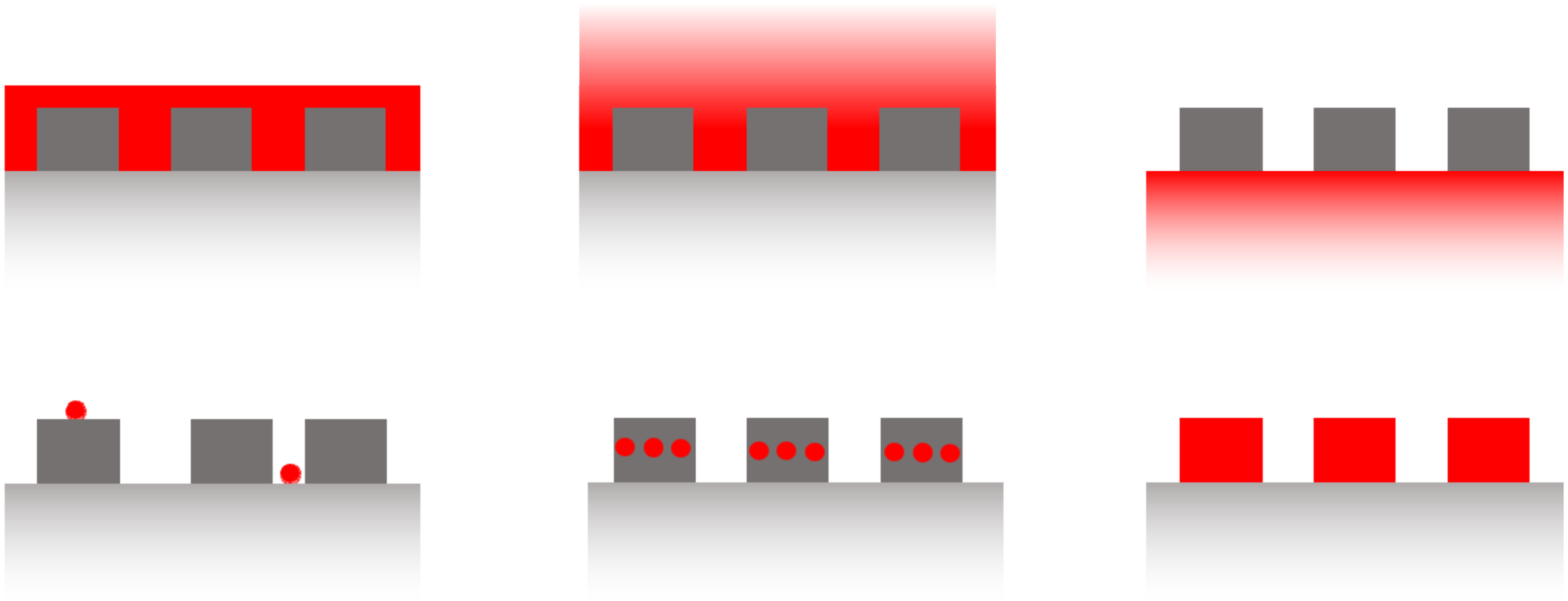
Far-Field Emission Calculations

- Popular methods: finite array simulations, inverse Floquet transformation
- Numerical calculation based on reciprocity principle:
  - Calculate angle-averaged (electric or magnetic) near-field enhancement inside active volume using e.g. the finite element method
  - Employ reciprocity principle $\boldsymbol{p}_2 \cdot \boldsymbol{E}_1(\boldsymbol{r}_2) = \boldsymbol{p}_1 \cdot \boldsymbol{E}_2(\boldsymbol{r}_1)$



A. Vaskin, R. Kolkowski, A. F. Koendrink, and I. Staude, *Nanophotonics*, accepted (2019).

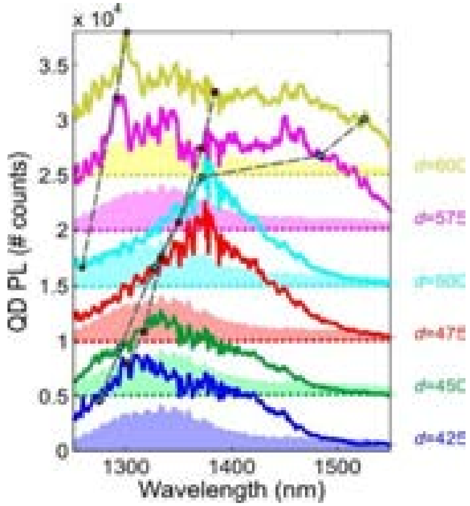
Integration Strategies for Emitters

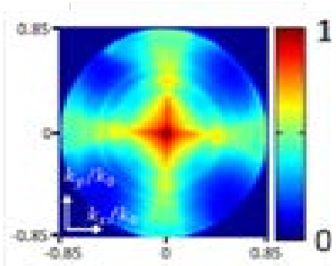


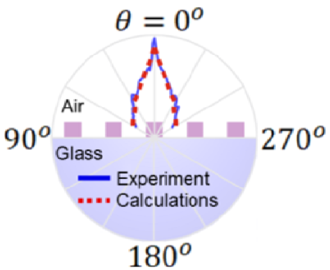
A. Vaskin, R. Kolkowski, A. F. Koendrink, and I. Staude, *Nanophotonics*, accepted (2019).

Light Emission from Dielectric Metasurfaces

Spectral & spatial shaping

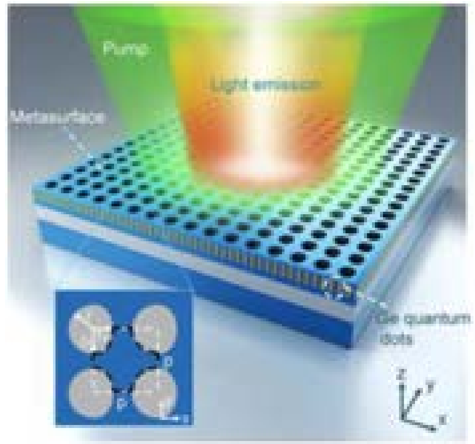


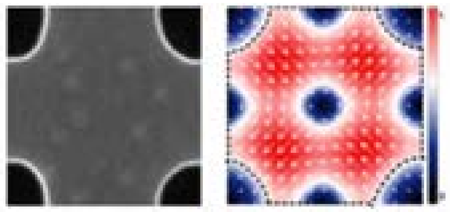


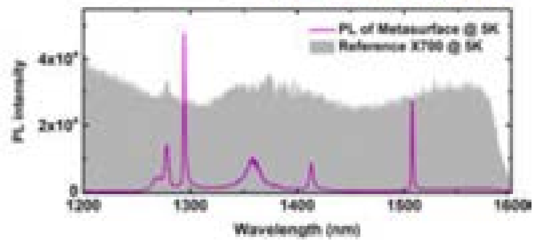


I. Staude *et al.*, *ACS Photonics* **2**, 172 (2015),
A. Vaskin *et al.*, *ACS Photonics* **5**, 1359 (2018).

Emission enhancement

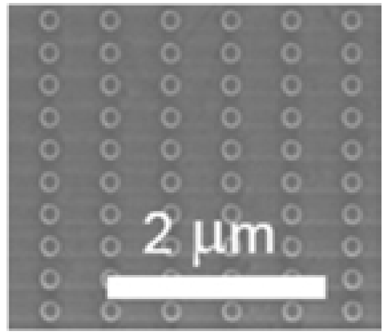


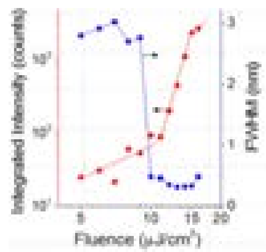


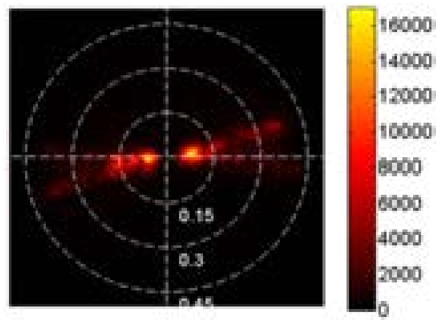


S. Yuan *et al.*, *ACS Nano* **11** 10704-10711 (2017).

Lasing

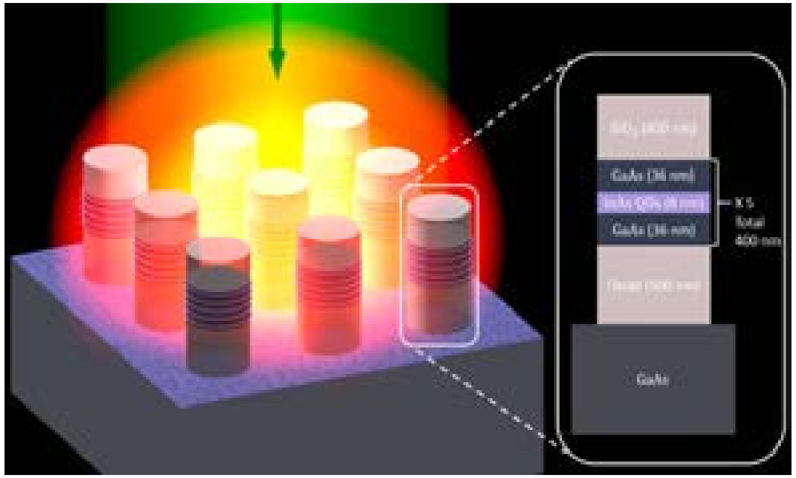






S. T. Ha *et al.*, *Nat. Nanotech*. **13**, 1042 (2018).

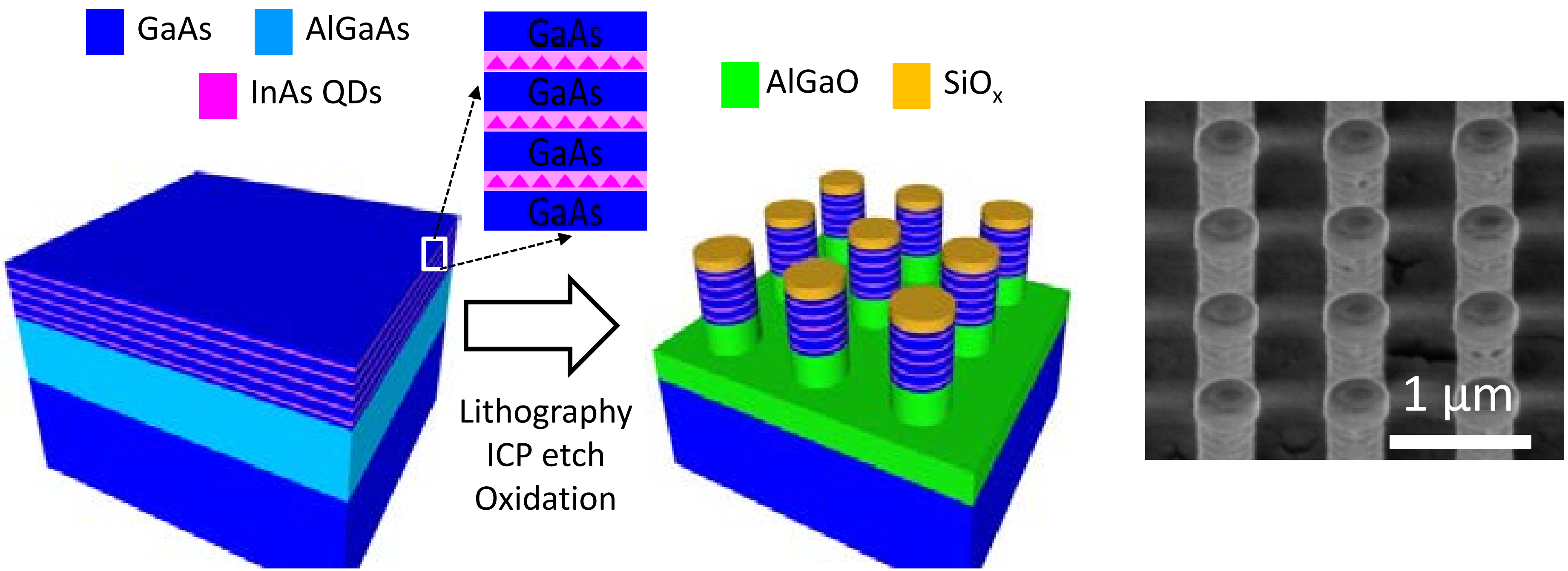
2 Examples of Light-Emitting MS



Monolithic III-V semiconductor metasurfaces incorporating QDs

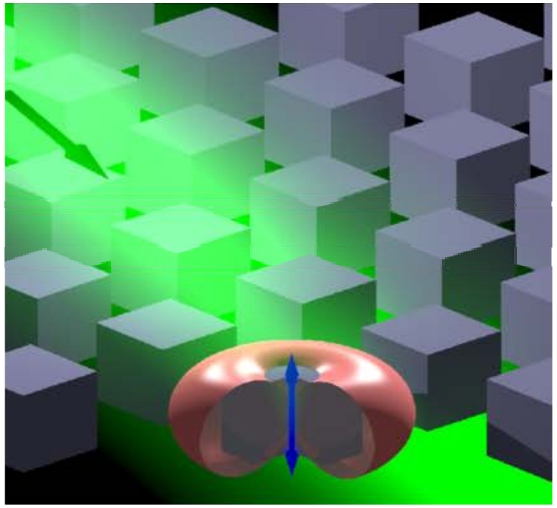
S. Liu *et al.*, *Nano Lett.* **18**, 6906–6914 (2018).

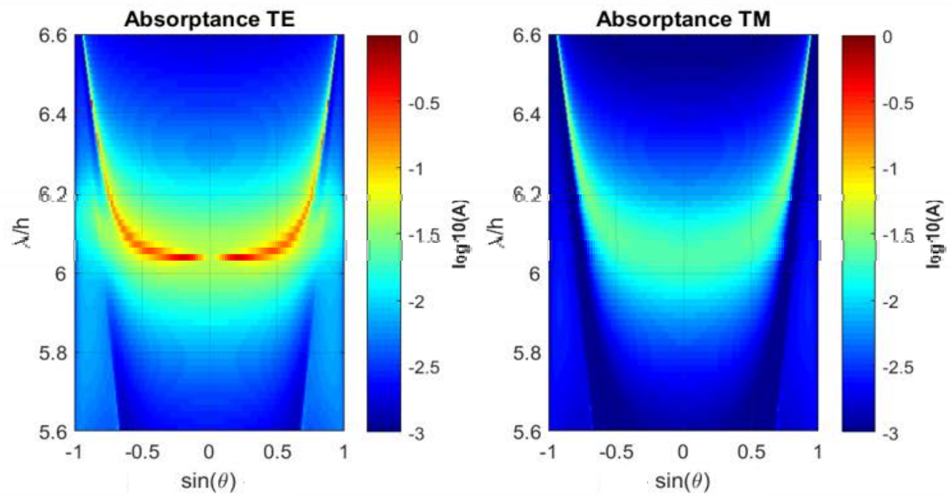
Integration of QDs into Metasurfaces

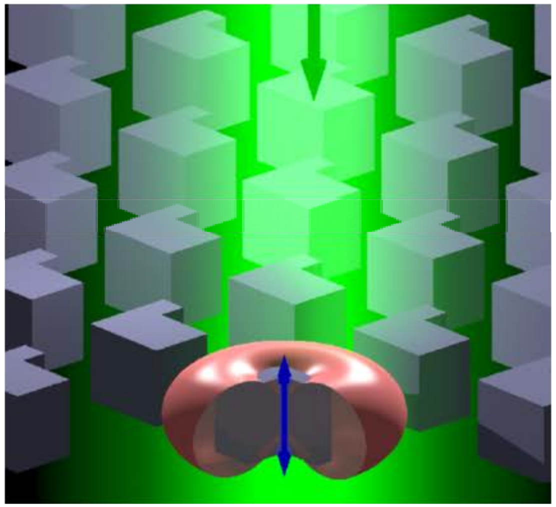


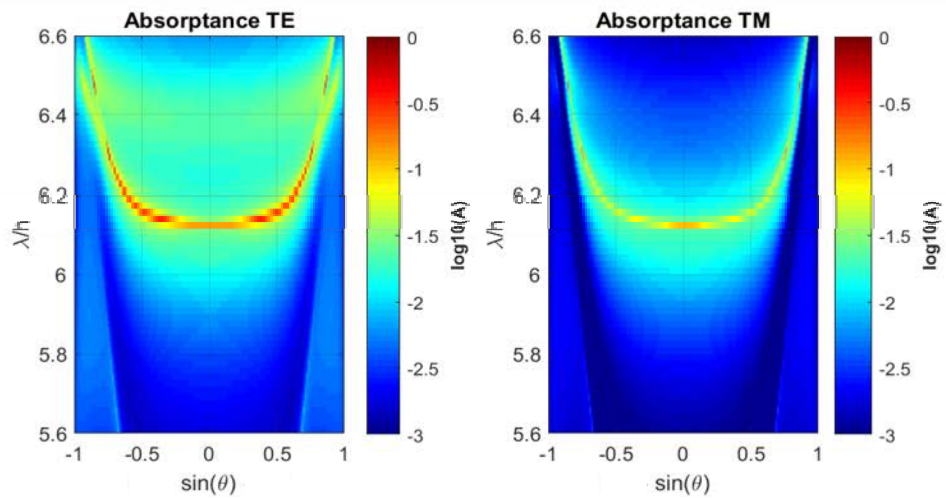
S. Liu *et al.*, *Nano Lett.* **18**, 6906–6914 (2018).

The Role of Symmetry for Emission



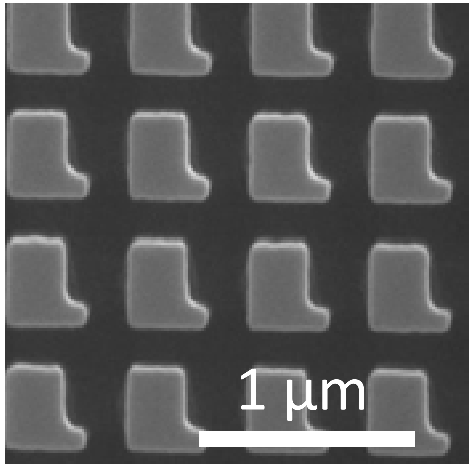


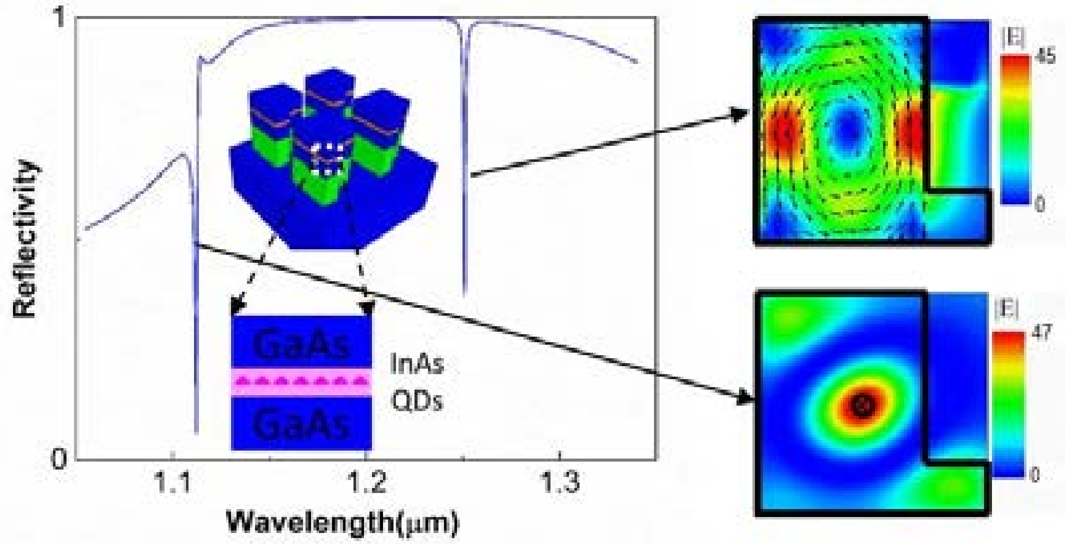


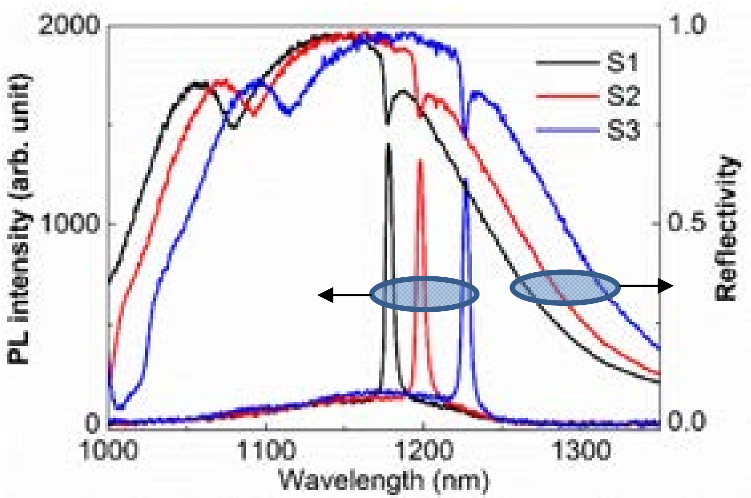


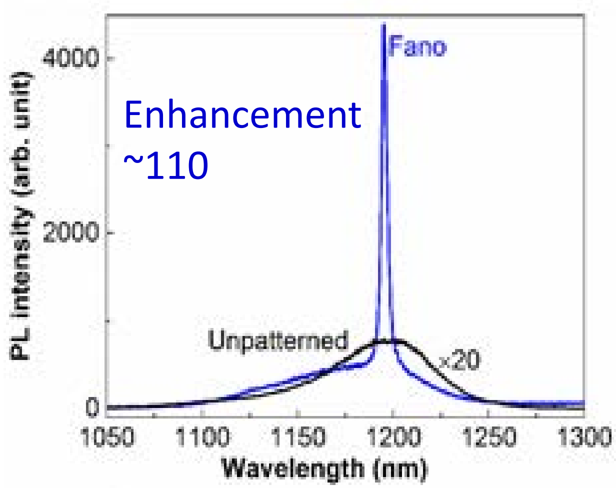
S. Liu *et al.*, *Nano Lett.* **18**, 6906–6914 (2018).

Asymmetric MS: PL Spectra





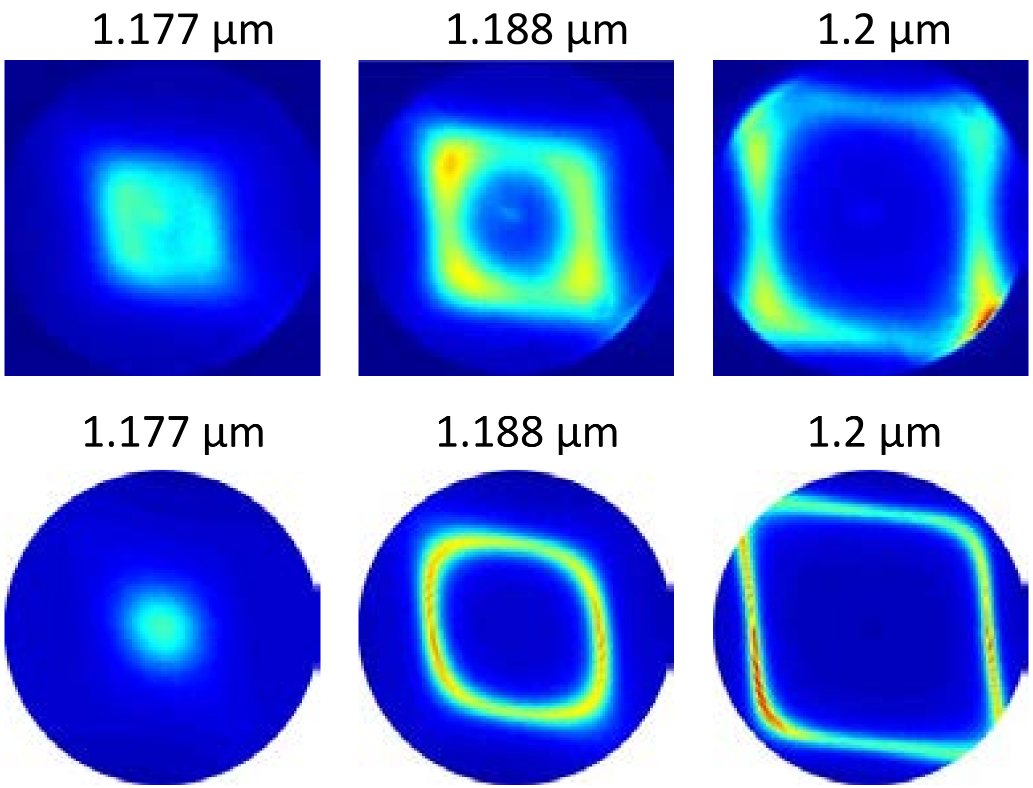


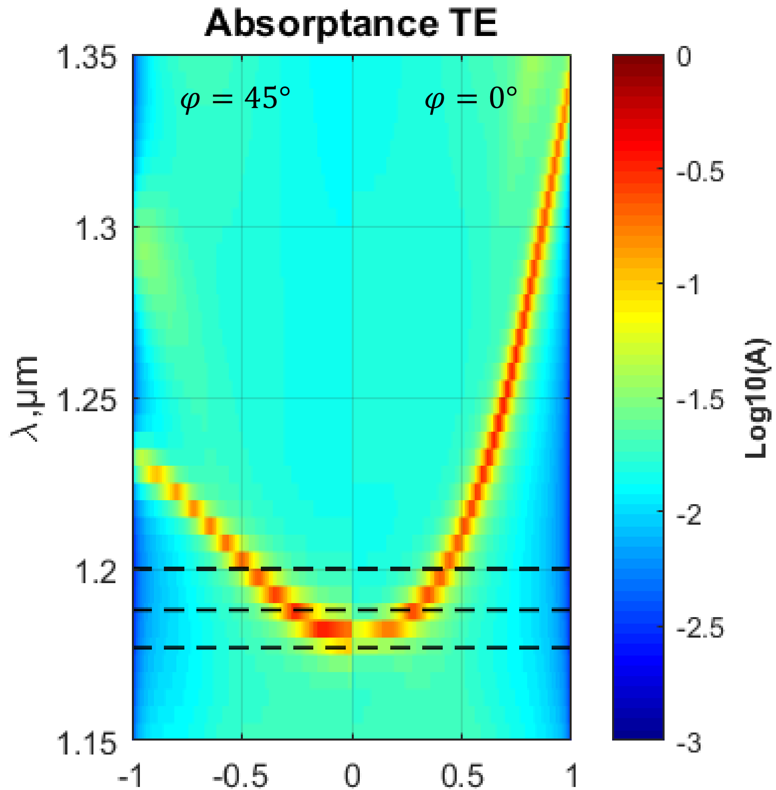


S. Liu *et al.*, *Nano Lett.* **18**, 6906–6914 (2018).

Asymmetric MS: Emission Pattern

NA = 0.65

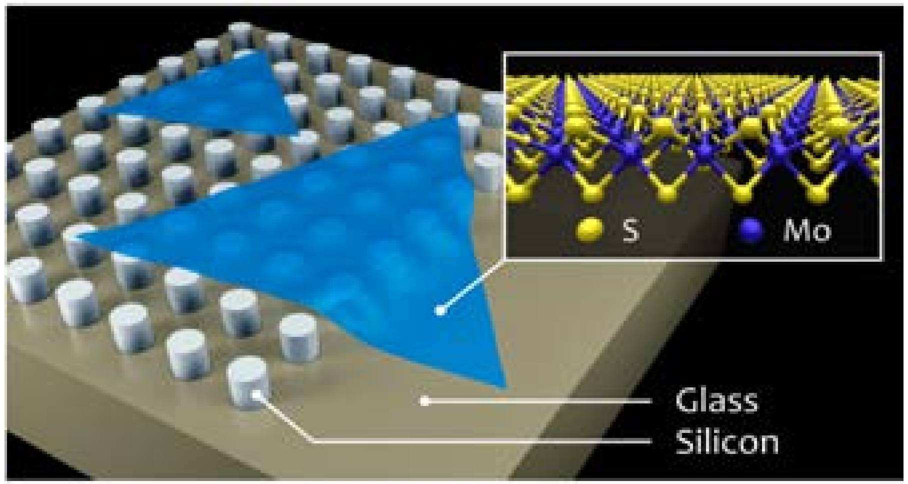




Spectral and directional shaping demonstrated for a metasurface based on active III-V semiconductor platform

S. Liu *et al.*, *Nano Lett.* **18**, 6906–6914 (2018).

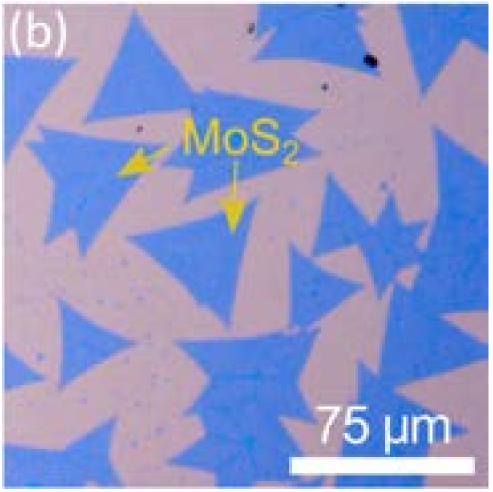
2 Examples of Light-Emitting MS



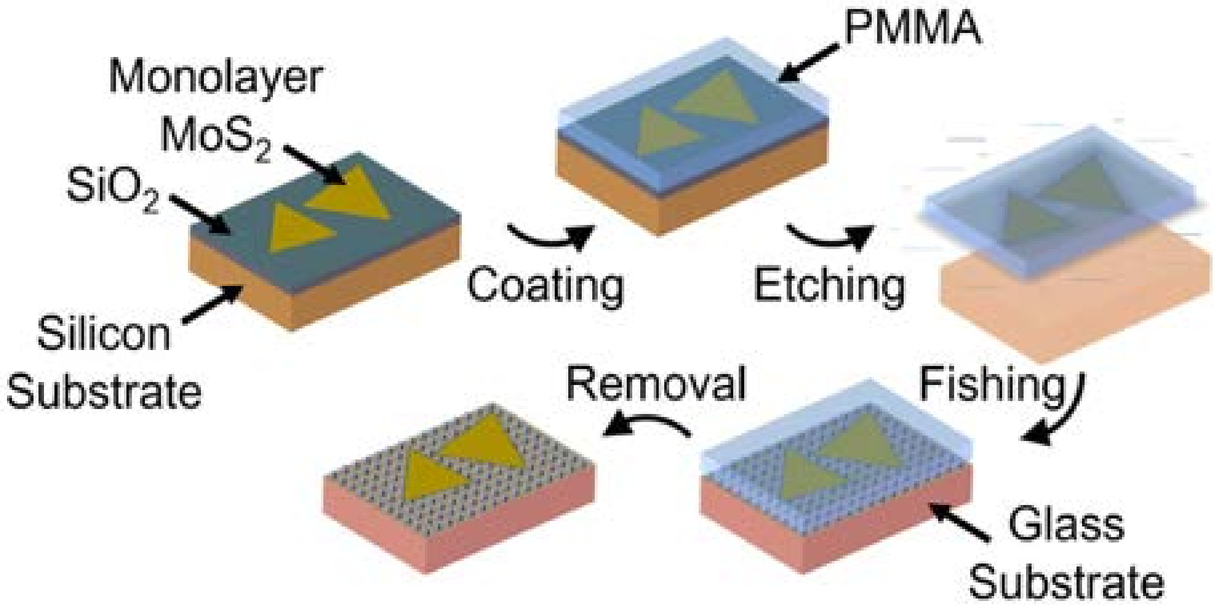
Silicon metasurfaces hybridized with two-dimensional semiconductors

T. Bucher *et al., ACS Photonics* **6**, 1002-1009 (2019).

Fabrication of Hybrid Structures

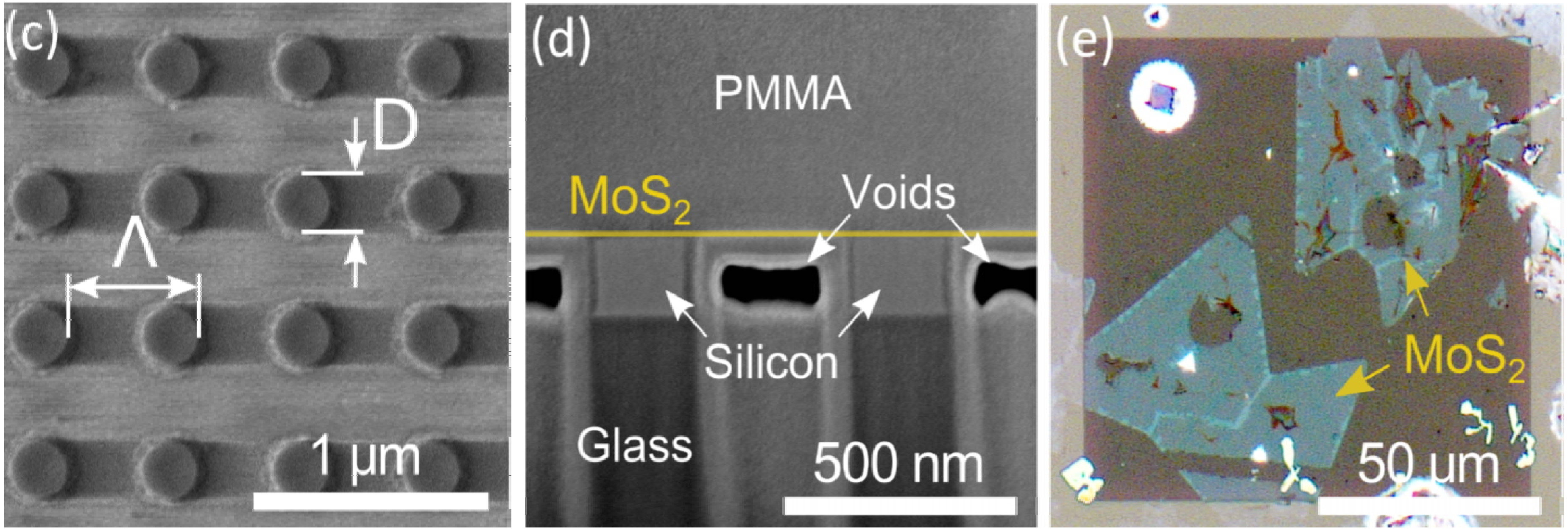


MoS_2 monolayers as-grown by CVD



T. Bucher *et al., ACS Photonics* **6**, 1002-1009 (2019).

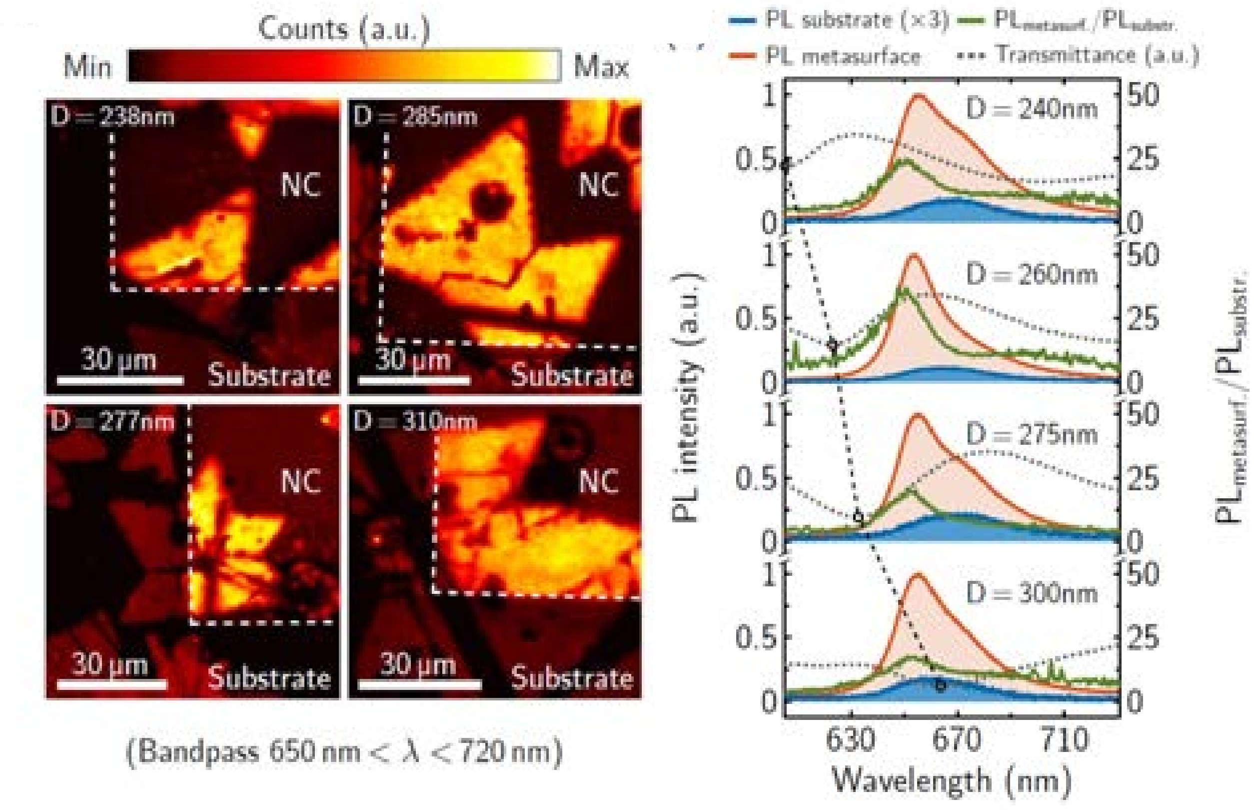
Fabricated Hybrid Structures



Fabrication of a series of metasurfaces with a variation of the nanocylinder diameter D

T. Bucher *et al., ACS Photonics* **6**, 1002-1009 (2019).

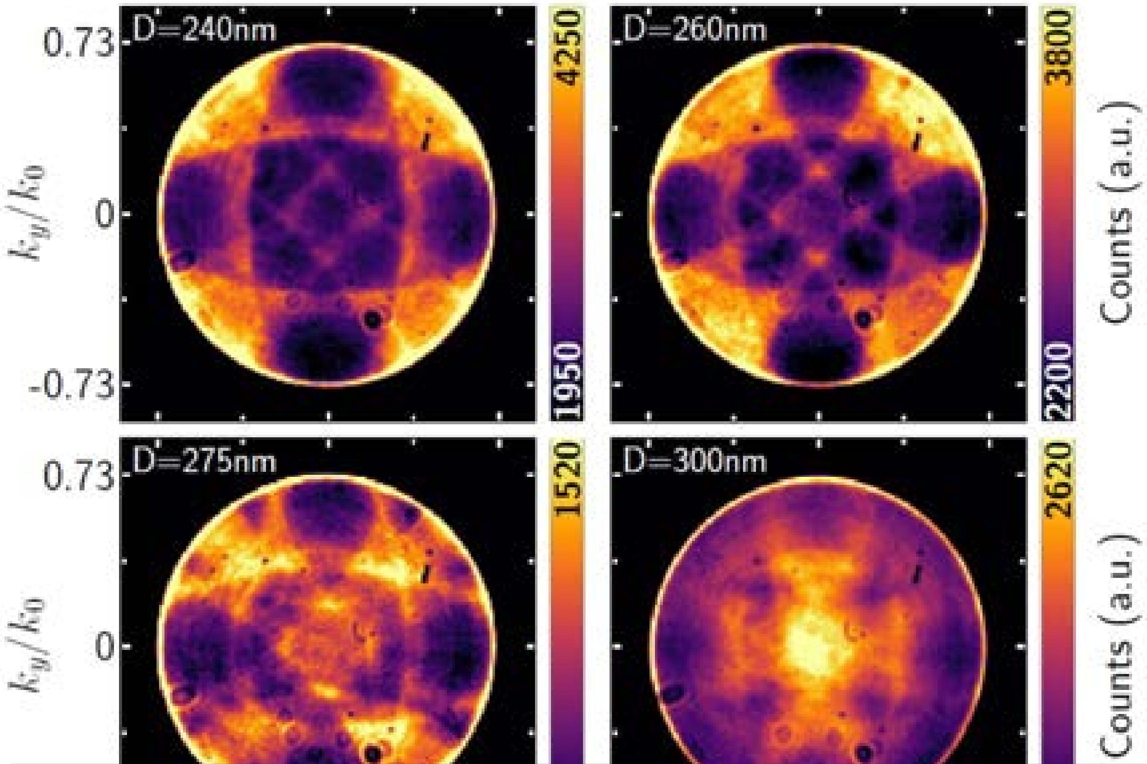
Photoluminescence of Hybrid Structures



- Confocal PL microscopy (NA 0.65), reflection configuration
- 532nm pulsed laser excitation
- Effect of the metasurface:
  - PL enhancement by a factor of 5-8
  - Spectral broadening
  - Blue shift of the emission maximum
- But: no strong dependence on diameter → negligible photonic effect

T. Bucher *et al., ACS Photonics* **6**, 1002-1009 (2019).

Back-Focal Plane Imaging of Emission

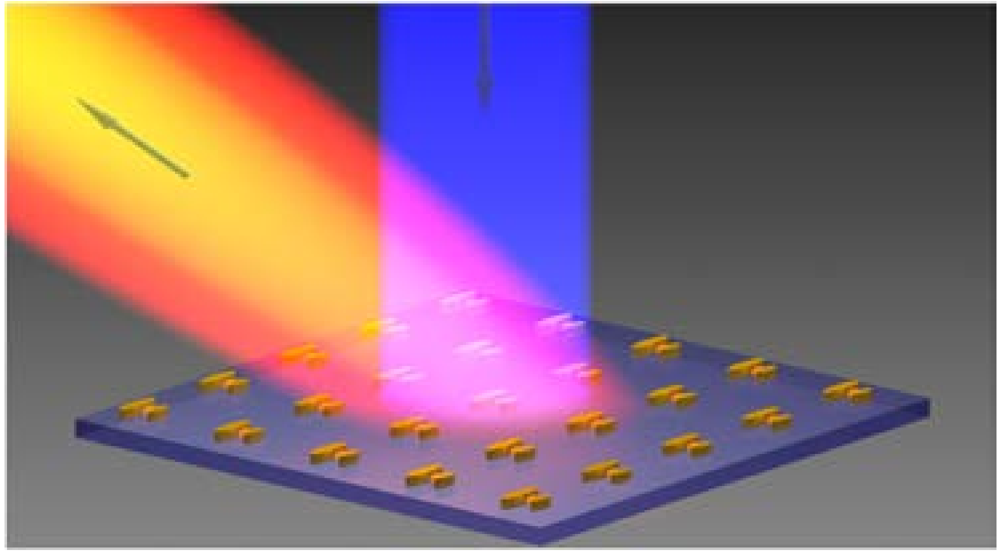


- Coupling to metasurface induces a reshaping of the emission pattern
- The more resonant the structure, the more directional the emission becomes

- Tailoring 2D-TMDC emission properties by engineering the combined photonic, electronic and topographic environment
- Care must be taken when interpreting PL enhancement effects

T. Bucher *et al., ACS Photonics* **6**, 1002-1009 (2019).

The Road Ahead



- Enhance complexity of spatial emission patterns
- Dynamic control of the emission pattern
- Explore different implementations
- Electrical driving schemes?
- Exploit valley-dependent directional coupling

Image: A. Vaskin, R. Kolkowski, A. F. Koendrink, and I. Staude, Nanophotonics, accepted (2019).

Recent Review Articles

M. Decker and I. Staude, *J. Opt.* **18**, 103001 (2016).
I. Staude und J. Schilling, *Nature Photon.* **11**, 274–284 (2017).
A. Vaskin, R. Kolkowski, A. F. Koenderink, and I. Staude, “Light-Emitting Metasurfaces“, *Nanophotonics*, accepted (2019).
C. Zou, J. Sautter, F. Setzpfandt, and I. Staude, „Resonant Dielectric Metasurfaces – Active Tuning and Nonlinear Effects”, *J. Phys. D: Appl. Phys*. accepted (2019).

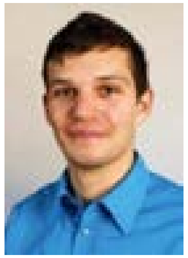
Current Team & Funding

Abbe Center of Photonics | JENA
Friedrich-Schiller-Universität


Rajeshkumar Mupparapu


Chengjun Zou


Aleksandr Vaskin


Dennis Arslan


Tobias Bucher


Jürgen Sautter


Anna Fedotova


Denizhan Sirmaci


Wenjia Zhou


Katsuya Tanaka


Cristina Amaya


Saif Alnairat

DFG Deutsche Forschungsgemeinschaft

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DAAD

Die Junge Akademie

Thank you for your attention!