Tailoring optical absorption via metasurfaces

Fundamentals of Plasmonics and Metaphotonics IV, Fall MRS 2022

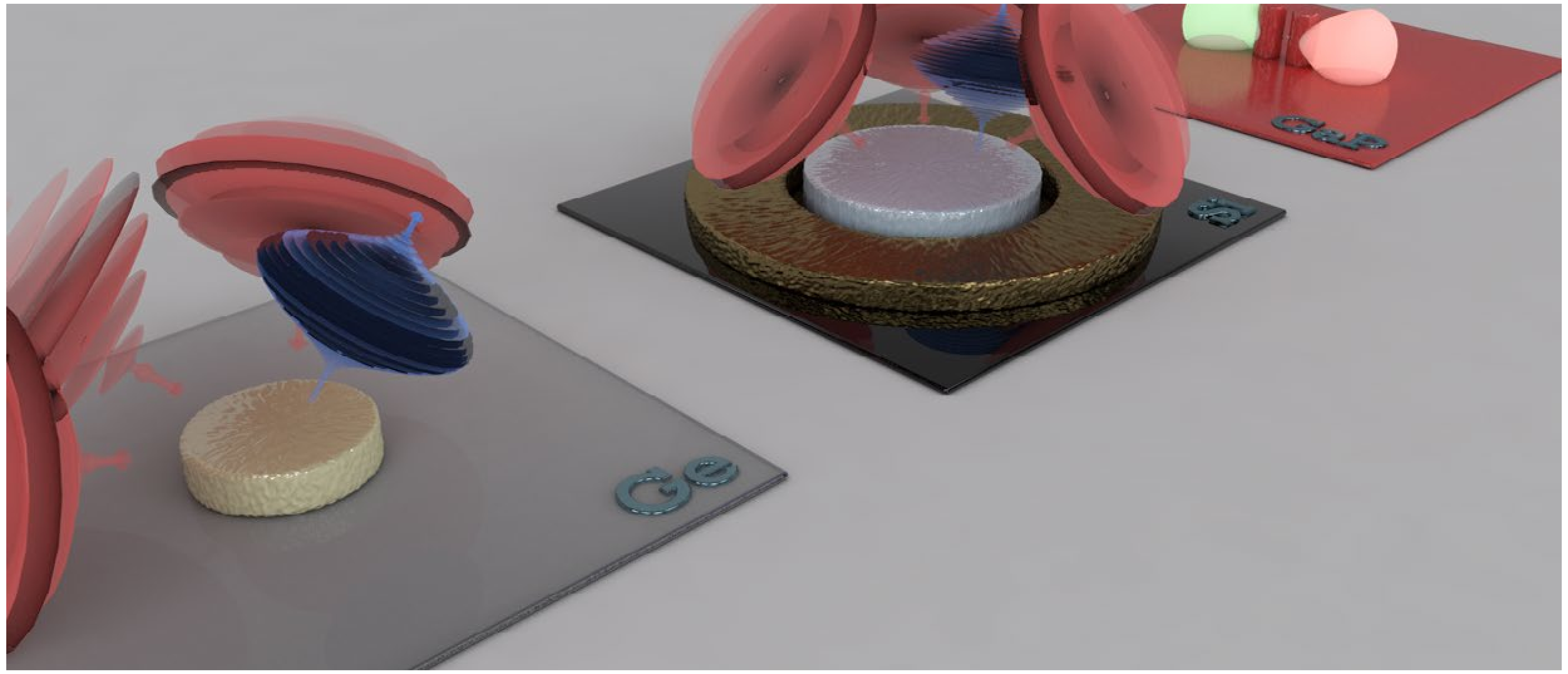
Stefan A Maier

School of Physics and Astronomy, Monash University, Melbourne, Victoria

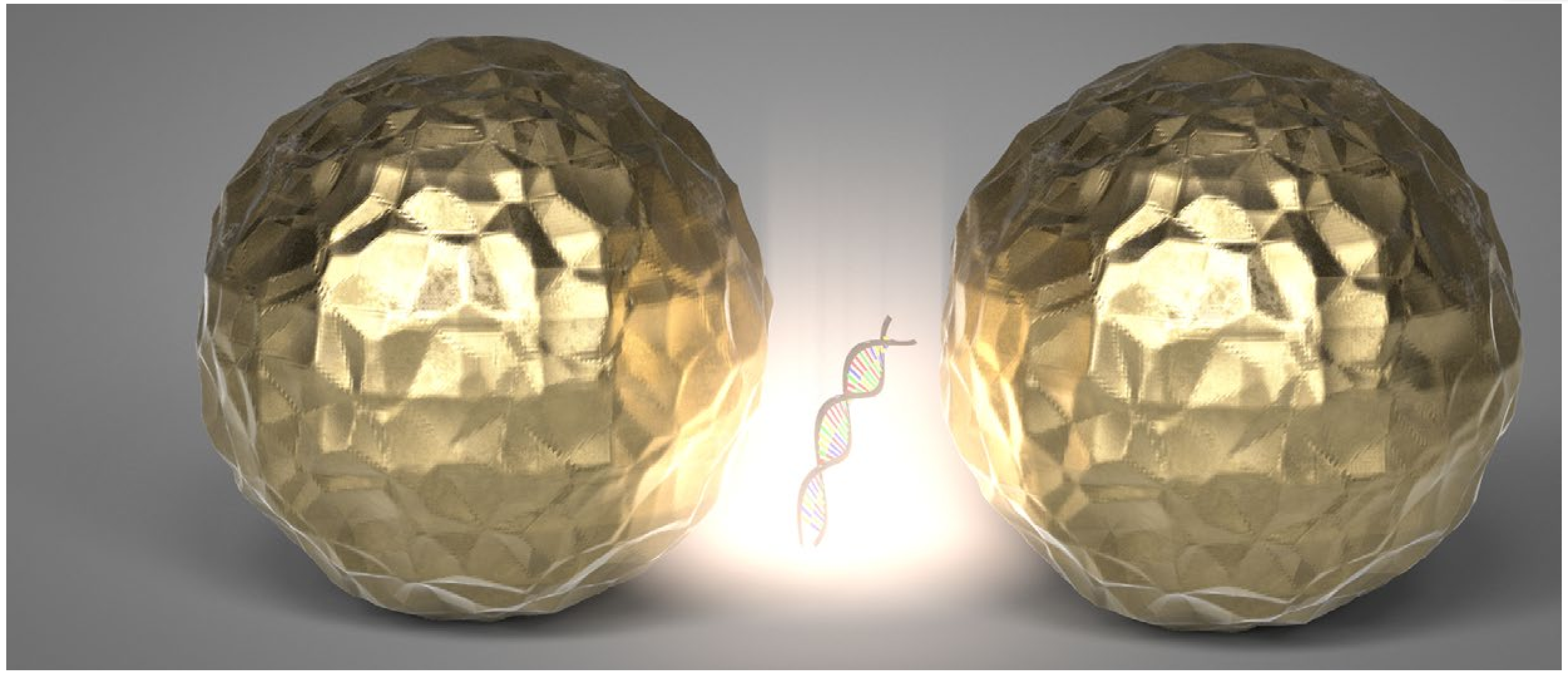
Lee-Lucas Chair in Experimental Physics, Imperial College London

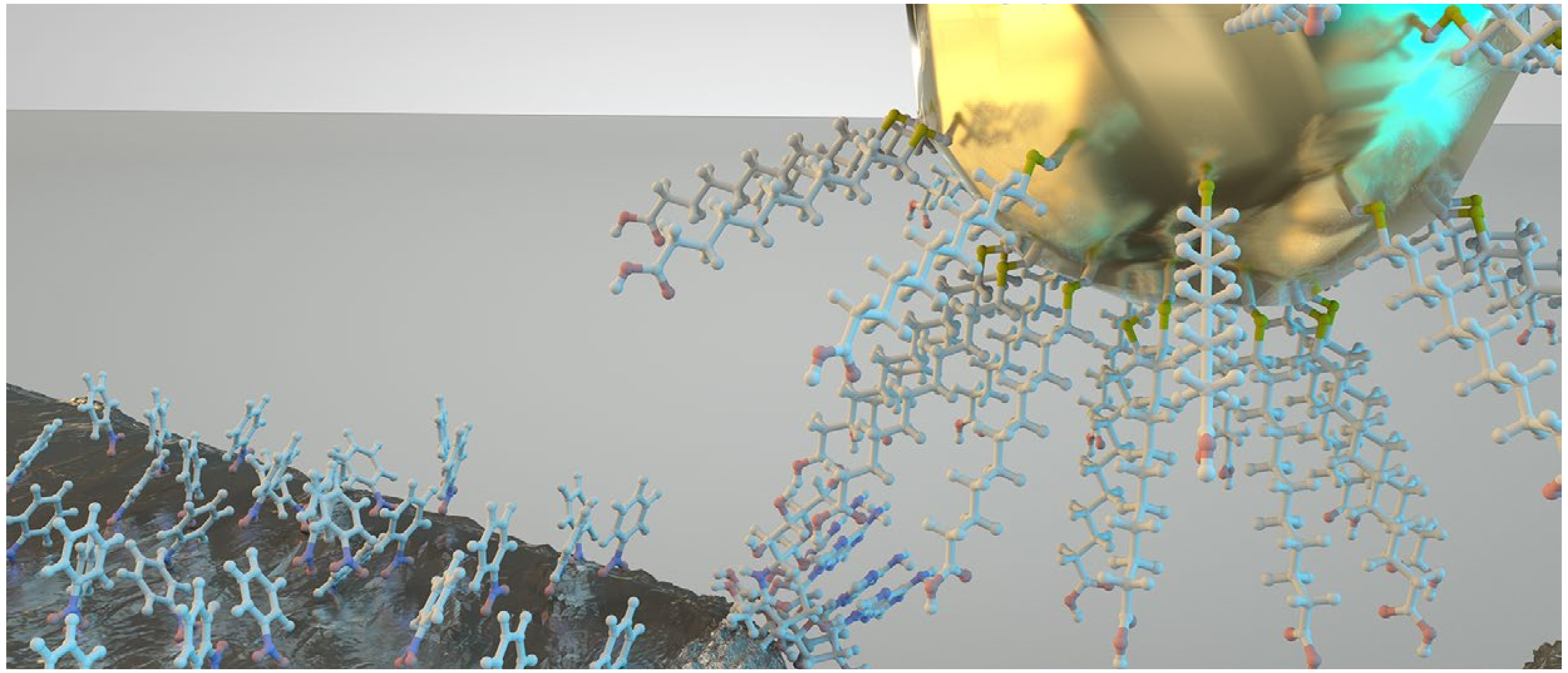
Stefan.Maier@monash.edu

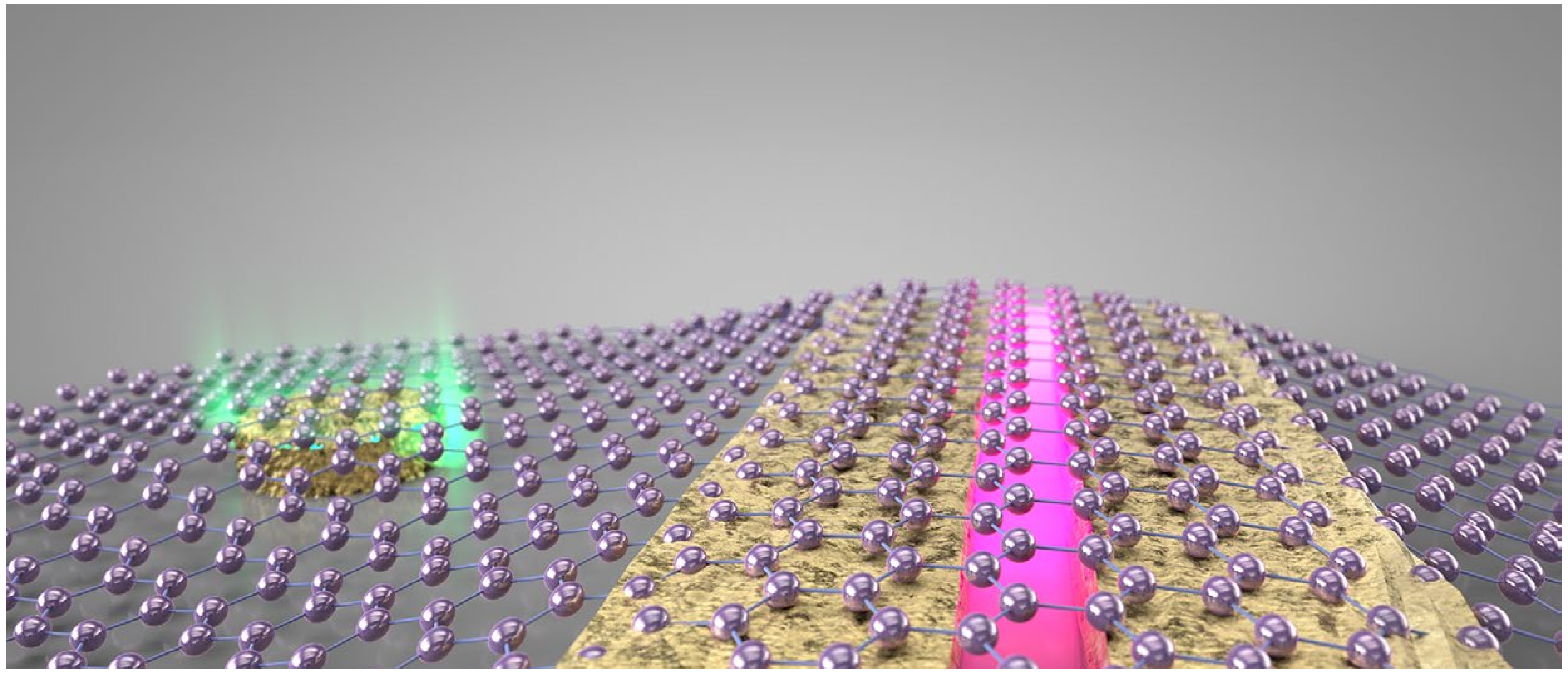
Nanophotonics for control of light-matter coupling



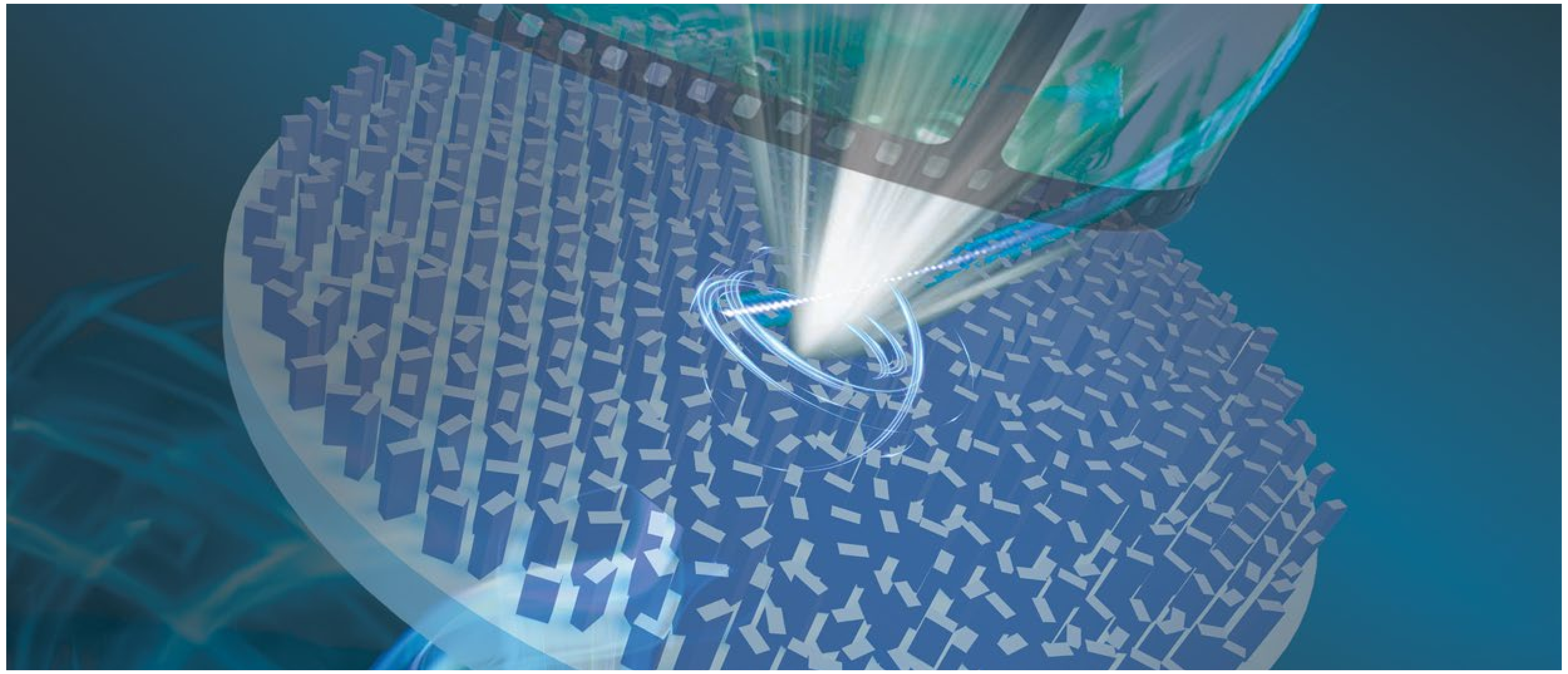
Non-linear interactions and emission control


Surface-enhanced sensing and spectroscopy

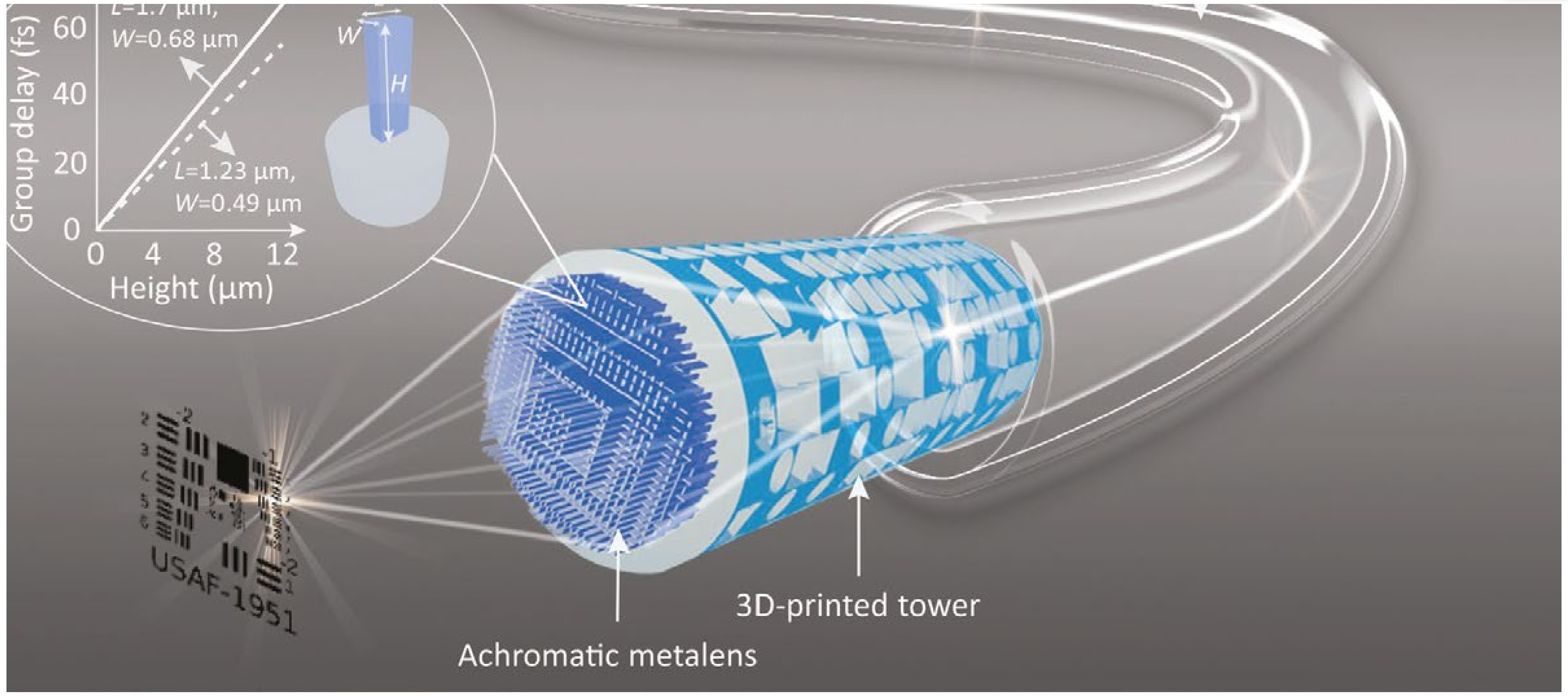

Energy conversion and plasmonic chemistry


Coupling to low-dimensional materials and devices

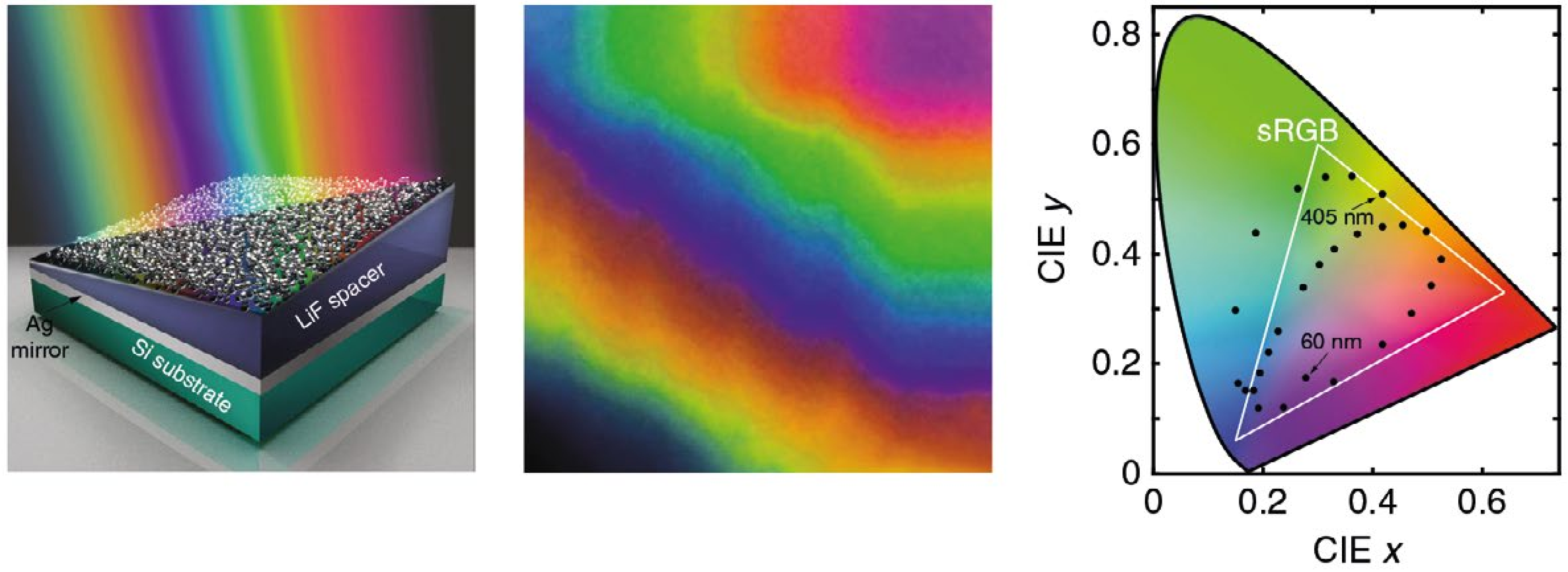
Meta-optics: Metasurfaces and metafibers



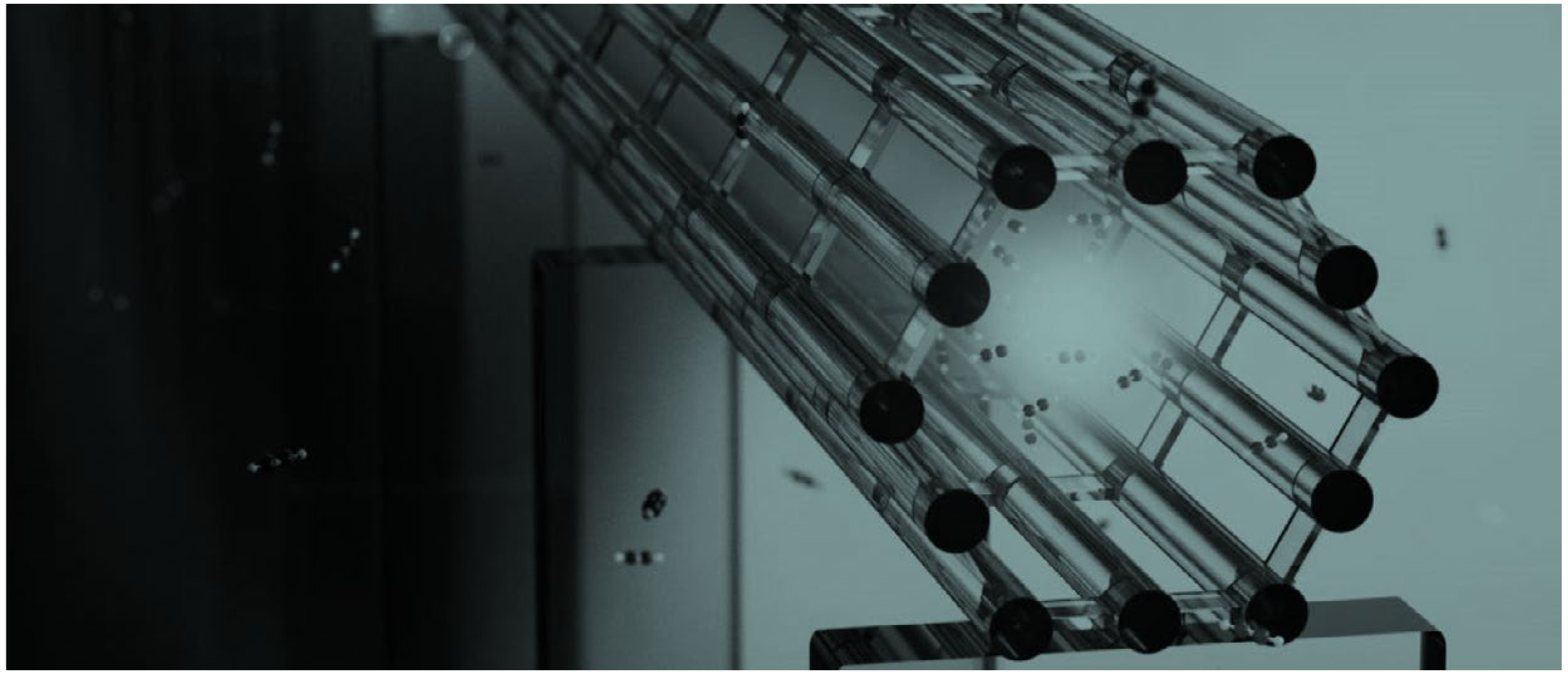
Holography



Telecommunications and fiber optics

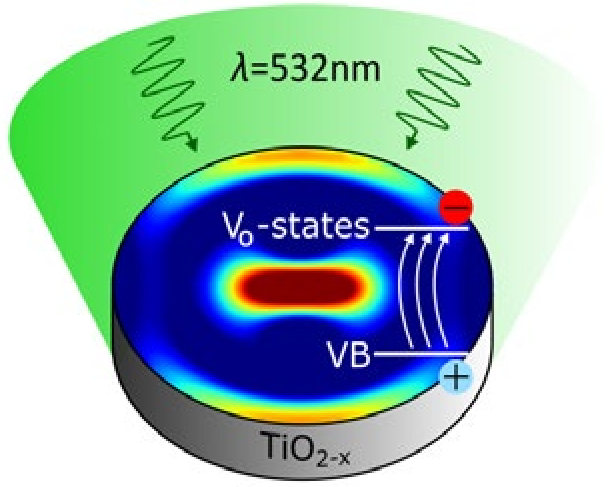


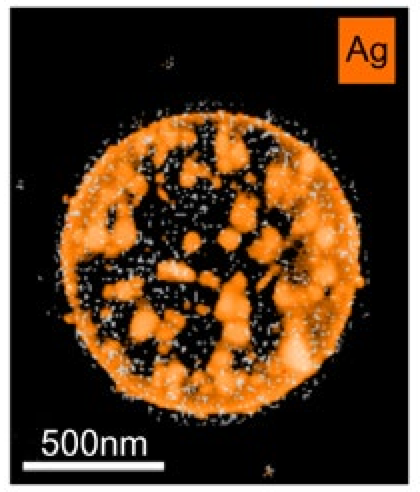
Light harvesting with disordered systems



Light cages for sensing and spectroscopy

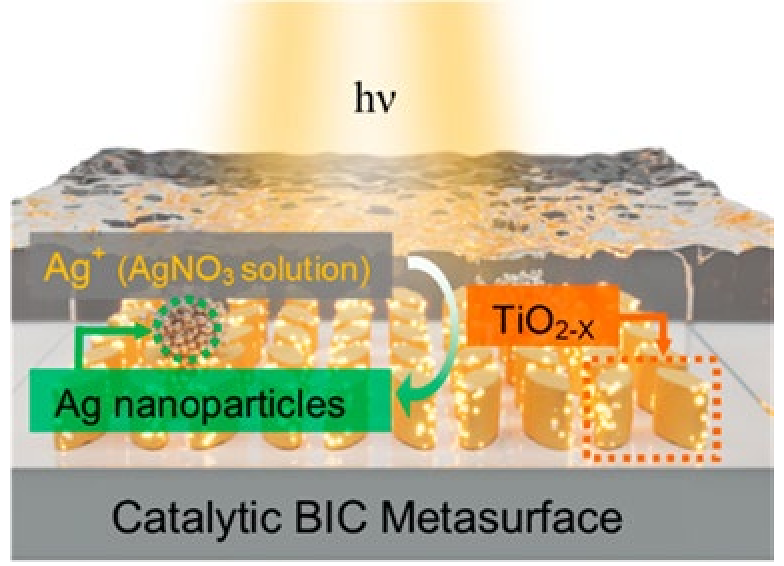
Outline

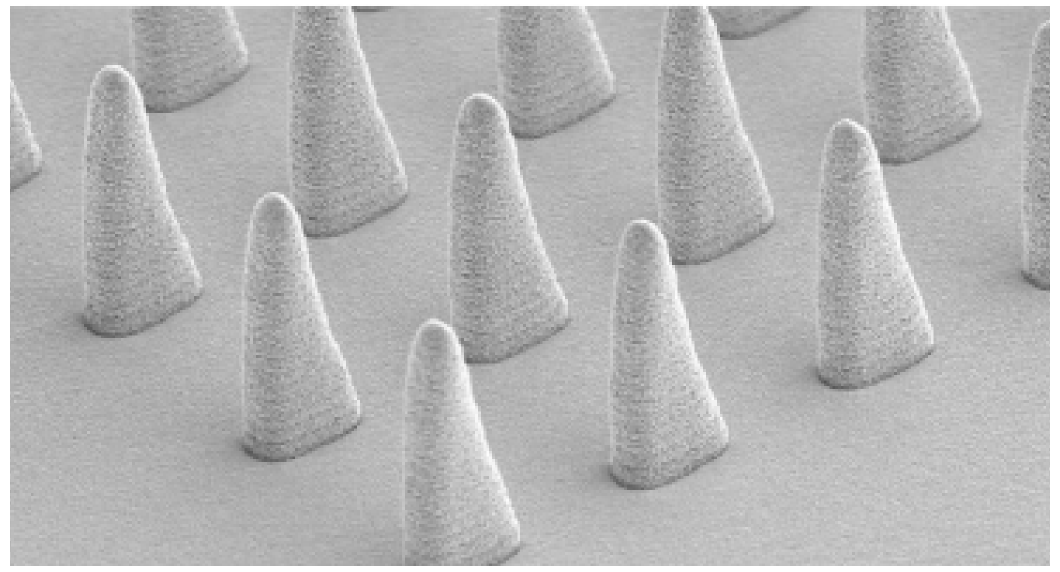




Anapoles and BICs for energy conversion

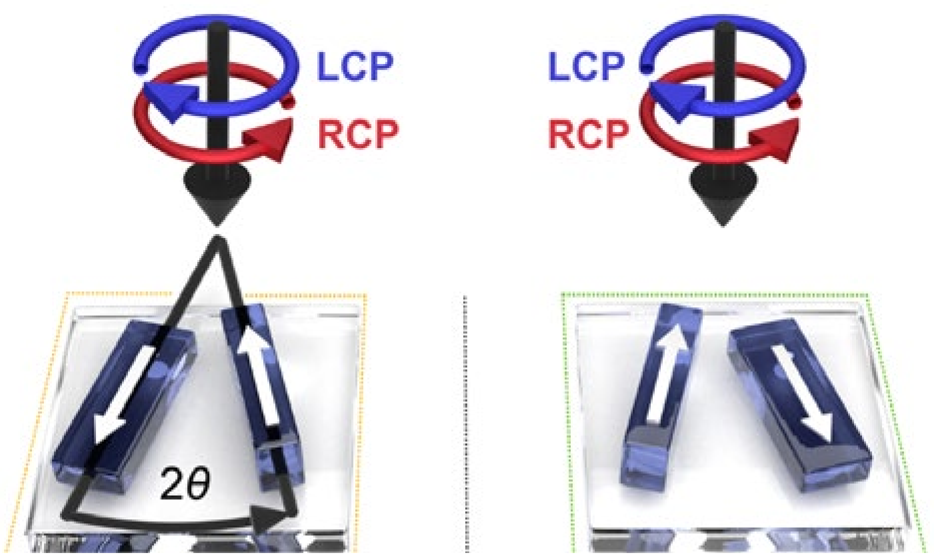
ACS Nano **16,** 13057 (2022)
Adv Energy Mater **11,** 2102877 (2021)
ACS Photonics **8,** 1469 (2021)
ACS Nano **14,** 2456 (2020)





BICs for infrared absorption and chirality

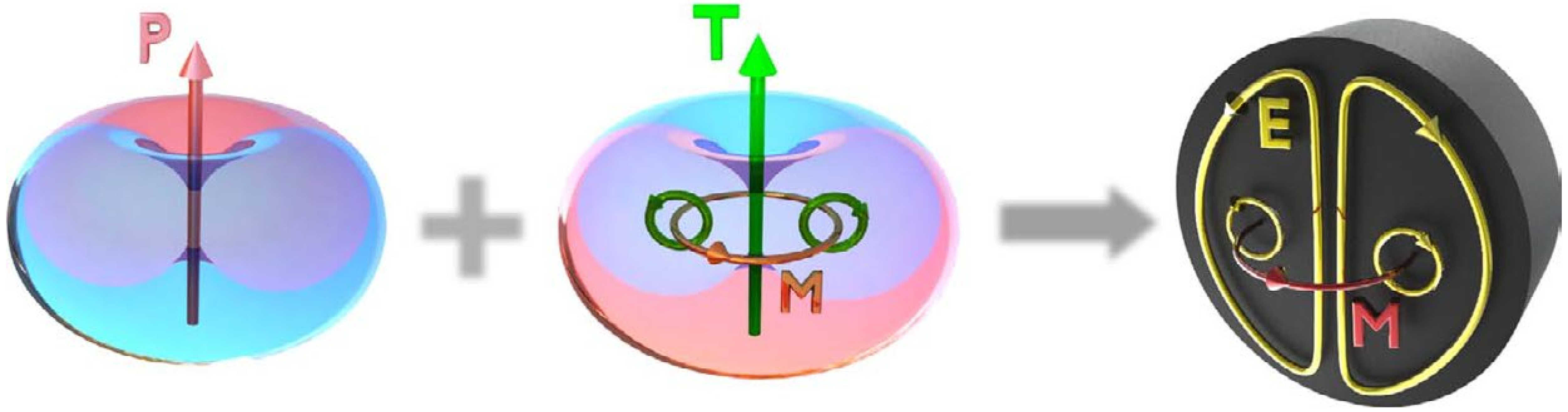
*arXiv:*2210.05339



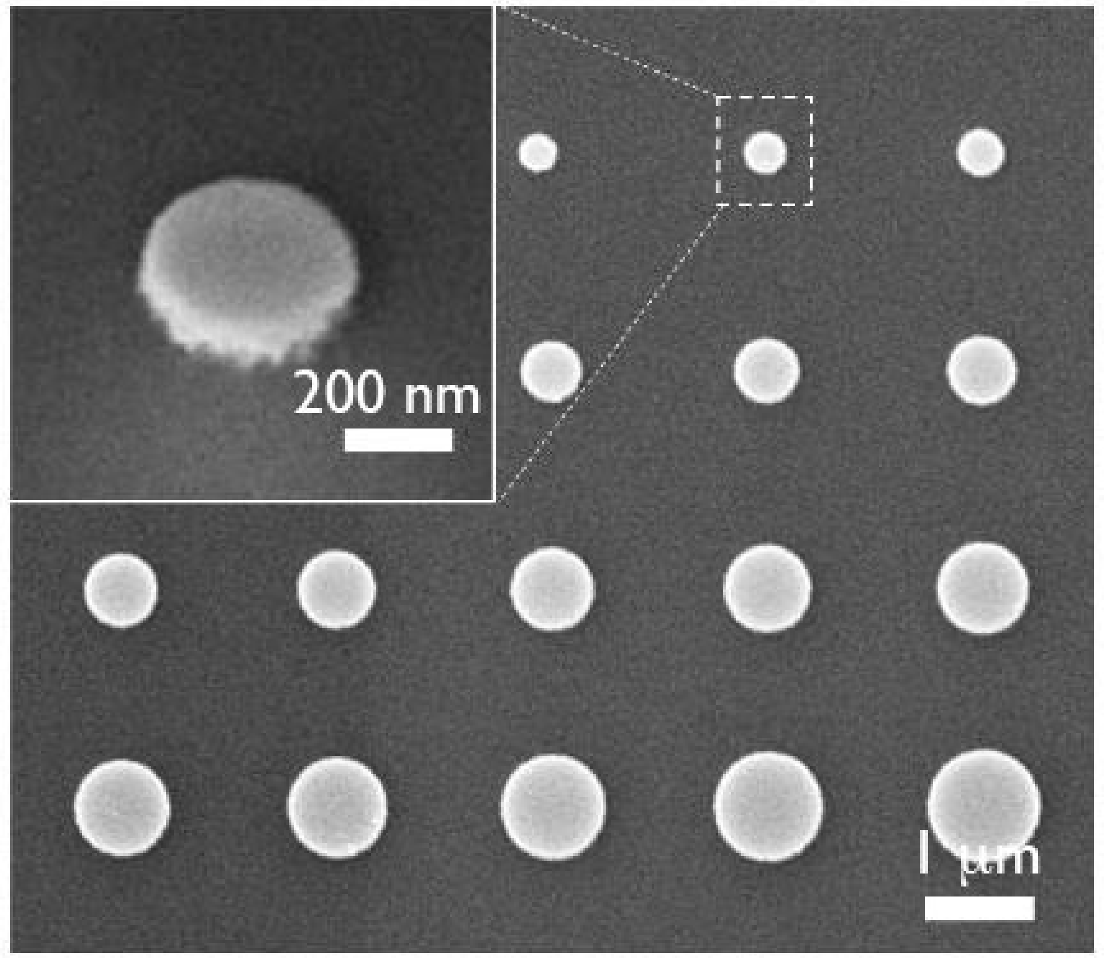
Maximizing field intensity within dielectric nanostructures

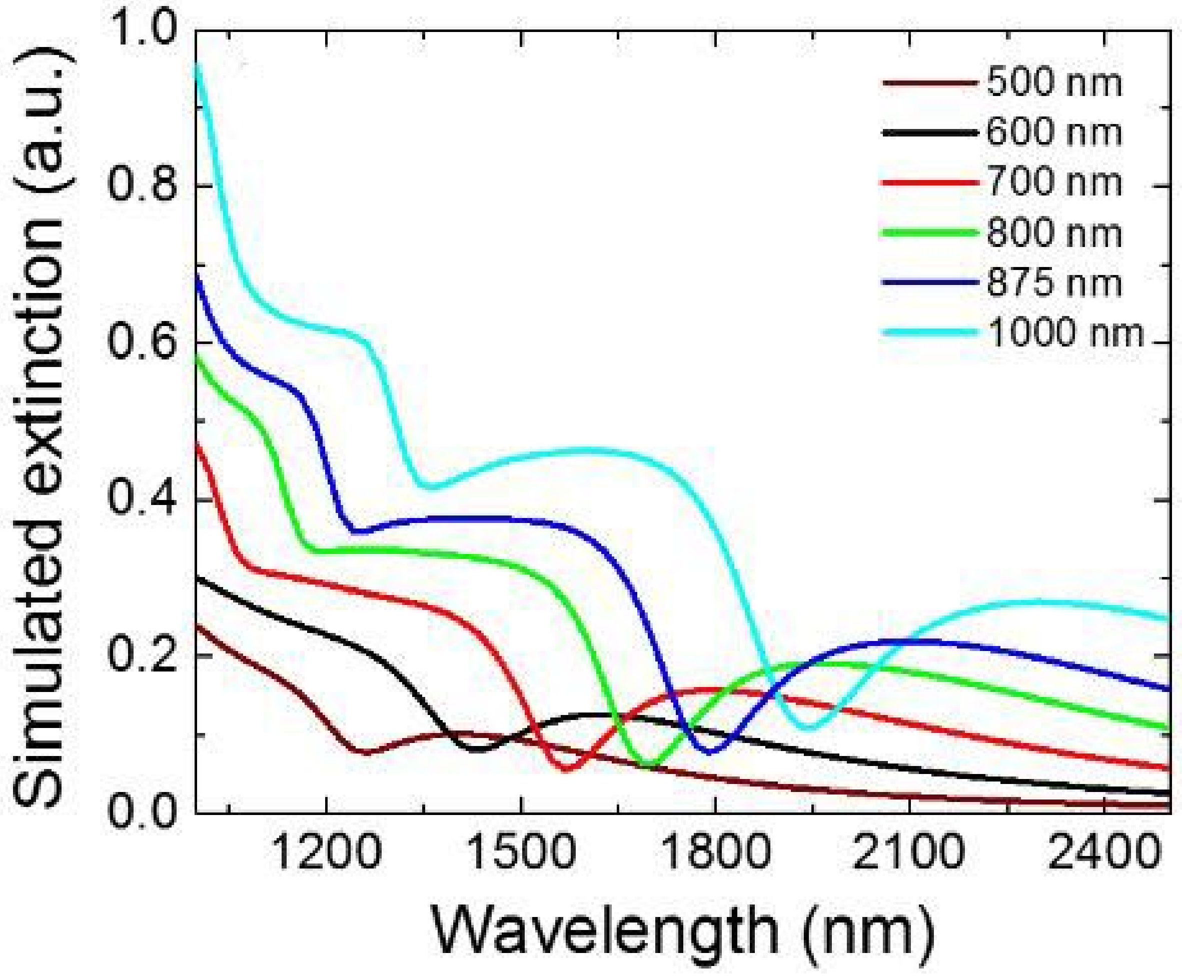
Nano Letters **16,** 4635 (2016)

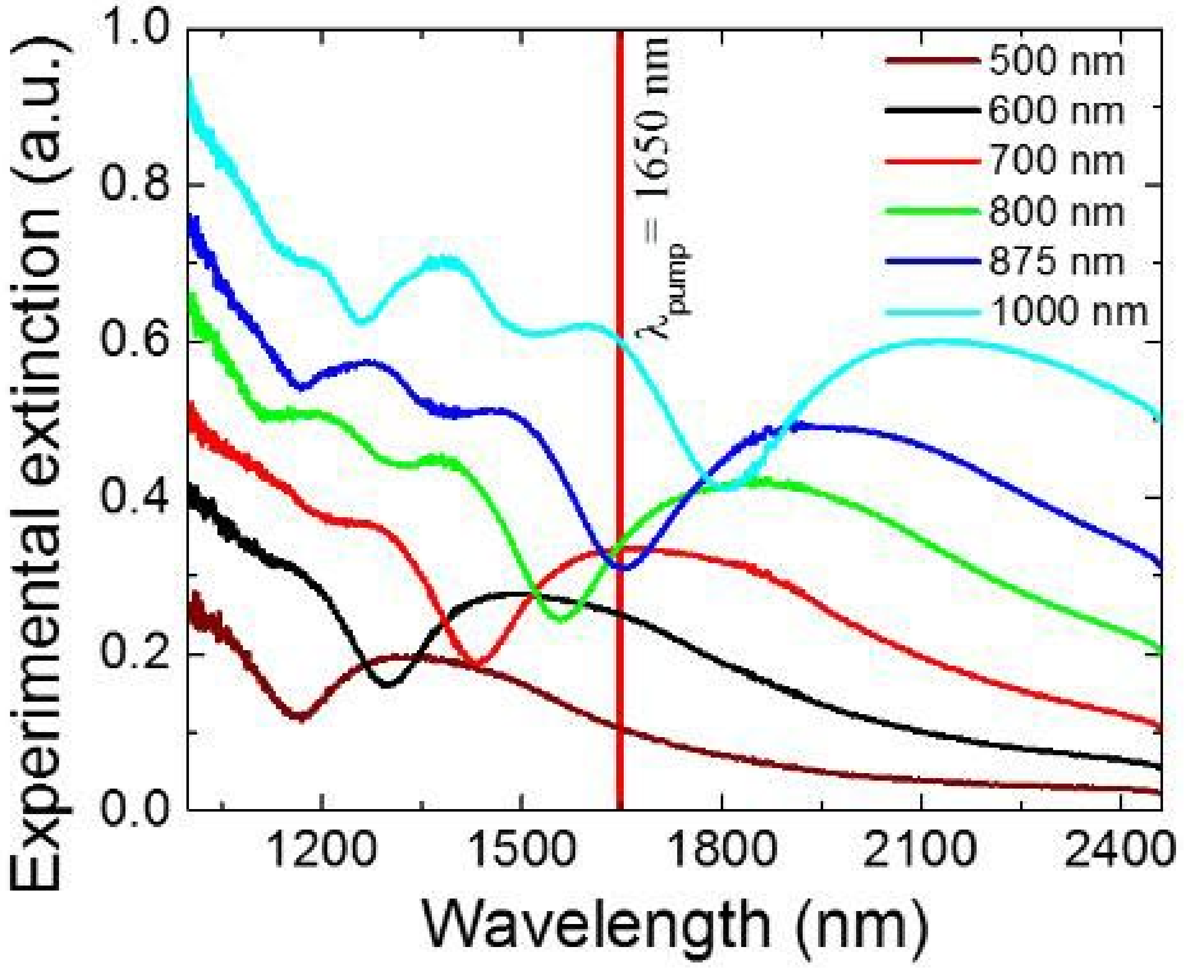
- Anapole excitations, composed of electric and toroidal dipole moments, show a pronounced valley in the scattering cross section due to destructive interference between their similar radiation patterns.
- cf toroidal metamaterial work by Zheludev group (Science 330, 1510 (2010))
- These excitations can occur in thin dielectric nanostructures, in our example 100 nm thick Ge nanodisks of an aspect ratio < 0.4.
- This provides a route to maximizing the electric field energy inside the particle.



Nature Communications **6,** 8069 (2015), Kivshar group



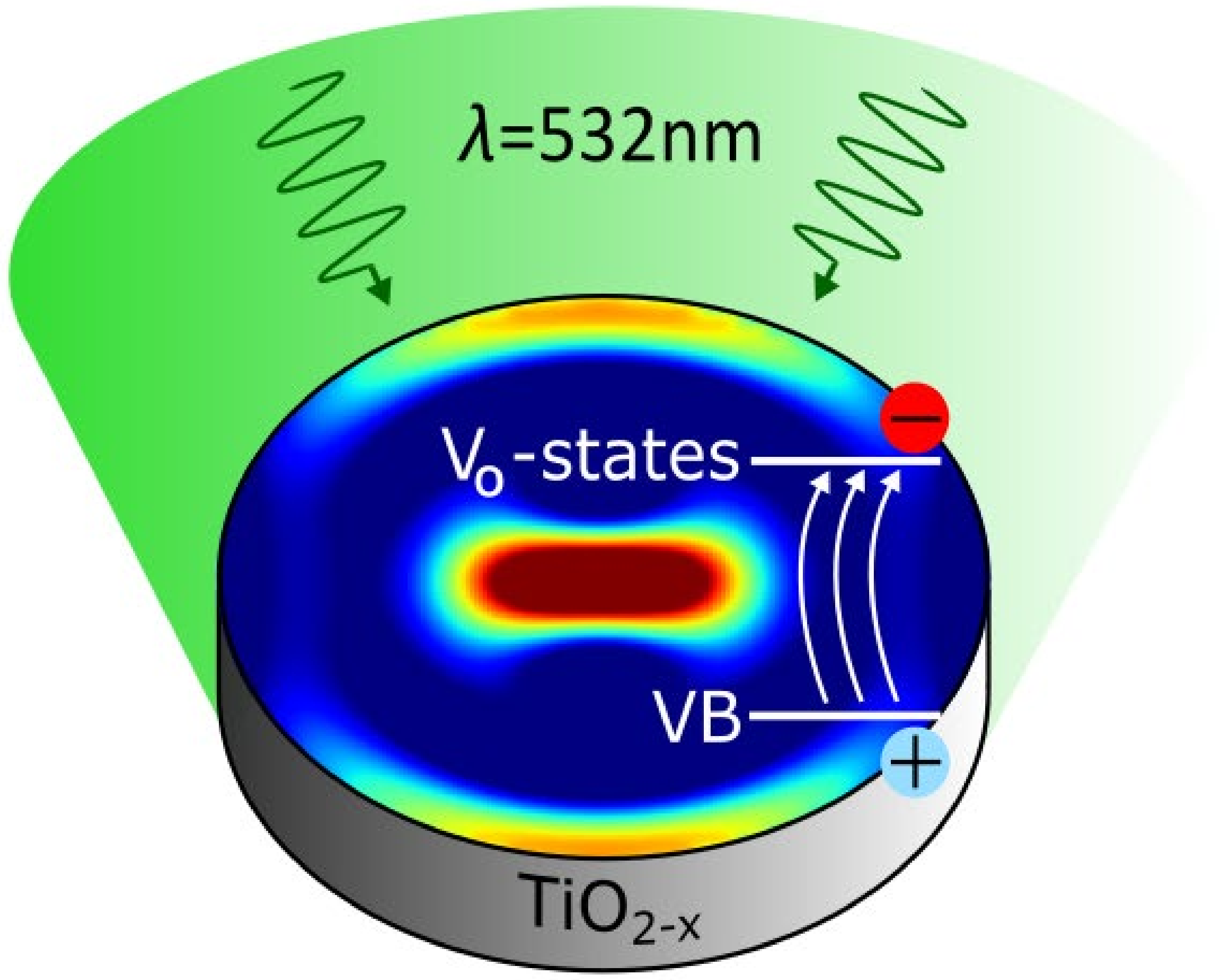


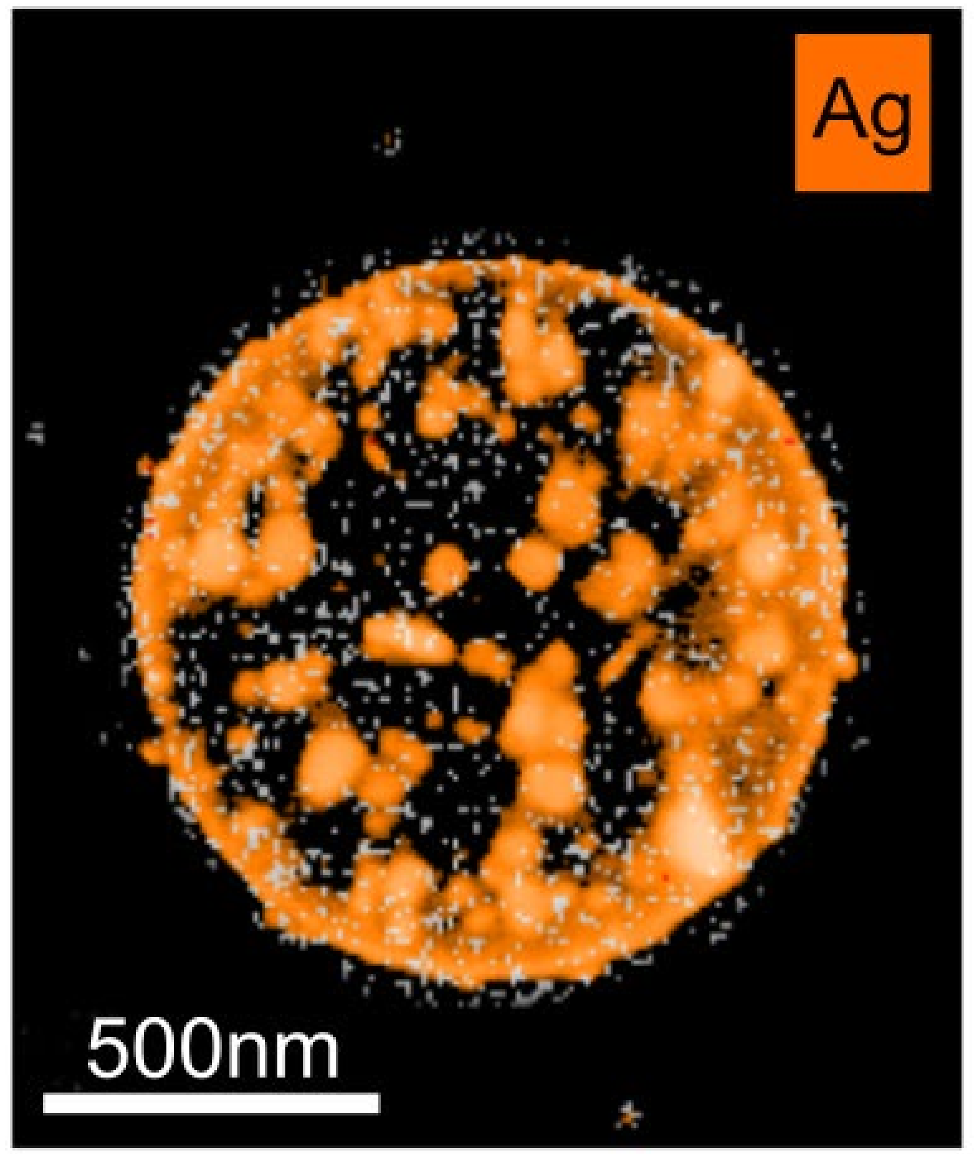


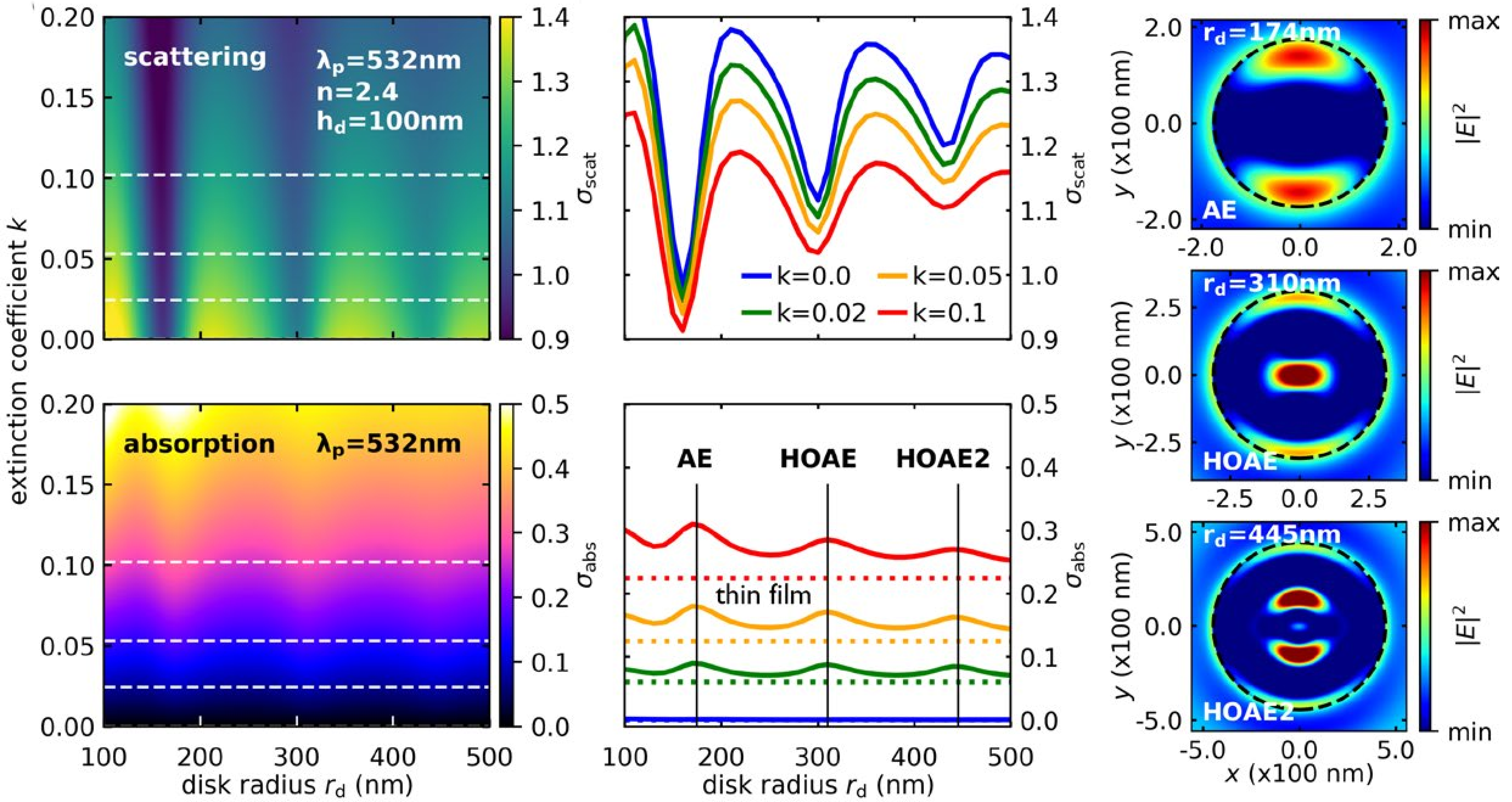
Anapole excitations as a route towards strong light/matter interactions

Anapole excitations to increase absorption

ACS Nano **14,** 2456 (2020)



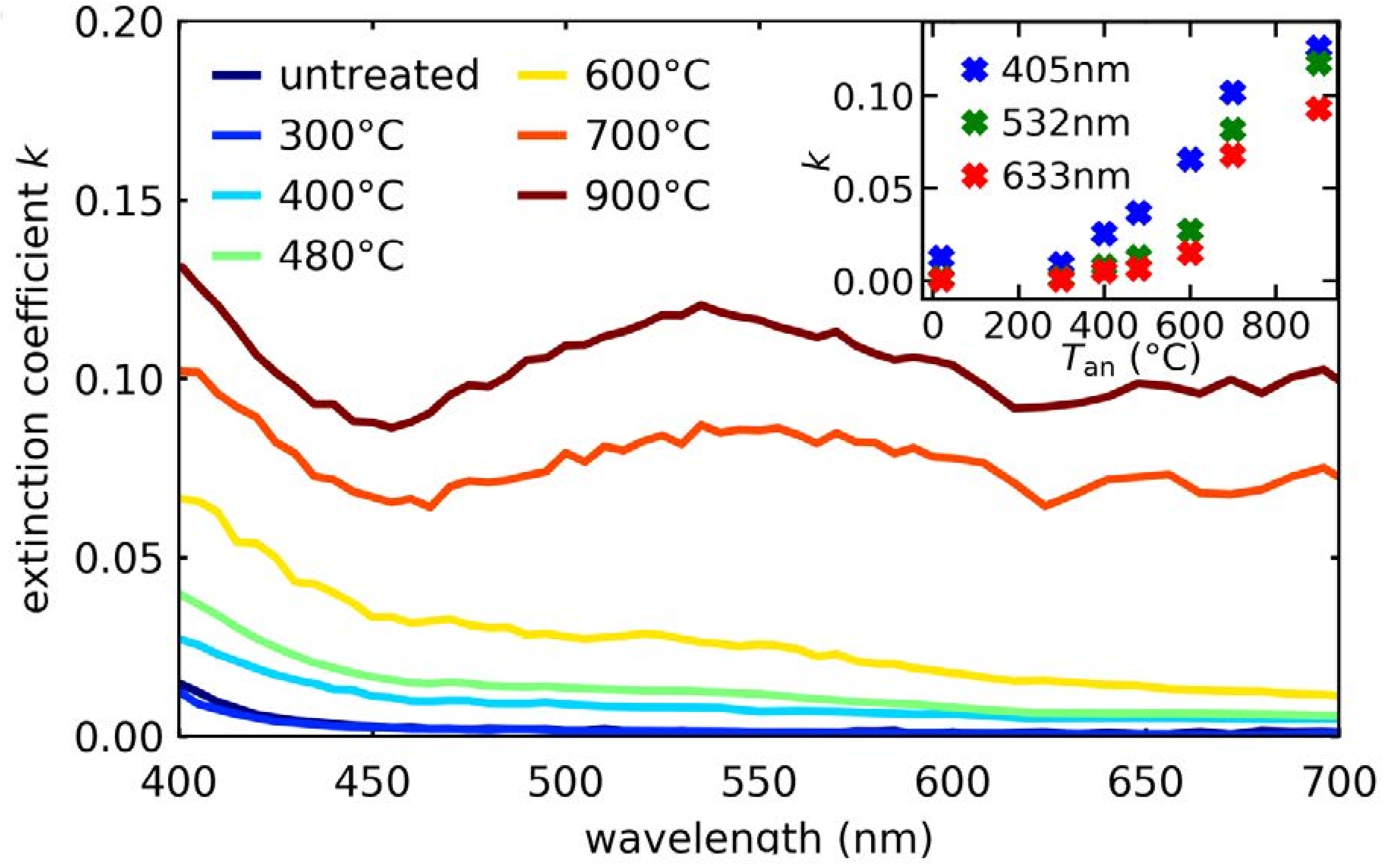


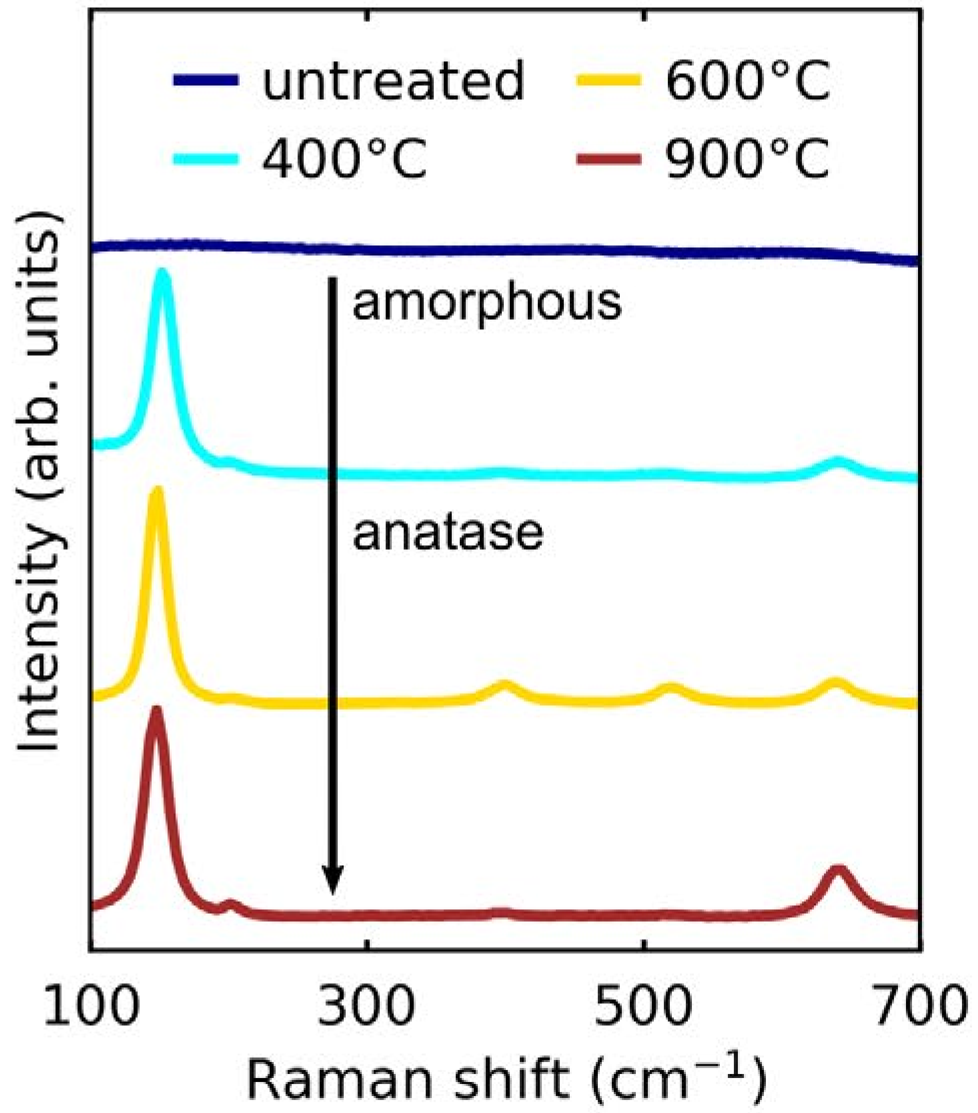


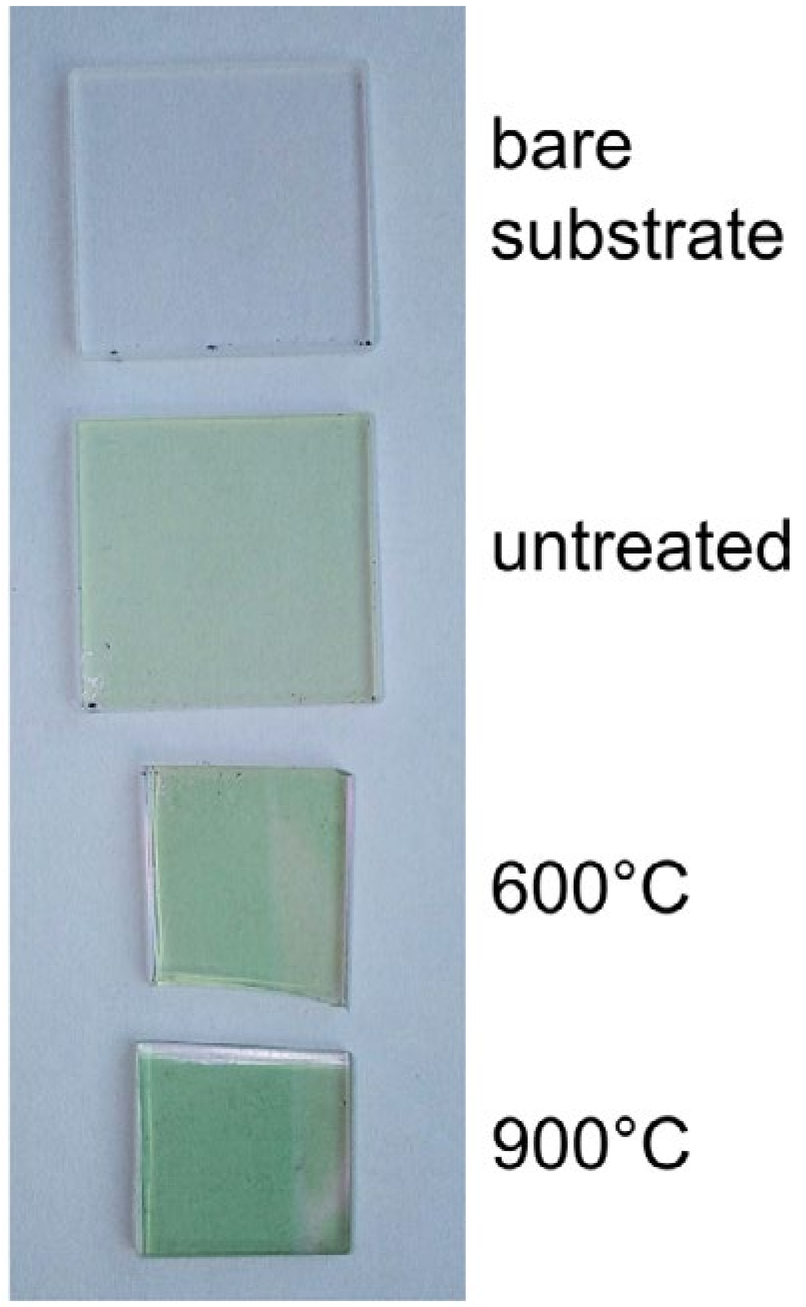
- goal: utilize anapole excitations to directly increase absorption for photo-generation of charge carriers in solar photocatalysis
- TiO_2 as a model system as it allows control of material absorption via oxygen vacancy generation
- photocatalytic activity monitored via Ag^+ reduction
- however TiO_2 not ideal due to relatively low refractive index compared to previous demonstrations of anapole modes (in Si, Ge, GaP, …)
- determine optimum extinction coefficient k for nanophotonic engineering
- low but non-zero extinction coefficient leads to reasonably high contrast between disk-engineered and bare film absorption in water

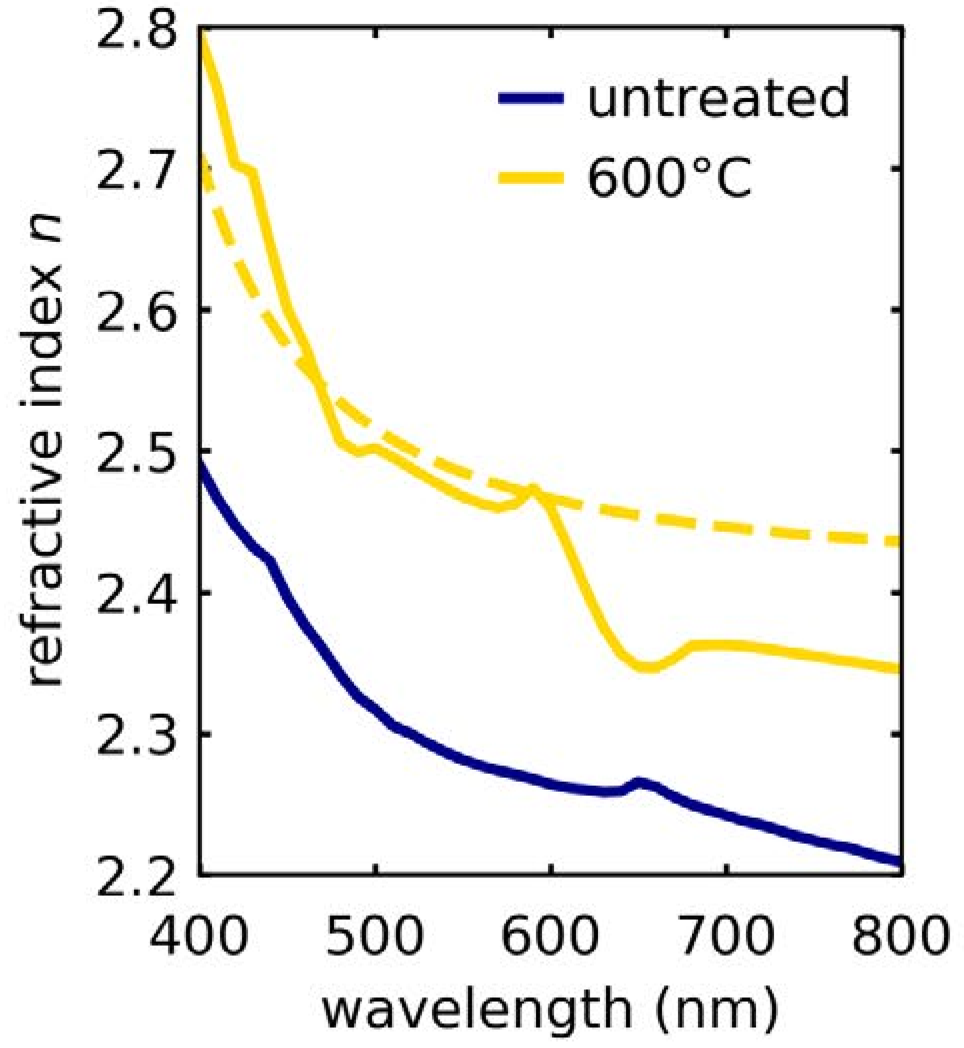
Oxygen vacancy creation via thermal annealing

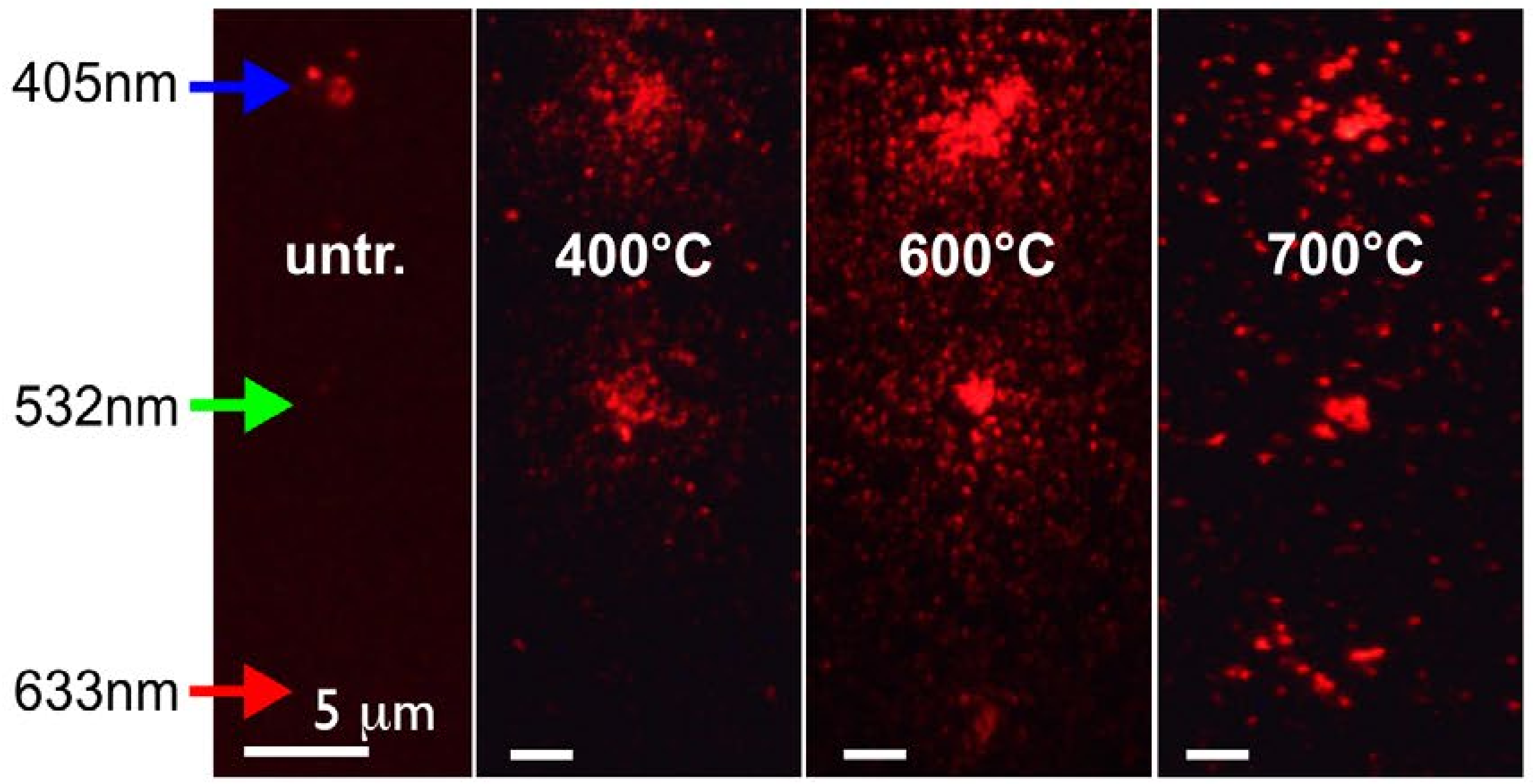
ACS Nano **14,** 2456 (2020)









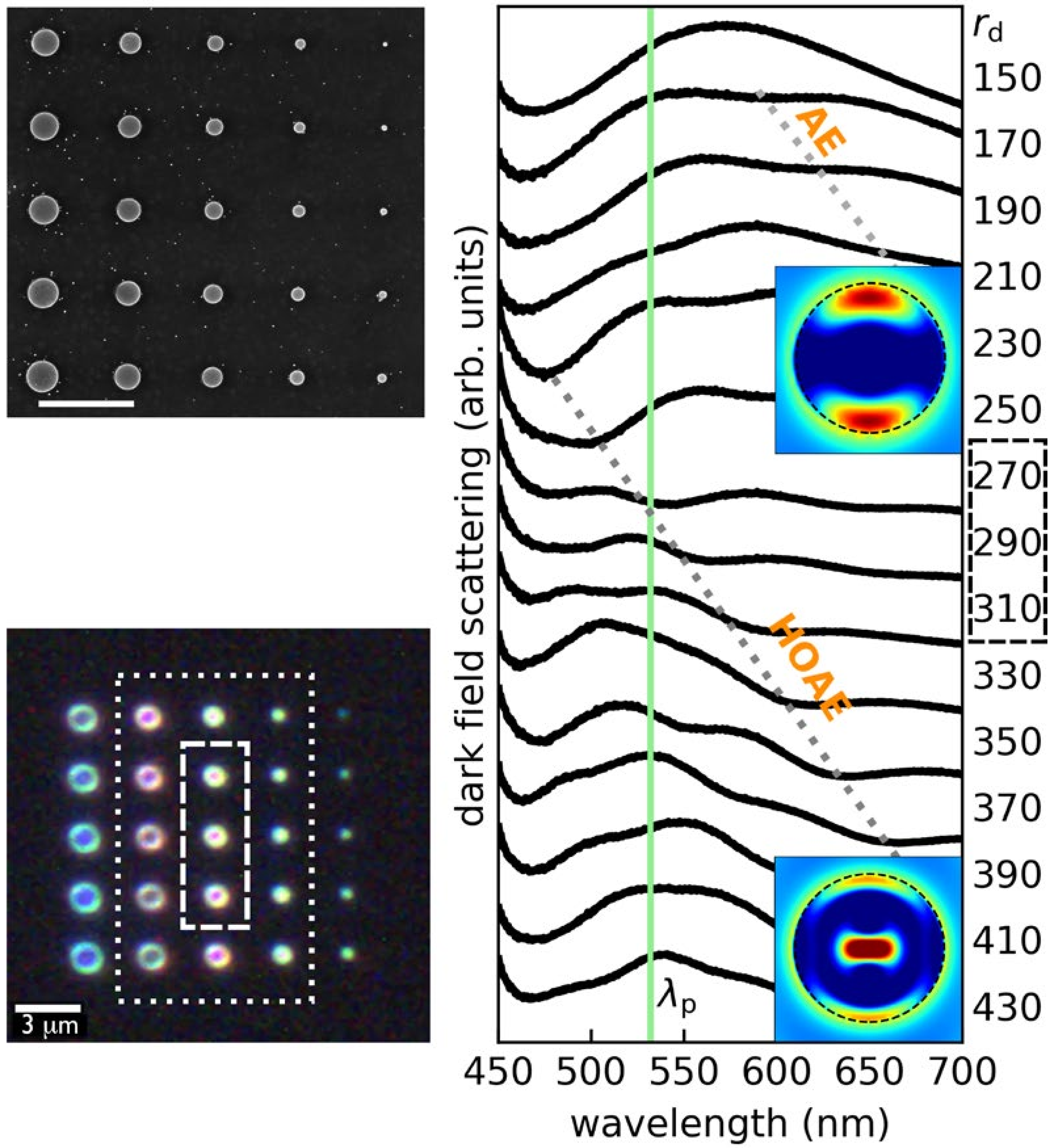


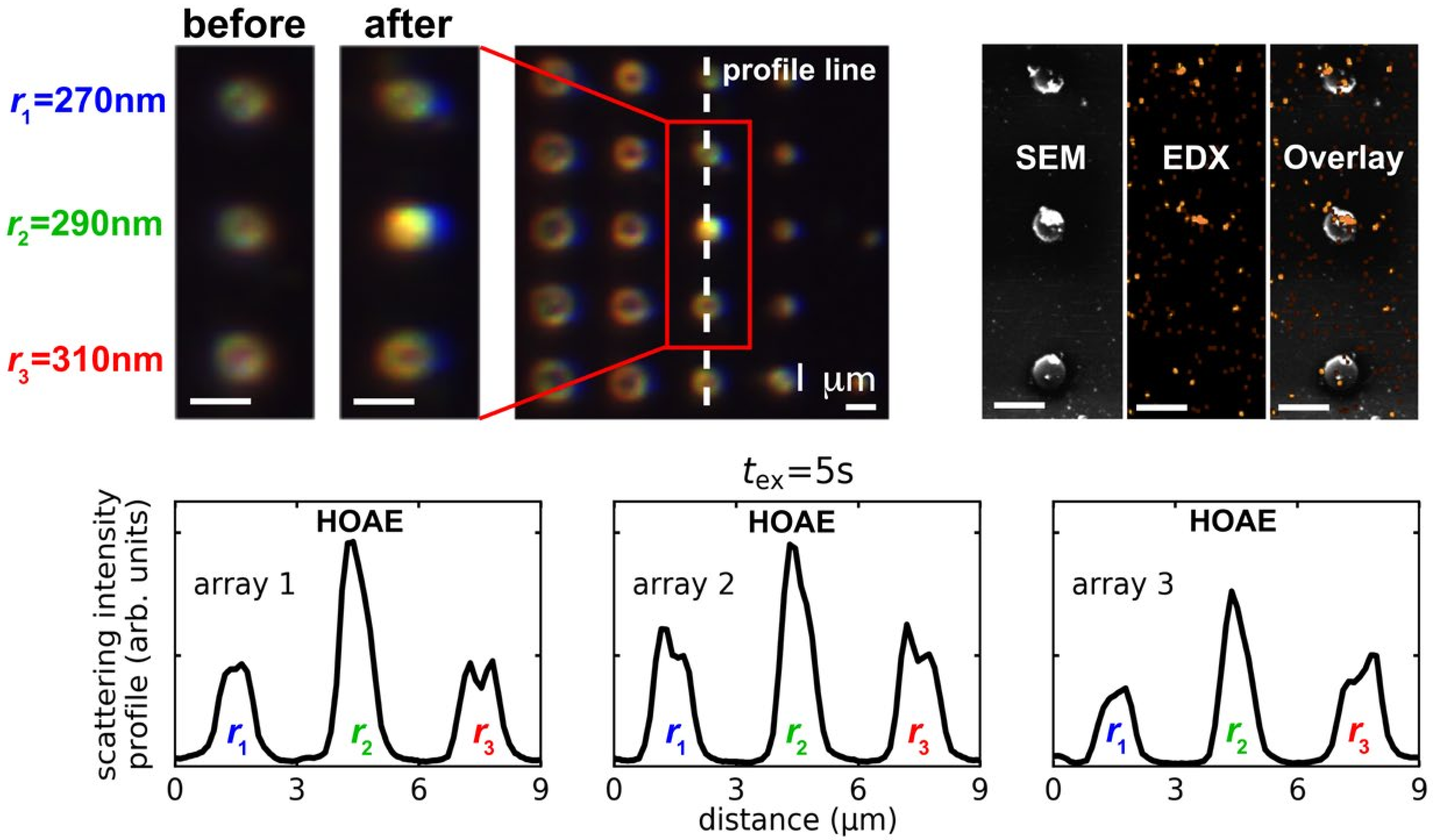
Ag cluster formation

- vacancy centre creation via thermal annealing of 160 nm films; absorption increase monitored via photothermal deflection spectroscopy
- k ≈ 0.03 @ 532 nm chosen (T = 600°C) in order not to lower n too significantly; additional problem of crack formation
- surface-activity of generated oxygen vacancy centres monitored via Ag^{+} photoreduction of AgNO3 salt
- for vacancy centre creation and monitoring via photoreduction cf Wu et al, *Science Advances* **5**, eaax0939 (2019)

Photoreduction in TiO_2 anapole disks

ACS Nano **14,** 2456 (2020)

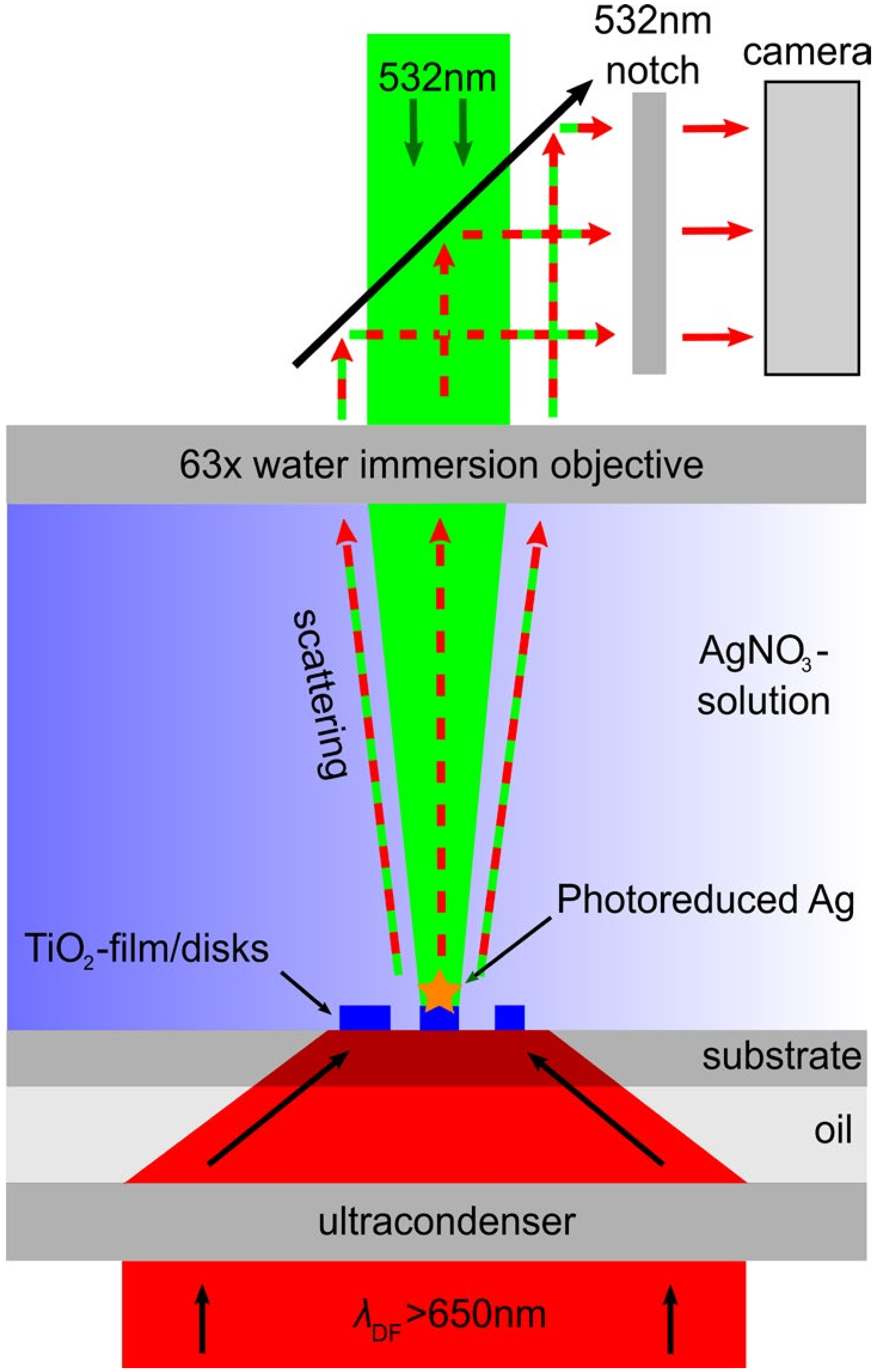


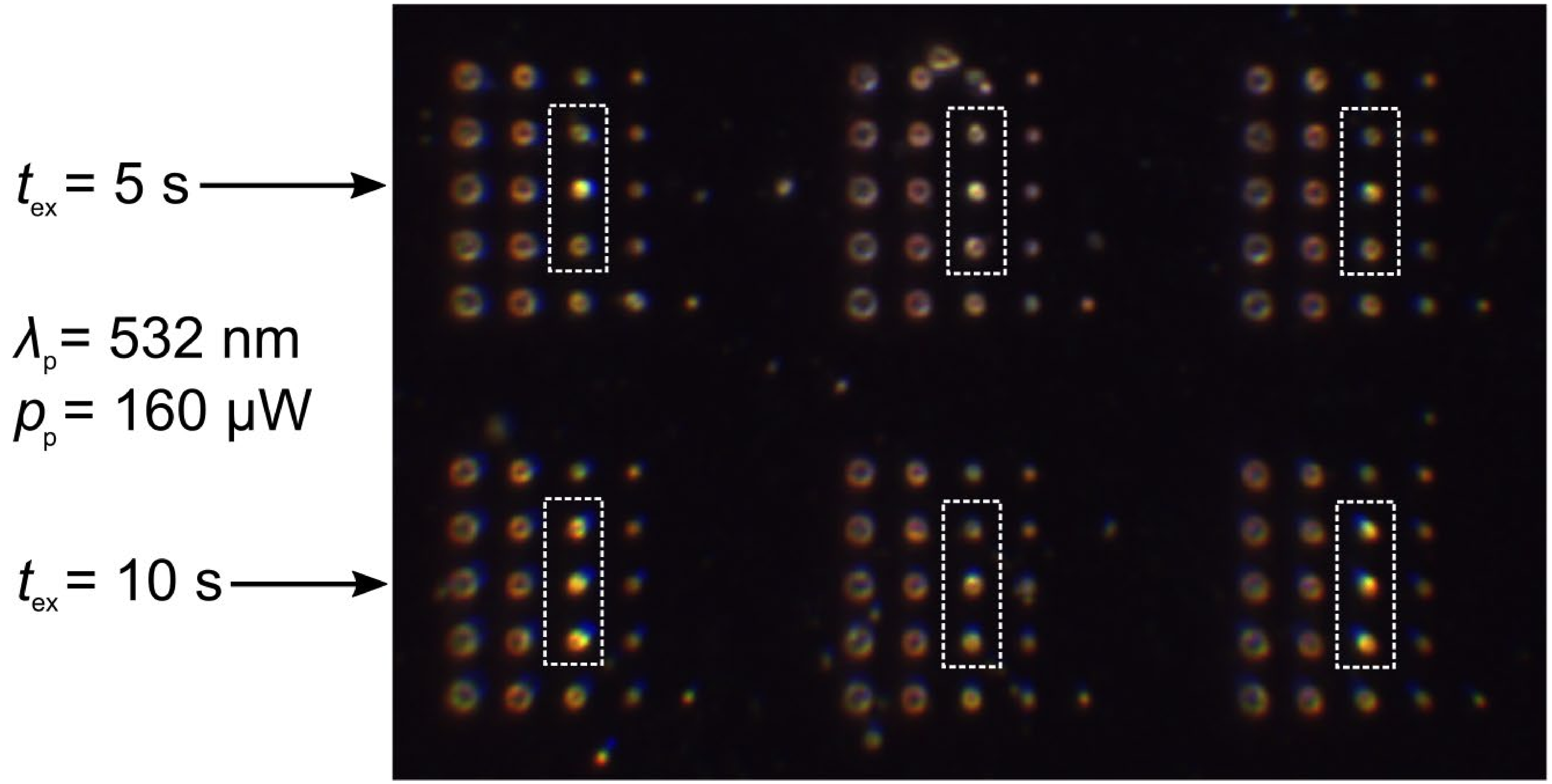


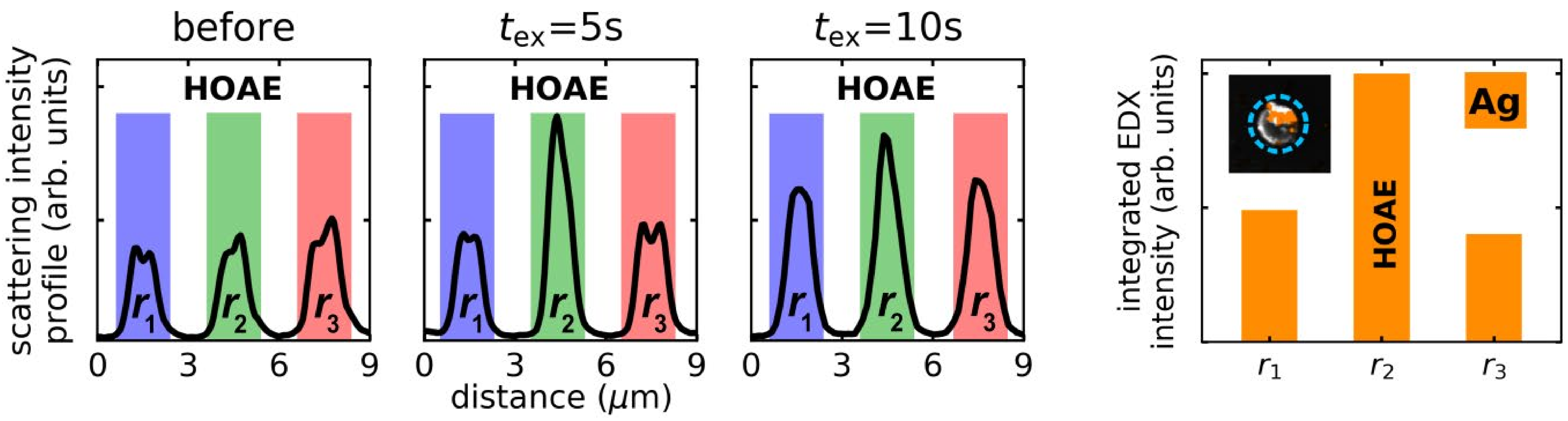
- utilization of higher-order anapole mode for demonstration of confinement-enhanced charge-carrier generation via Ag^+ photoreduction in 1mM $AgNO_3$ aqueous solution
- simulations predict 25 nm blue-shift of absorption maximum with respect to scattering minimum ⇒ 290 nm disk
- excitation at 532 nm with 160 mW for 5s
- Ag cluster formation confirmed via EDX, quantitative assessment difficult
- lower bound of photocatalytic enhancement given by geometrical cross section ratio of 1.14 (310 and 290 nm diameter disks)

Additional photoreduction statistics

ACS Nano **14**, 2456 (2020)







Generalization to higher-index dielectrics

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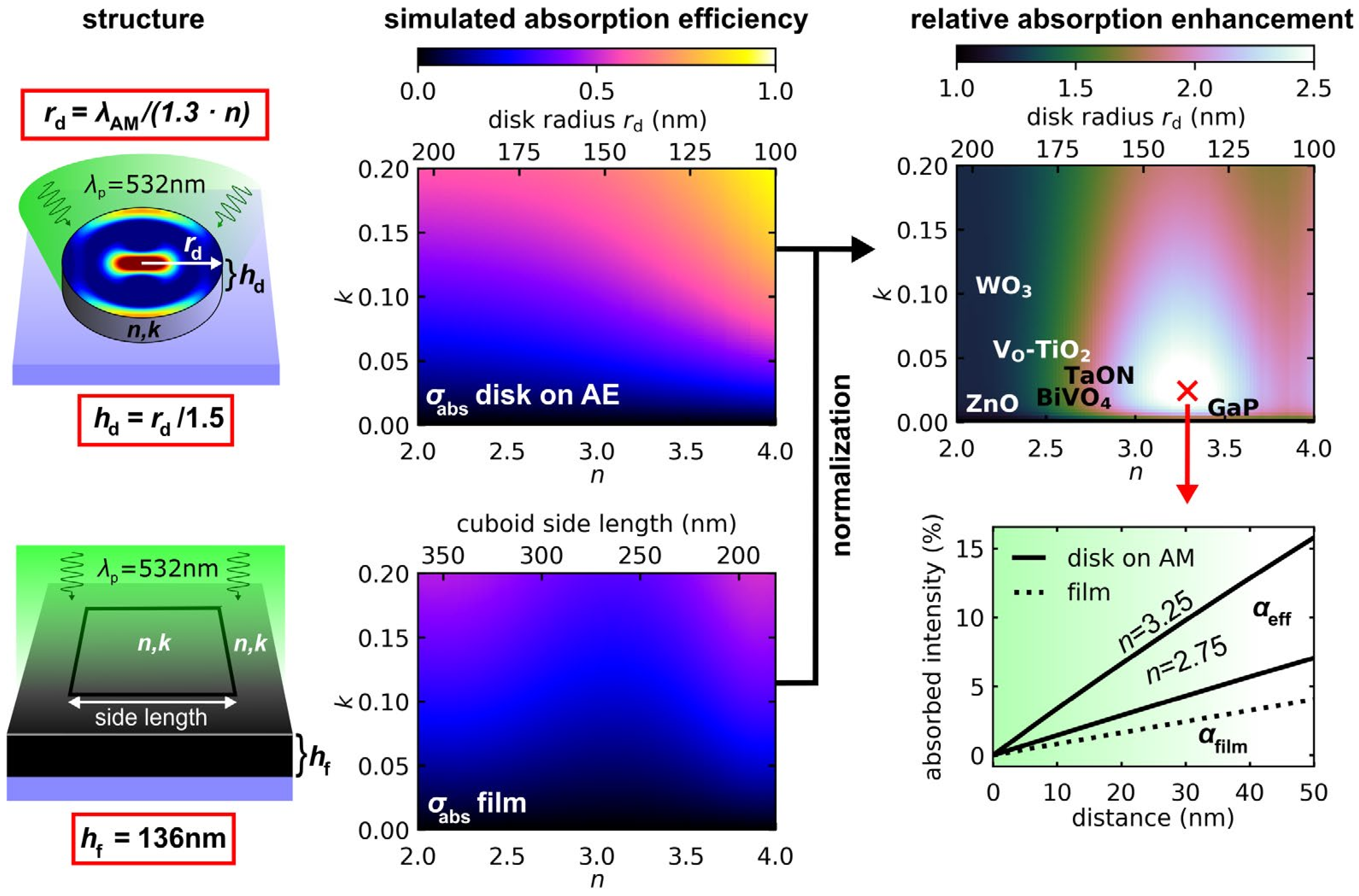
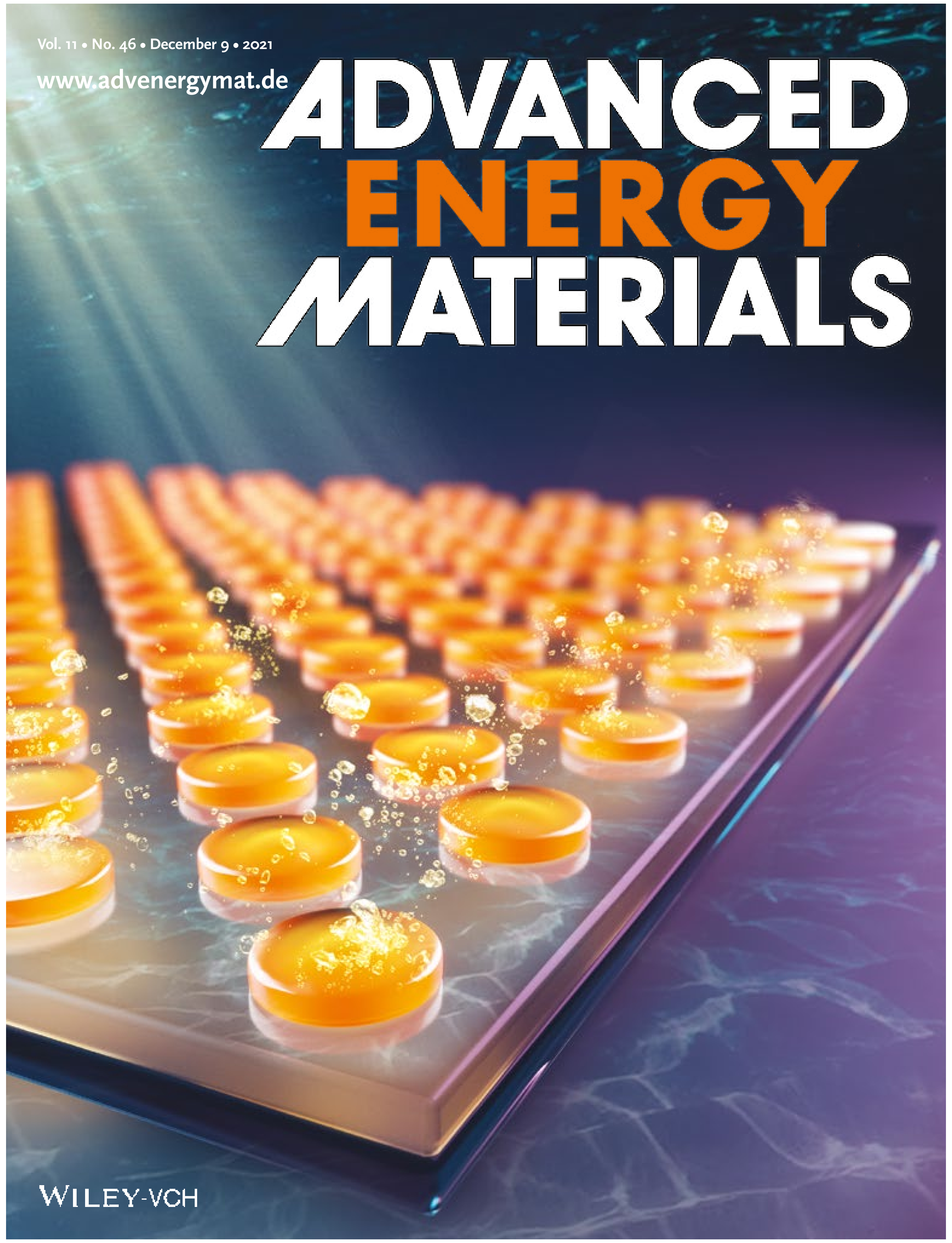


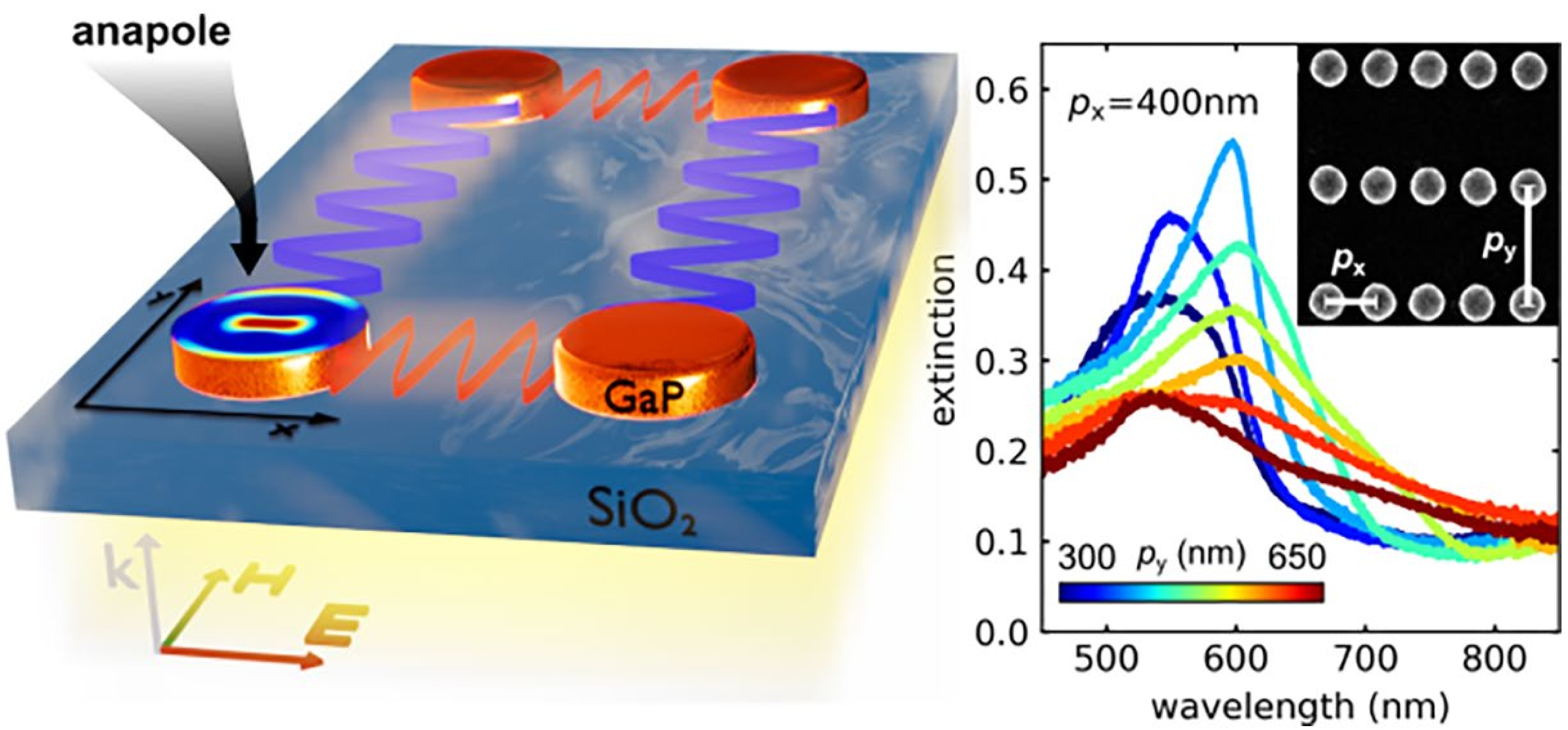
Engineered absorption enhancement favourable for higher-index materials such as GaP

Towards large-area light harvesting in a reactor

Adv Energy Mater **11,** 2102877 (2021)

ACS Photonics **8,** 1469 (2021)





Large-area patterning necessitates study of anapole-anapole interactions in a 2D grating

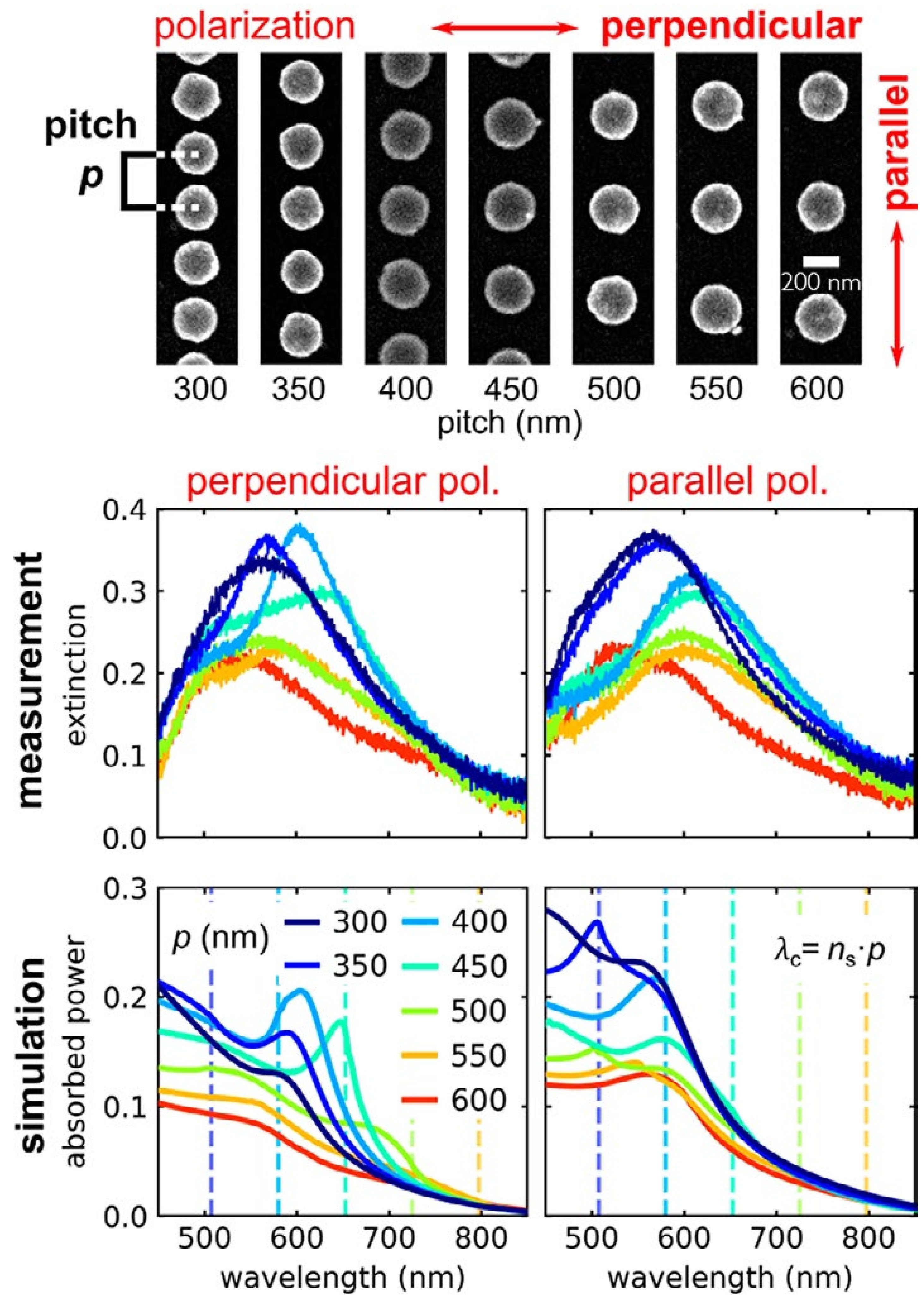
Asymmetry in coupling mediated via lattice resonances

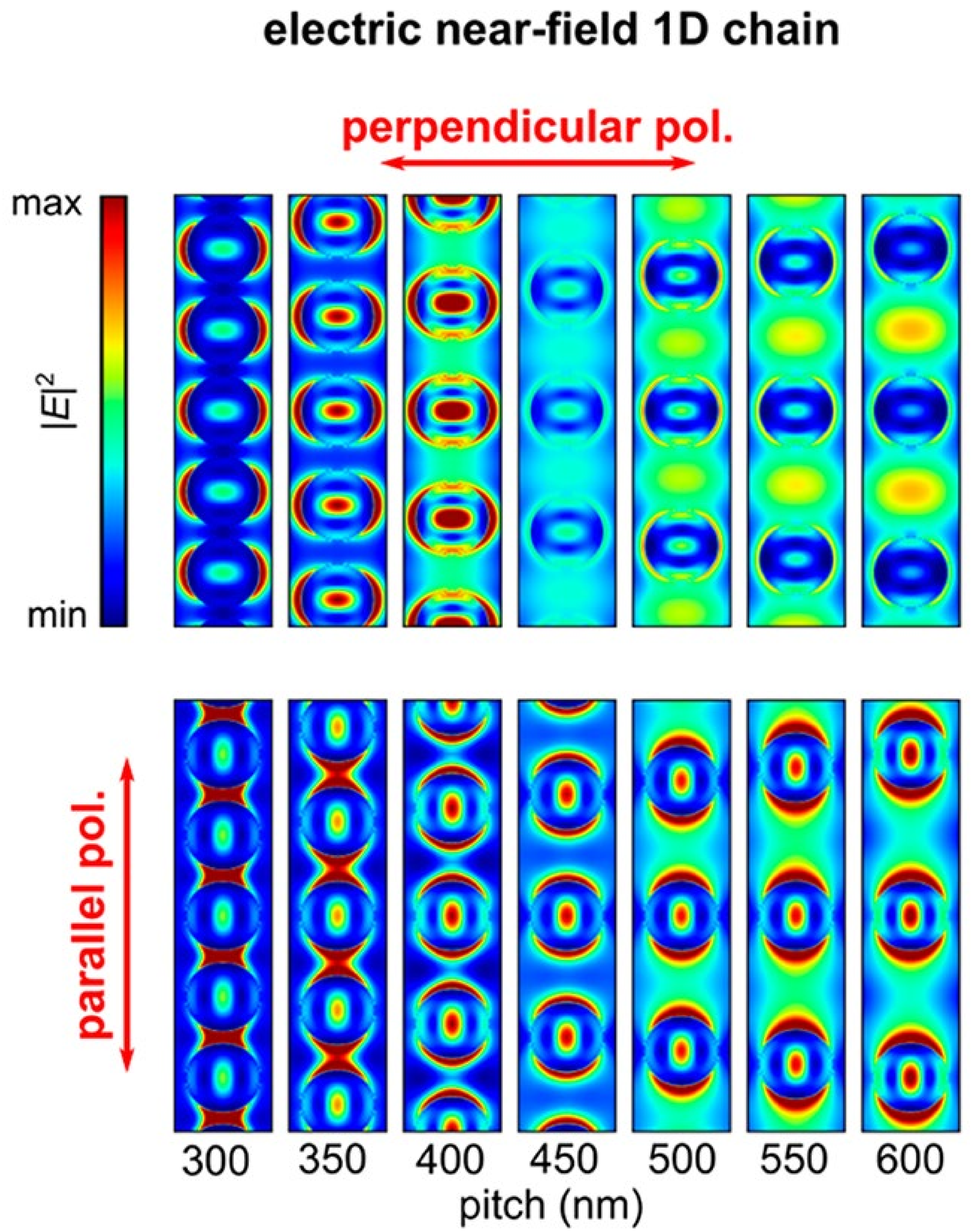
ACS Photonics **8,** 1469 (2021)

Highest absorption enhancement (300%) not achieved for densest packing but for optimum spacing

Separation of coupling mechanisms

ACS Photonics **8,** 1469 (2021)

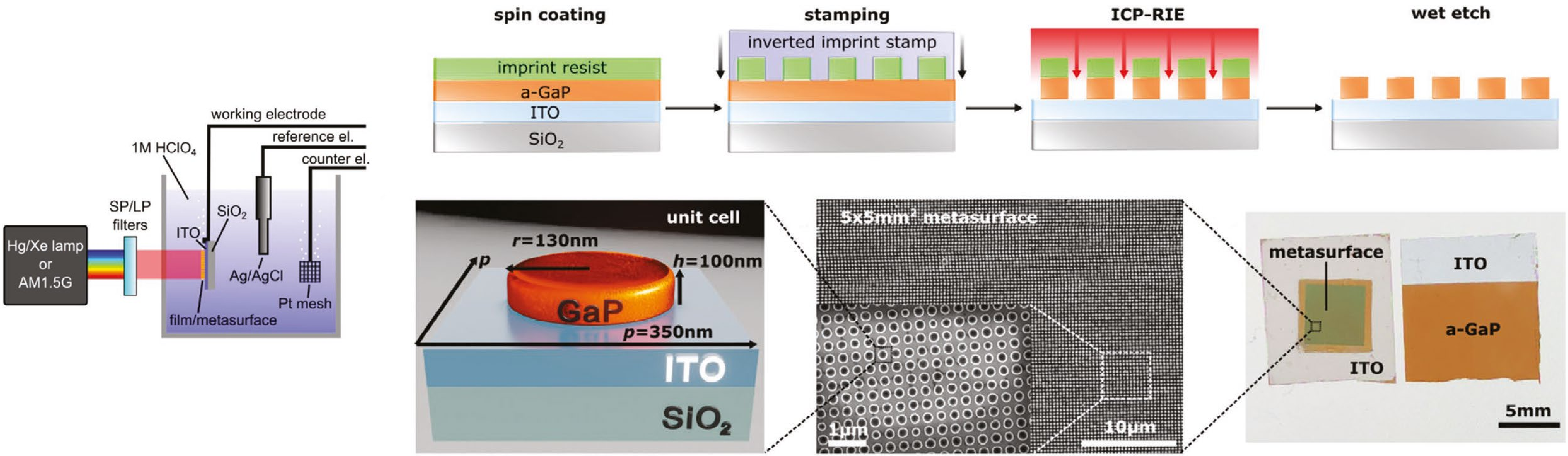




Highest absorption for optimized lattice coupling while *maintaining the anapole condition*

Metasurface photoelectrodes via nanoimprint patterning

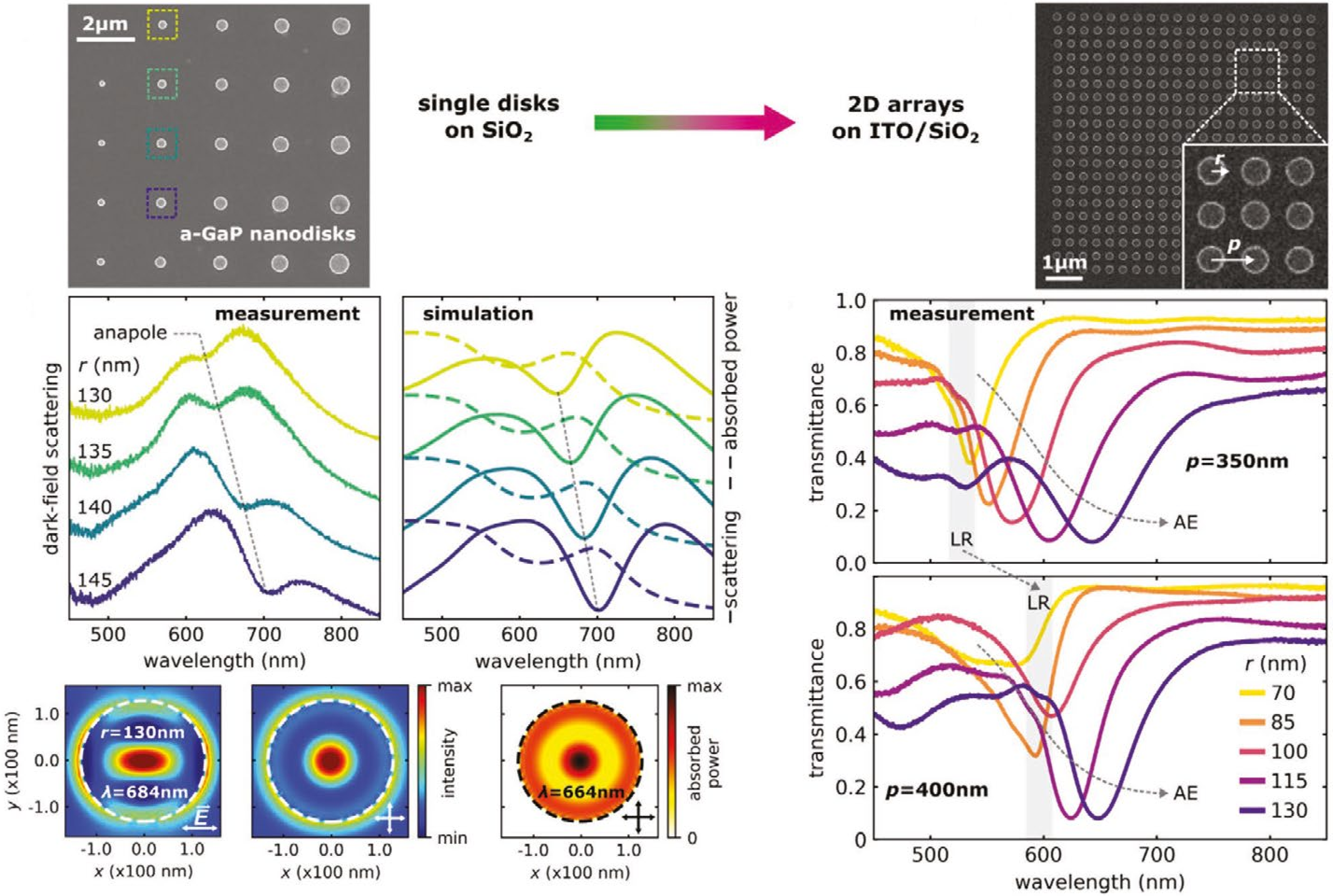
Adv Energy Mater **11,** 2102877 (2021)



Study of hydrogen evolution reaction with a-GaP metasurface photoelectrodes

Spectrally separated lattice resonance and anapole

Adv Energy Mater **11,** 2102877 (2021)



Spectral separation allows assessment of respective contribution to photocatalytic enhancement

Field profiles of lattice resonance and anapole excitation

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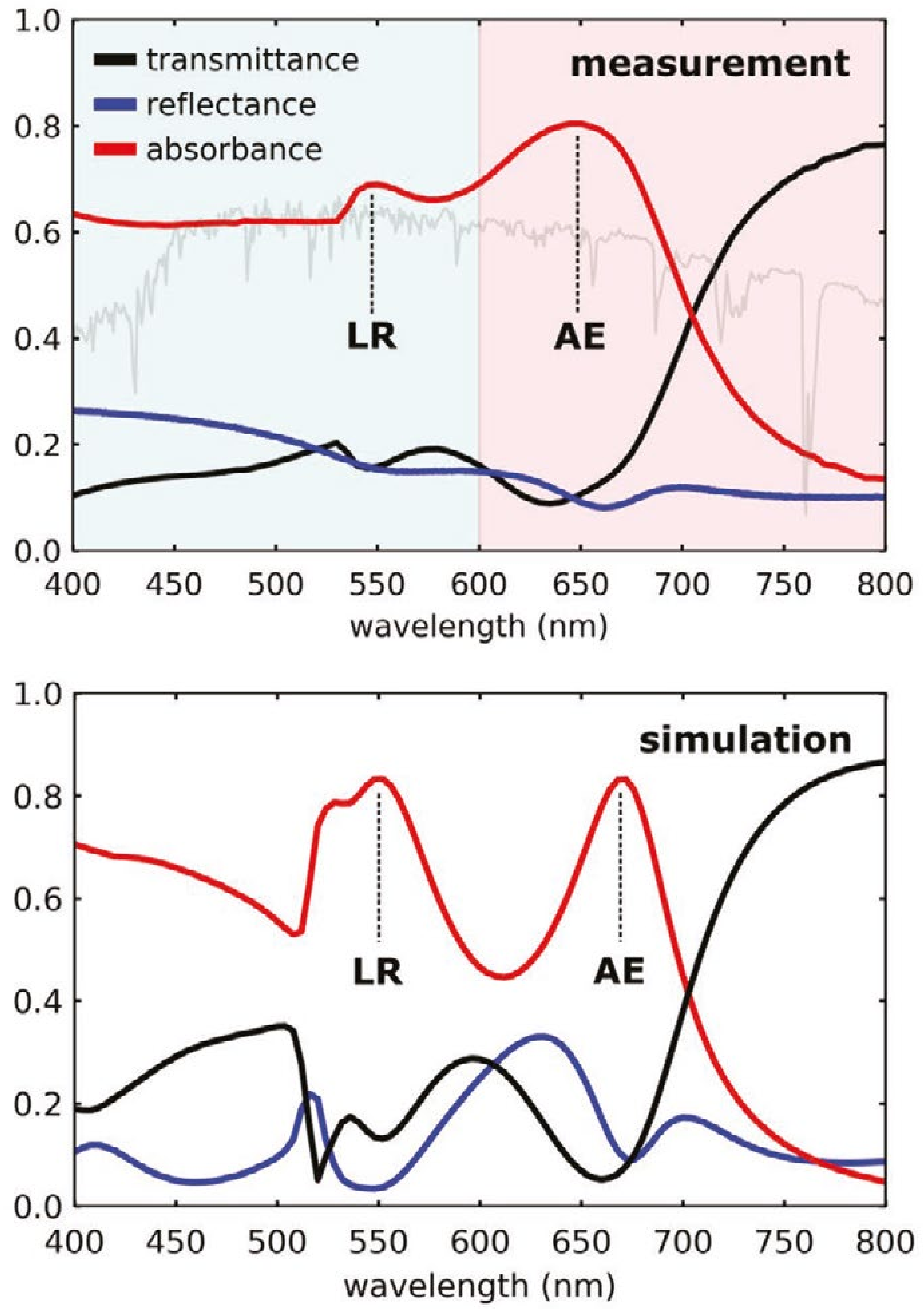

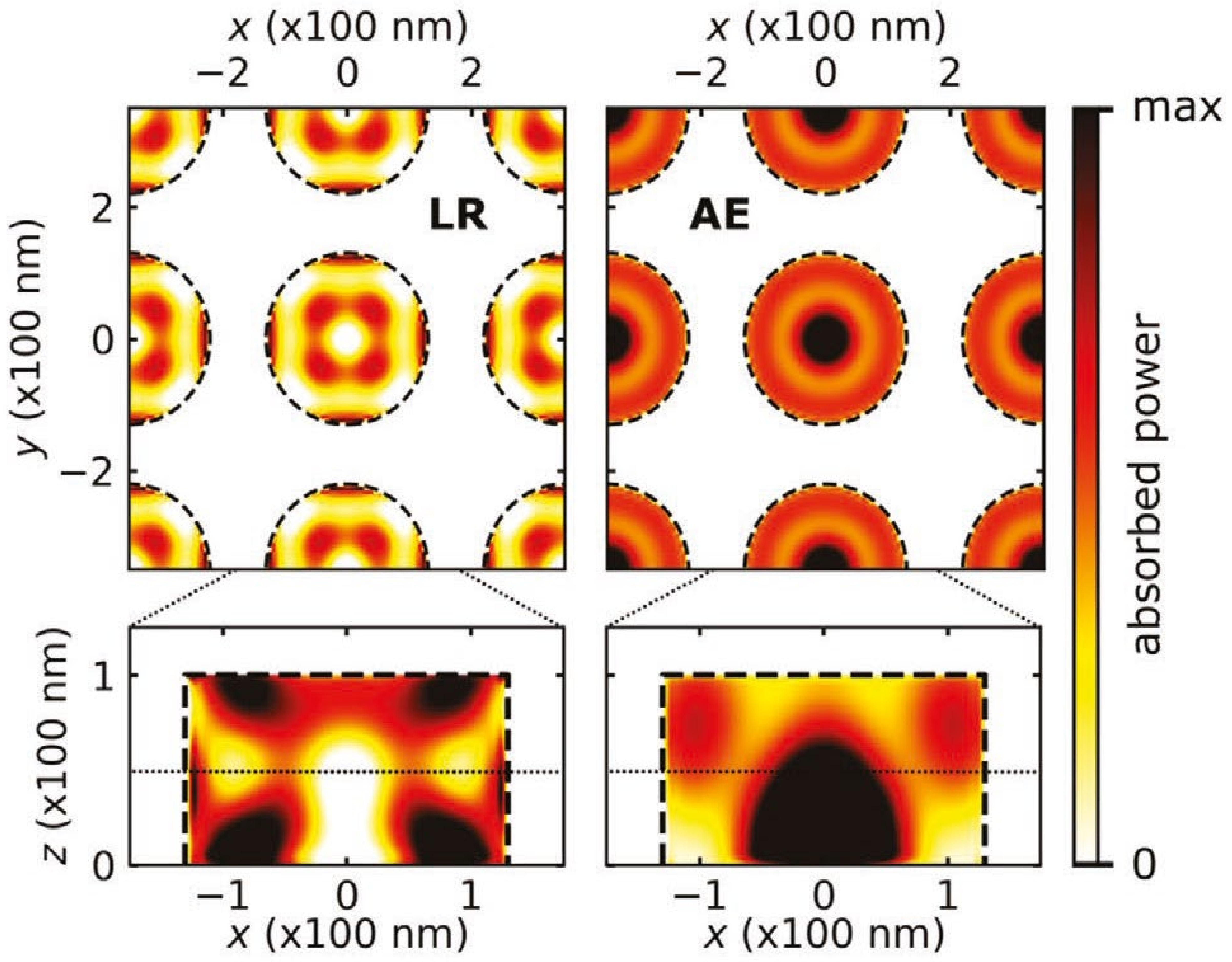

Lattice resonance promotes absorption hot spots on the surface

Photoelectrochemical characterization

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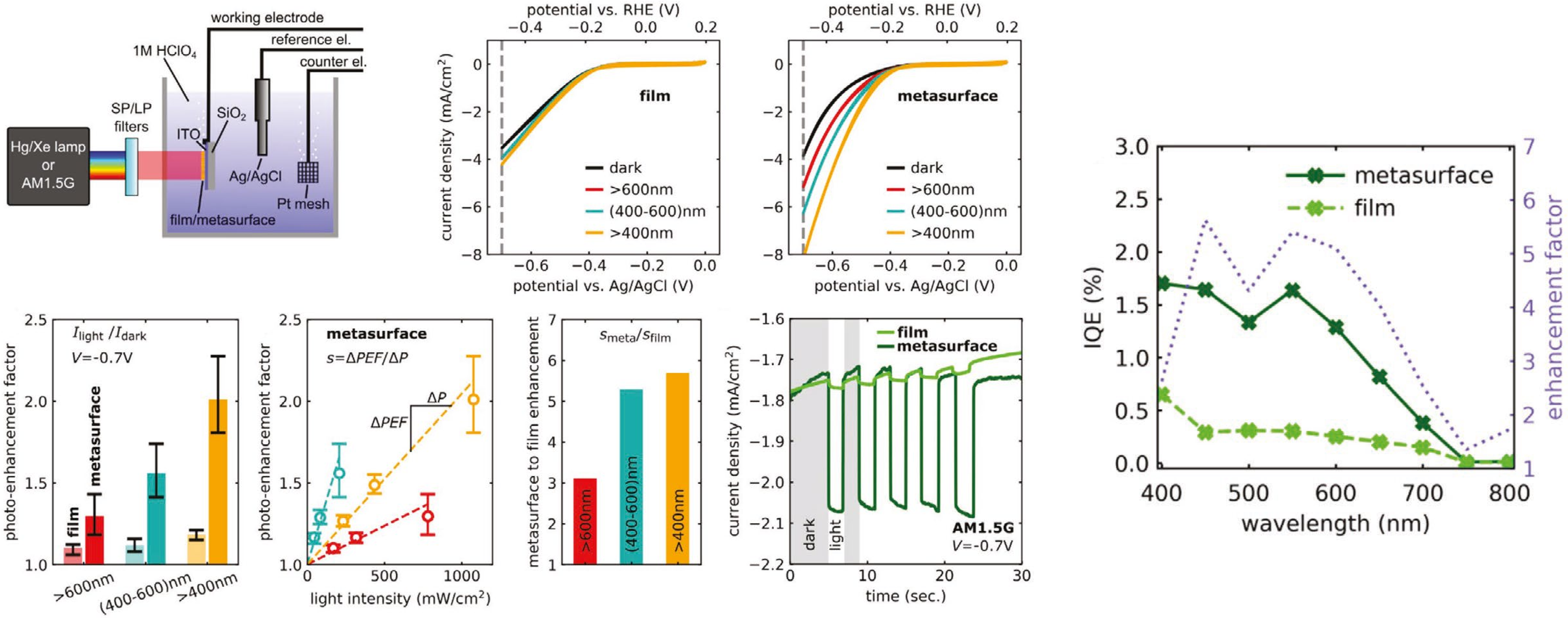
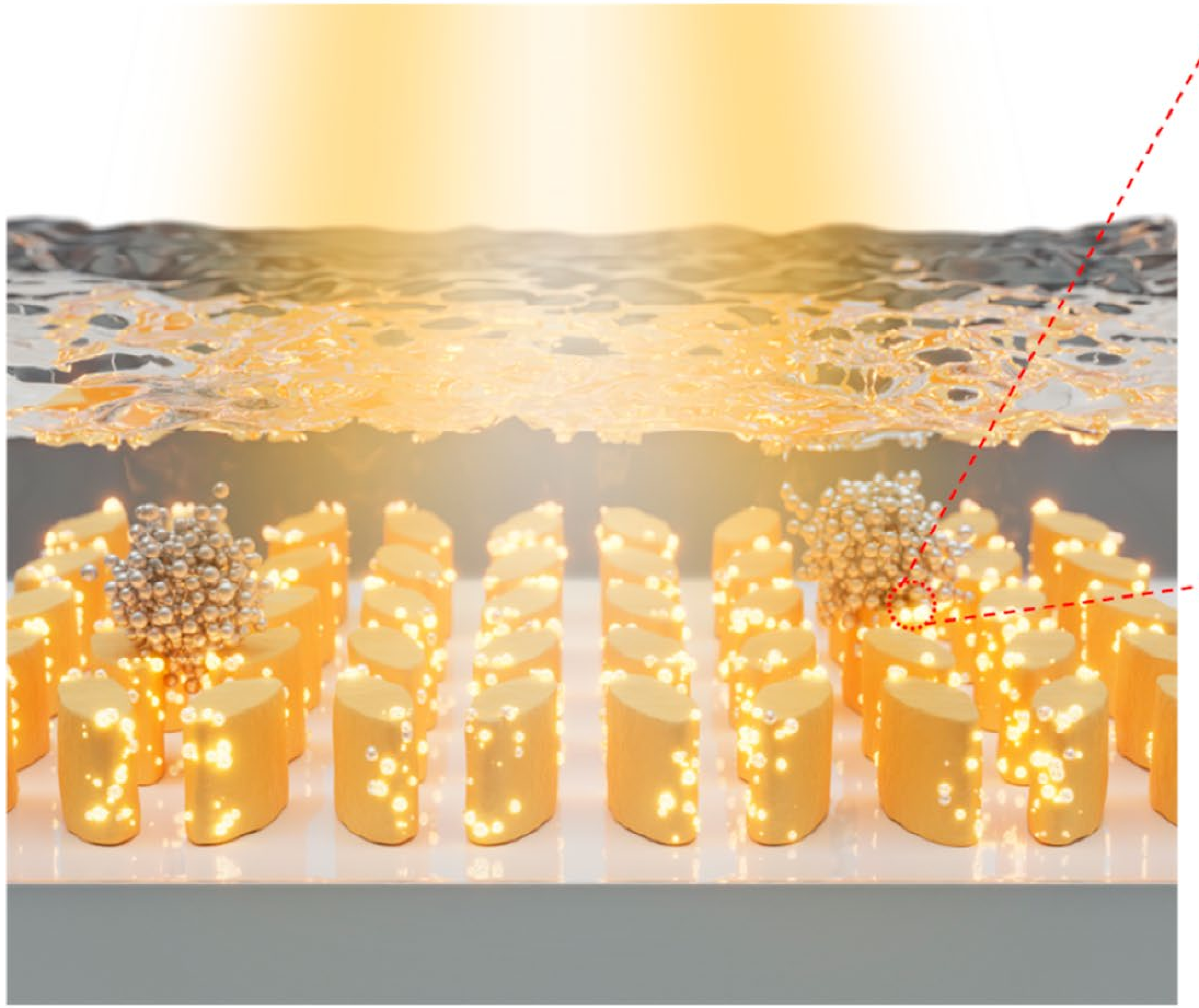
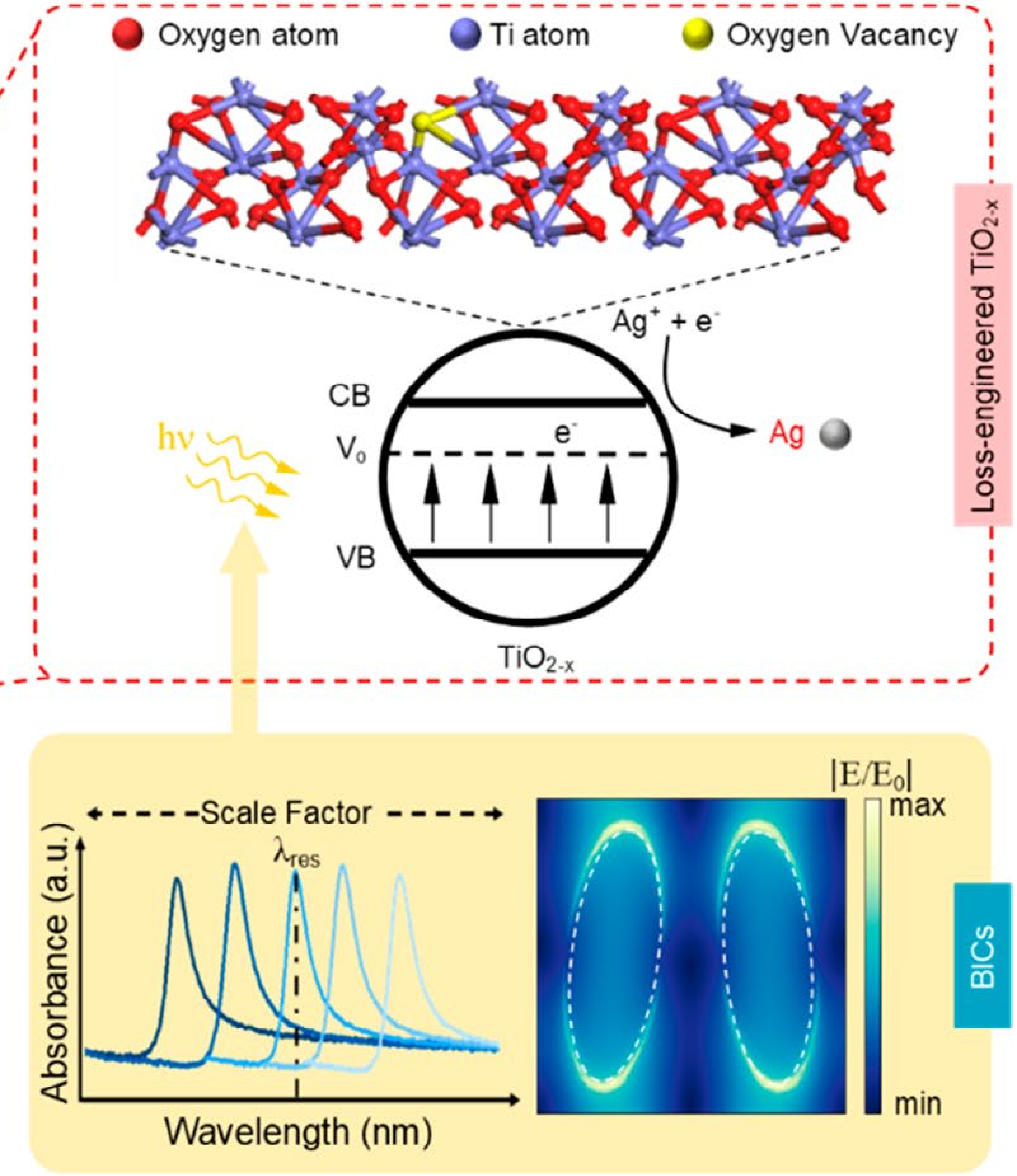


- unintentional n-doping of a-GaP revealed via surface photovoltage measurement ⇒ not ideal for hydrogen evolution reaction
- clear enhancement of photocurrent compared to bare film
- metasurface-to-film enhancement factor ~ 5 for white light
- strongest contribution of lattice resonance to overall enhancement due to near-surface absorption hot spots

Catalytic metasurfaces via bound states in the continuum

ACS Nano **16,** 13057 (2022)





Optical absorption engineering via BICs enables thin, low-materials-loss catalytic metasurfaces

Tunability of resonance: frequency and field enhancement

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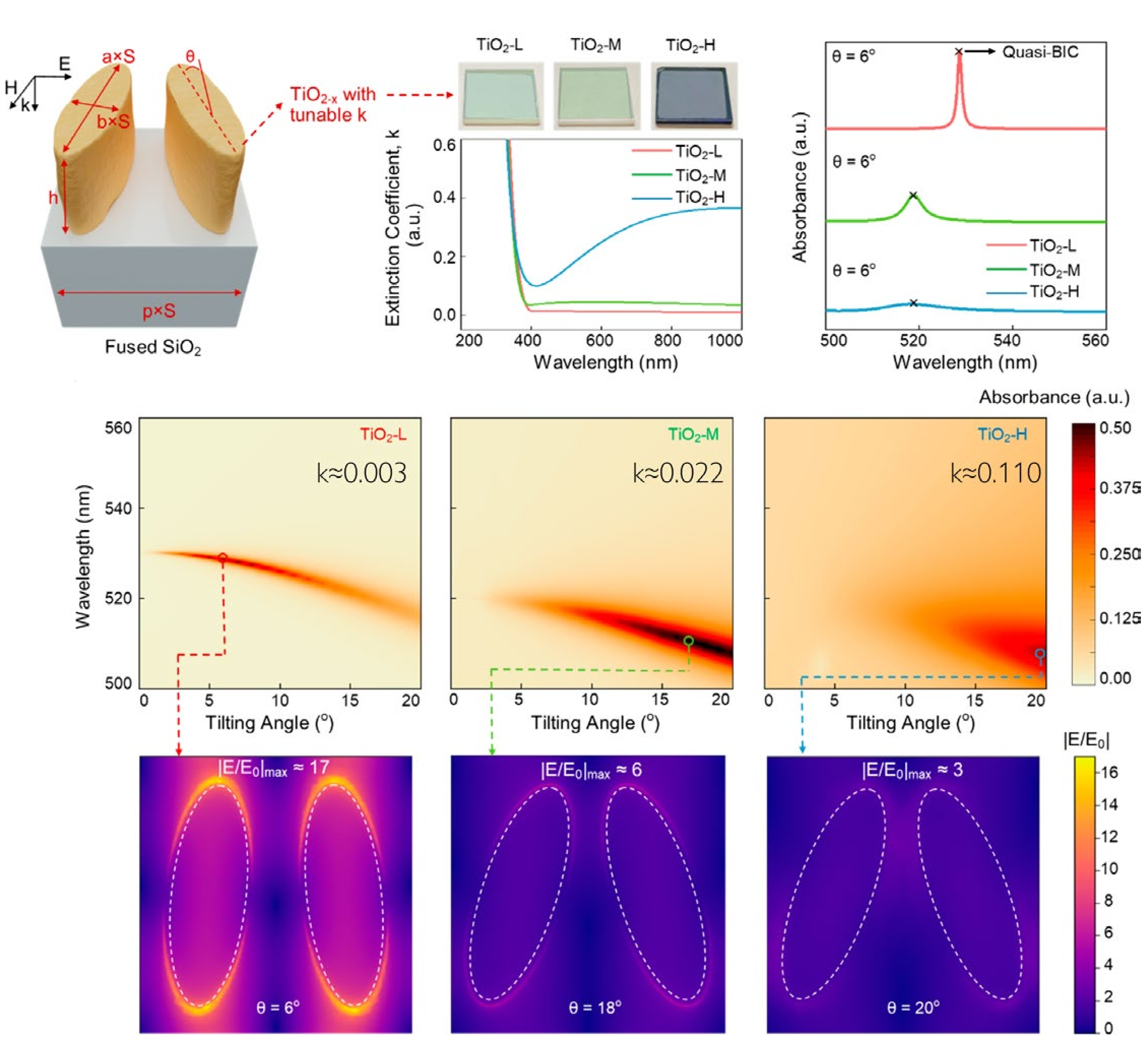

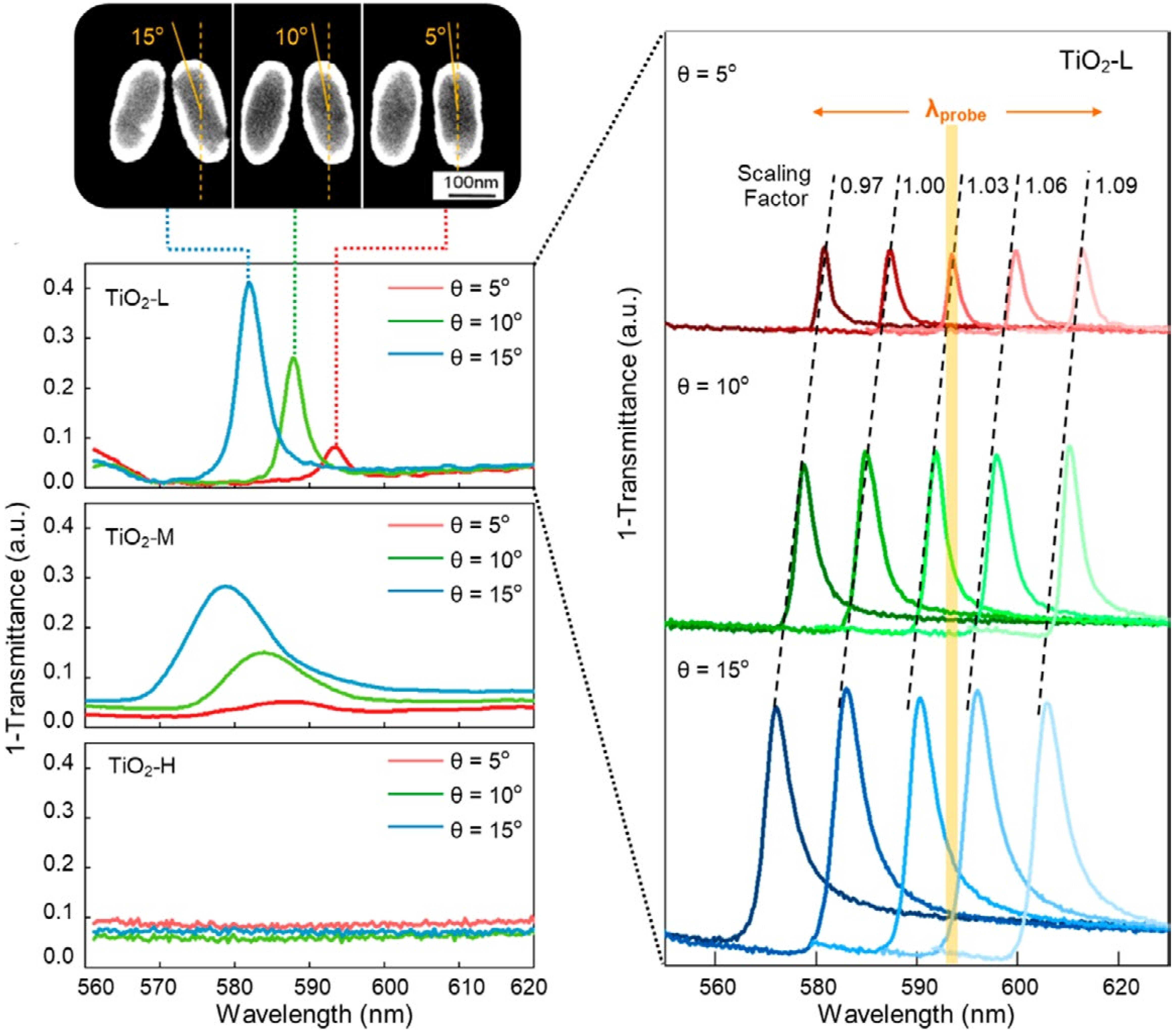

Bound states in the continuum enable a large amount of design flexibility

Experimental monitoring of silver reduction

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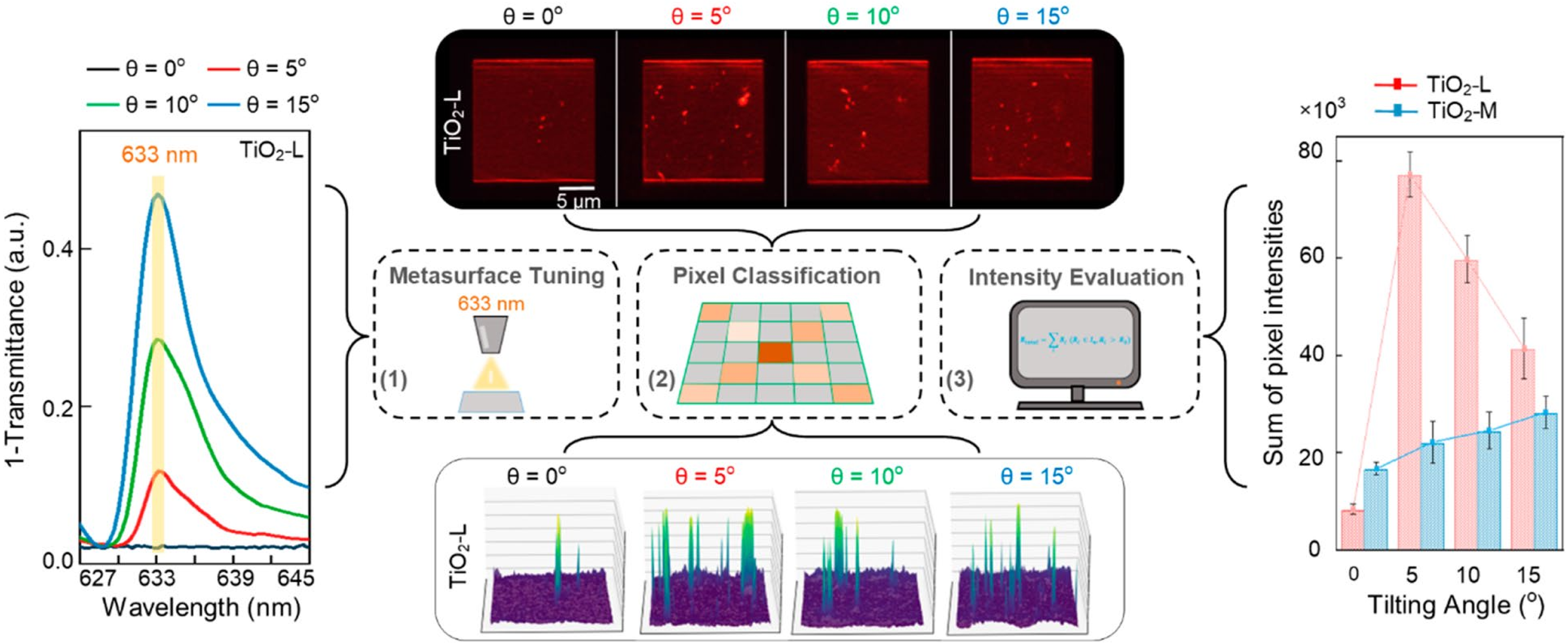

Low-loss TiO_2 outperforms higher-loss TiO_2 due to resonant field enhancement

Critical coupling model of photocatalytic performance

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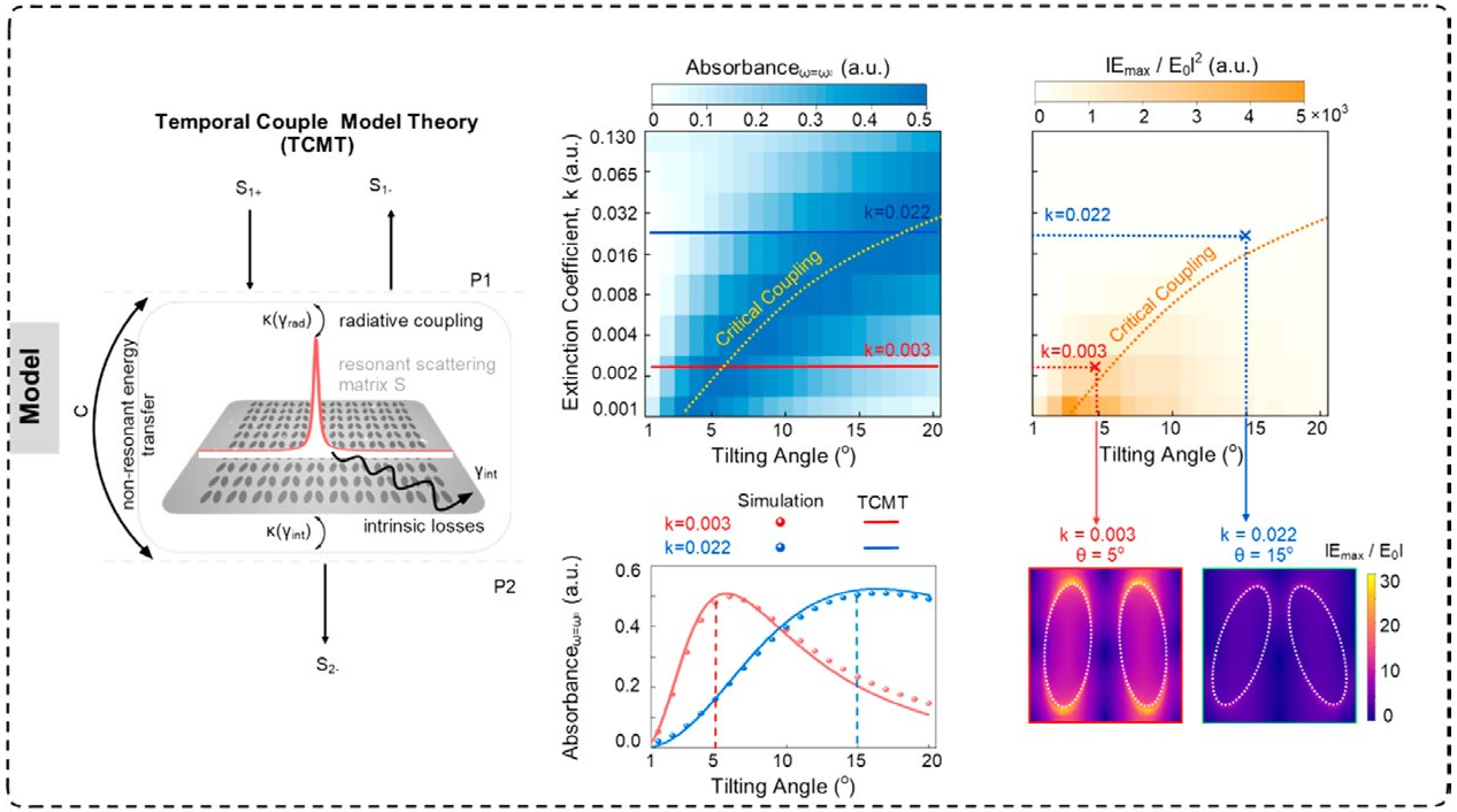
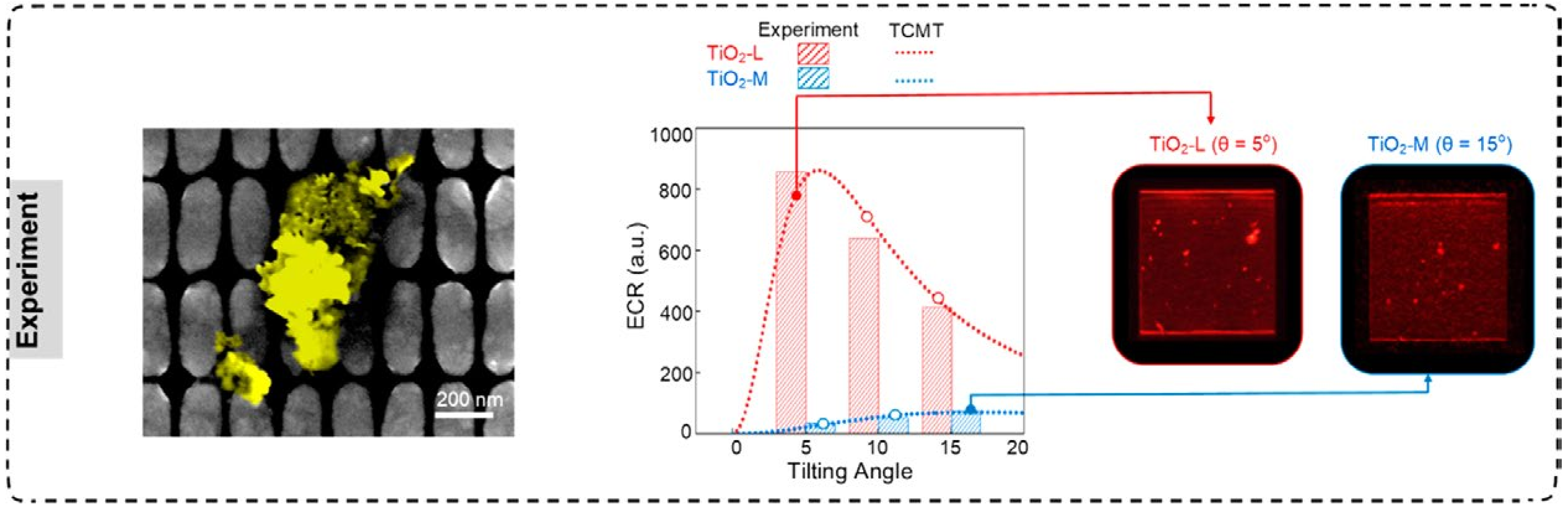




- intrinsic loss tunability via change in ALD precursors γ_{int}~k
- radiative loss tunabiliy via BIC γ_{rad}~α^2=$\sin^2\theta$
- *effective Ag coverage ratio (ECR)* can be related to field-enhancement via fitting parameter β(k)
- enhancement of ECR between low-loss and high-loss TiO_2 mainly driven by six-fold increase of electric near-field intensity
- reduction rate does not scale linearly with electric near-field intensity:
  β(k≈0.003)=39±1; β(k≈0.022)=24±2

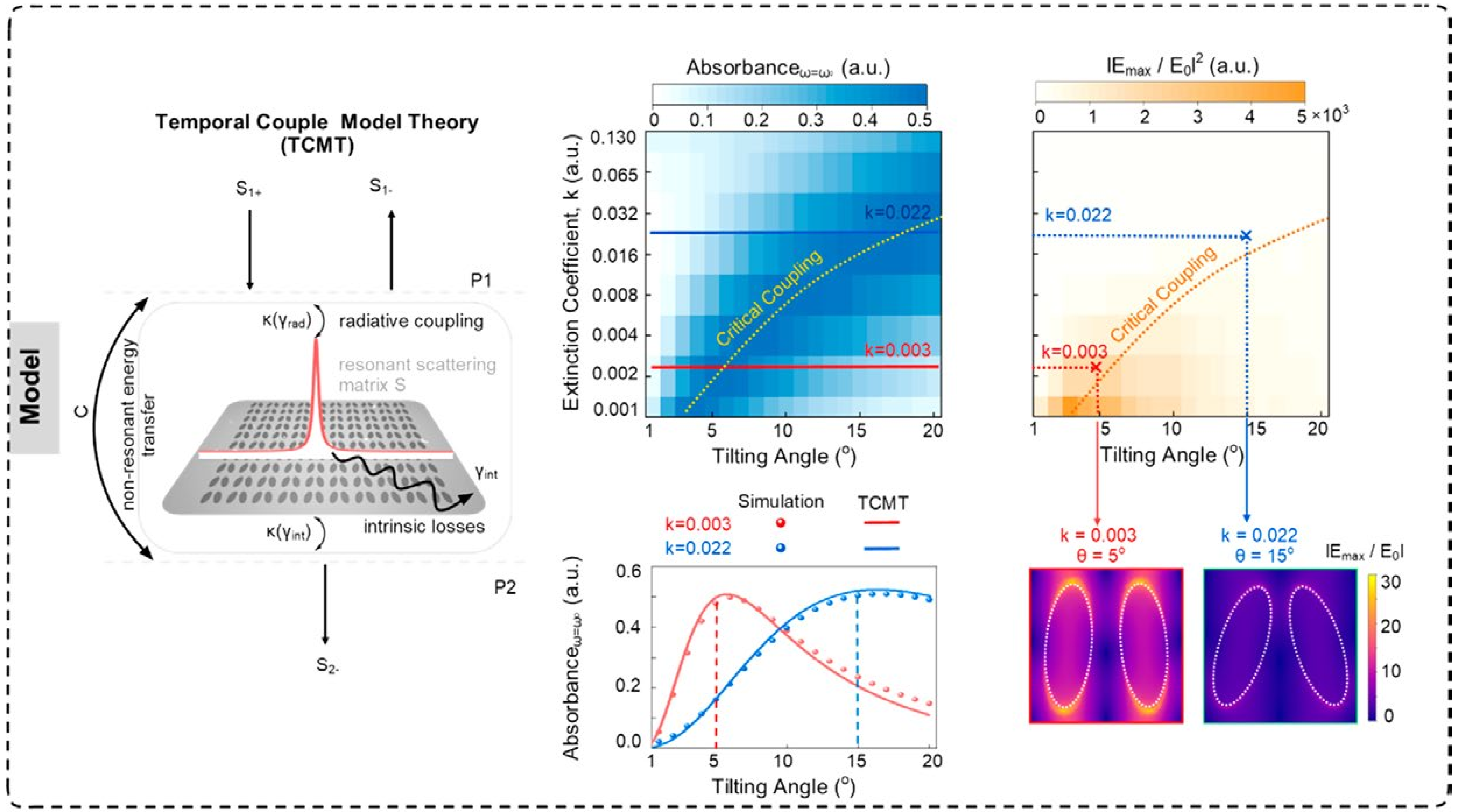
$$\mathrm{ECR}(\theta,\, k) = \frac{R_{\theta,k} - R_{\theta=0,k}}{R_{\theta=0,k}} = \beta(k)\cdot|E/E_0|^2(\theta,\, k)$$

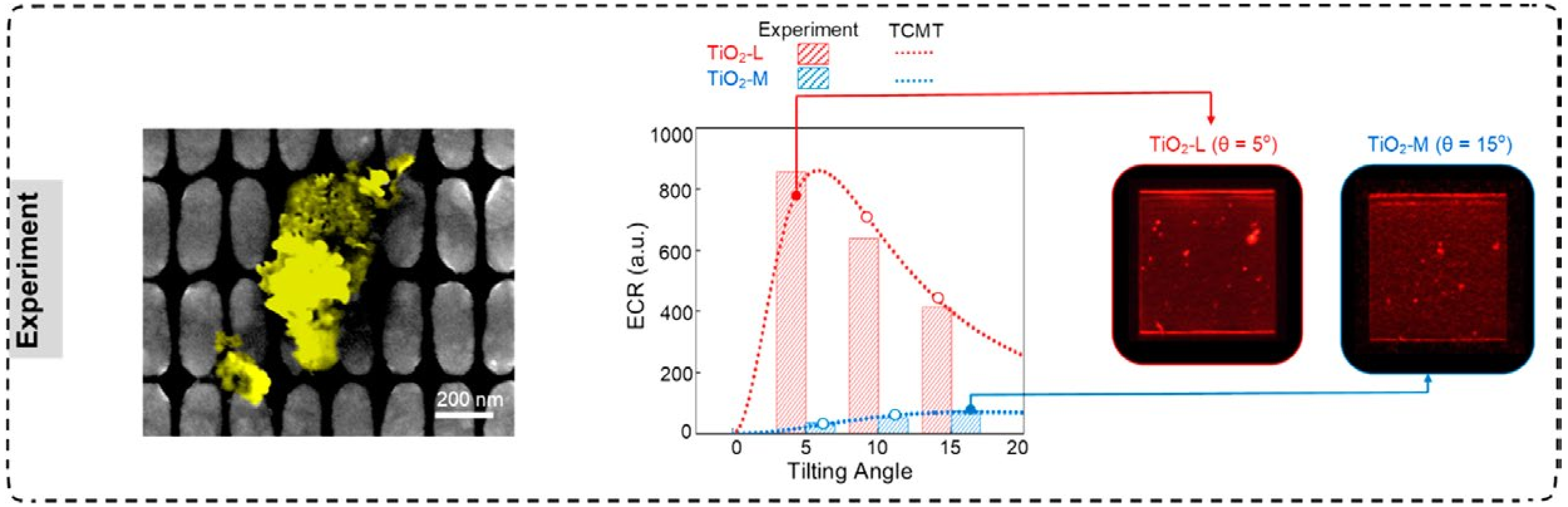
Low defect concentrations, low extinction, are favoured more strongly!

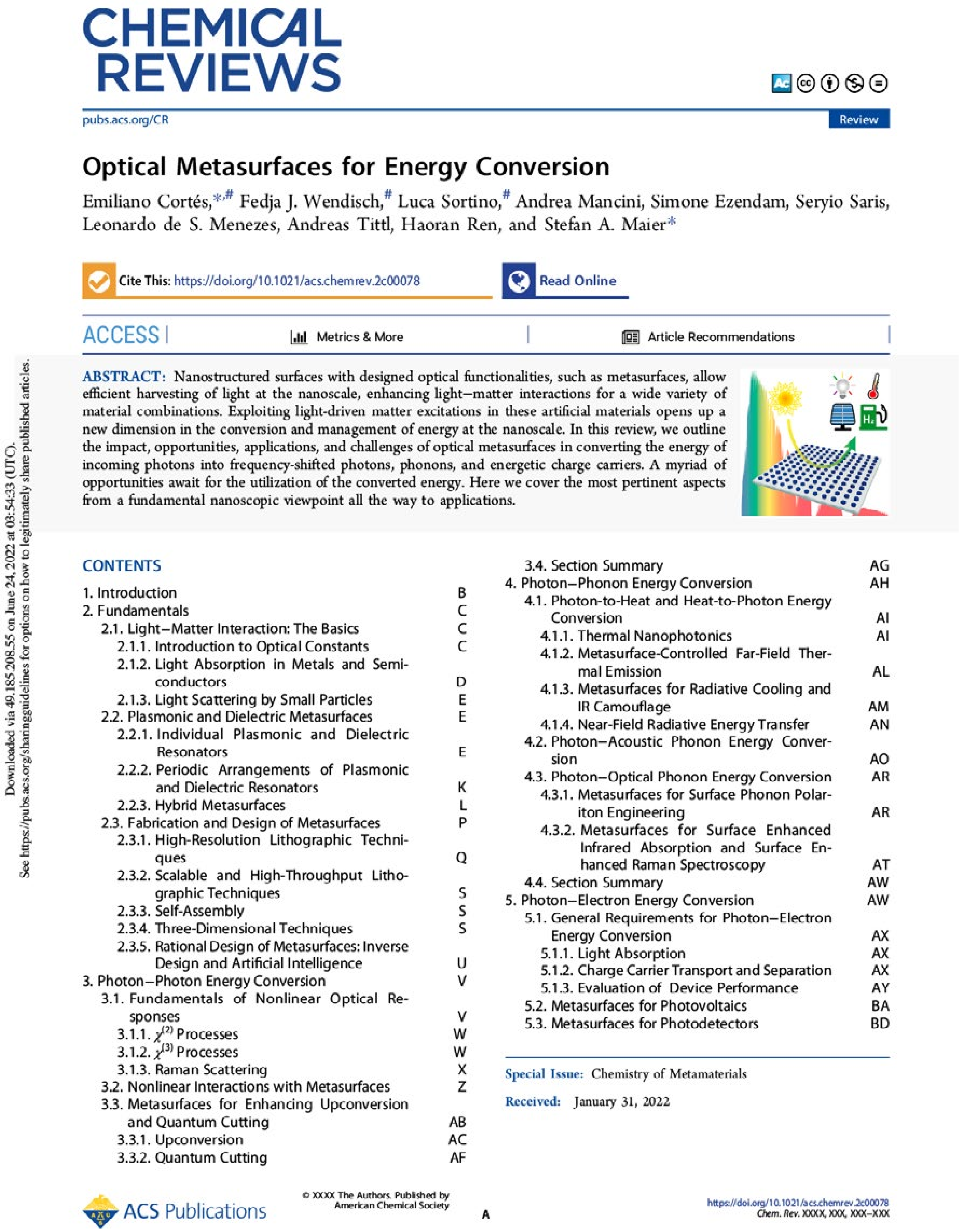
Metasurfaces: a versatile platform for energy conversion

ACS Nano **16,** 13057 (2022)

Chemical Reviews **122,** 15082 (2022)







CHEMICAL REVIEWS

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Optical Metasurfaces for Energy Conversion

Emiliano Cortés,*,# Fedja J. Wendisch,# Luca Sortino,# Andrea Mancini, Simone Ezendam, Seryio Saris, Leonardo de S. Menezes, Andreas Tittl, Haoran Ren, and Stefan A. Maier*

Cite This: https://doi.org/10.1021/acs.chemrev.2c00078 Read Online

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ABSTRACT: Nanostructured surfaces with designed optical functionalities, such as metasurfaces, allow efficient harvesting of light at the nanoscale, enhancing light–matter interactions for a wide variety of material combinations. Exploiting light-driven matter excitations in these artificial materials opens up a new dimension in the conversion and management of energy at the nanoscale. In this review, we outline the impact, opportunities, applications, and challenges of optical metasurfaces in converting the energy of incoming photons into frequency-shifted photons, phonons, and energetic charge carriers. A myriad of opportunities await for the utilization of the converted energy. Here we cover the most pertinent aspects from a fundamental nanoscopic viewpoint all the way to applications.

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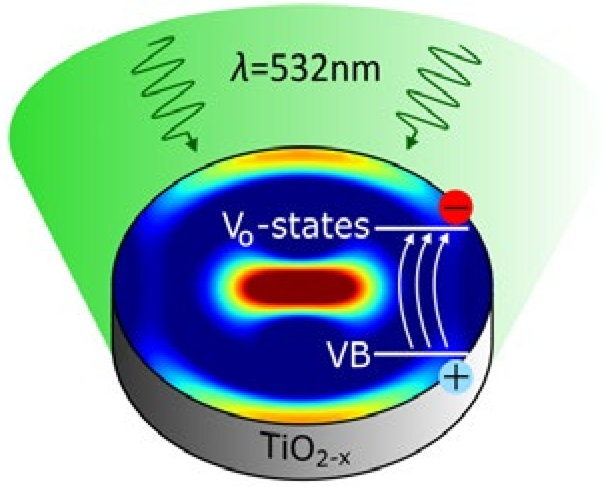
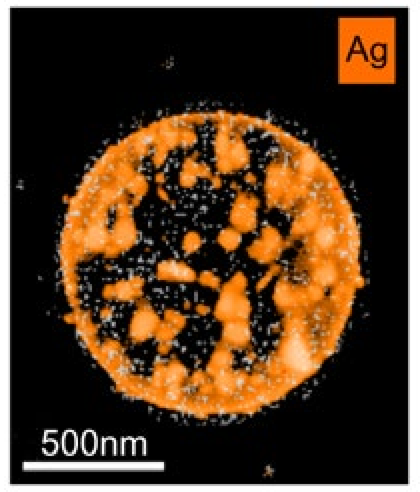
Chem. Rev. XXXX, XXX, XXX–XXX

Outline





Anapoles and BICs for energy conversion

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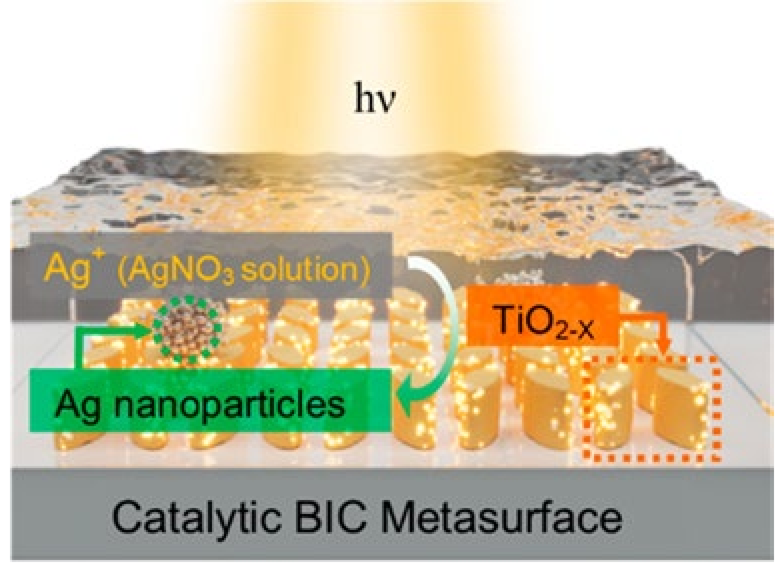
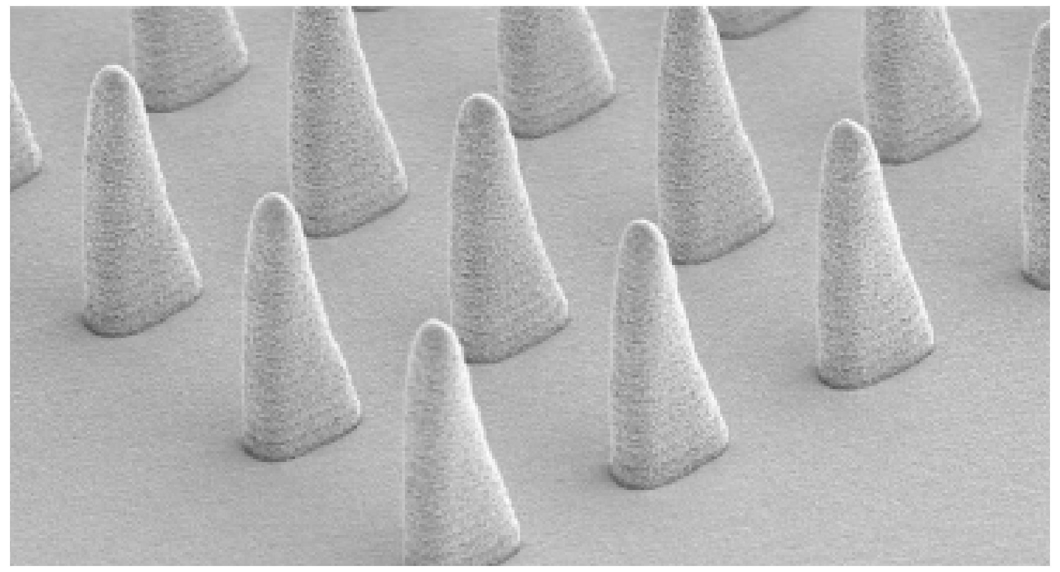
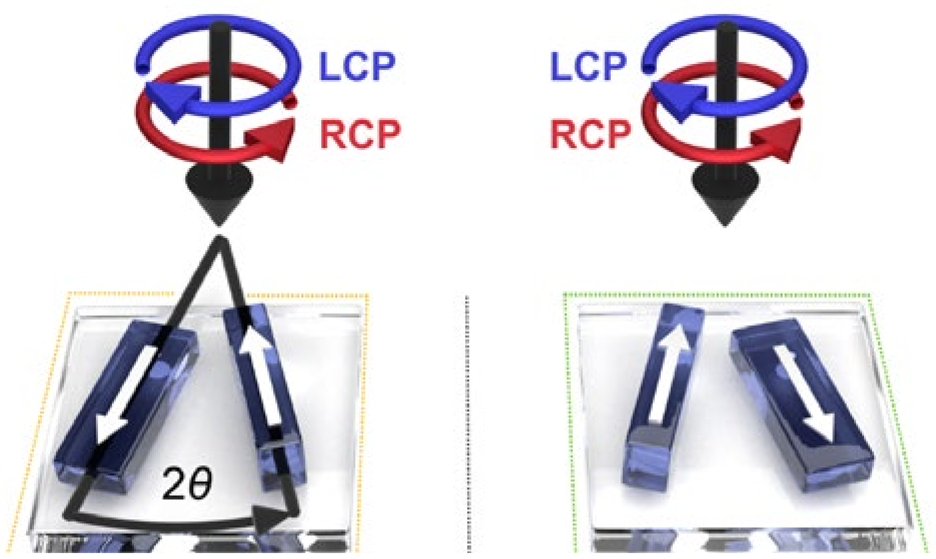


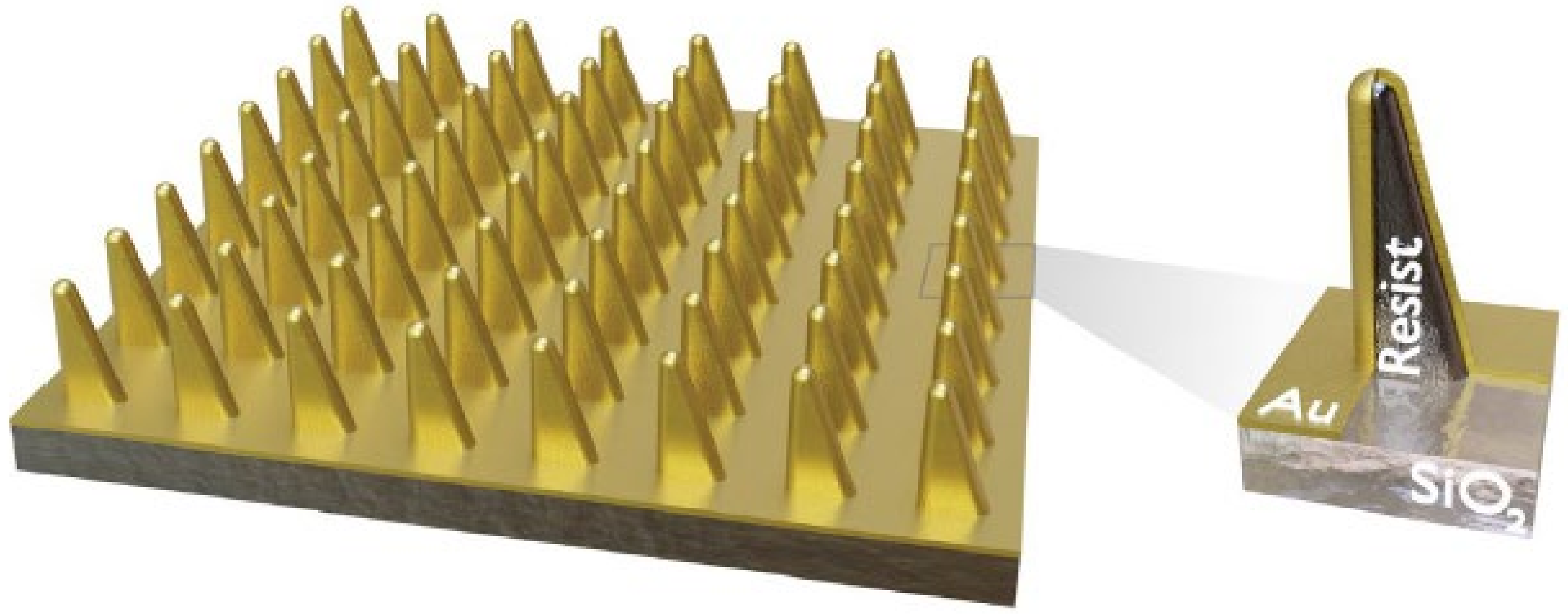


BICs for infrared absorption and chirality

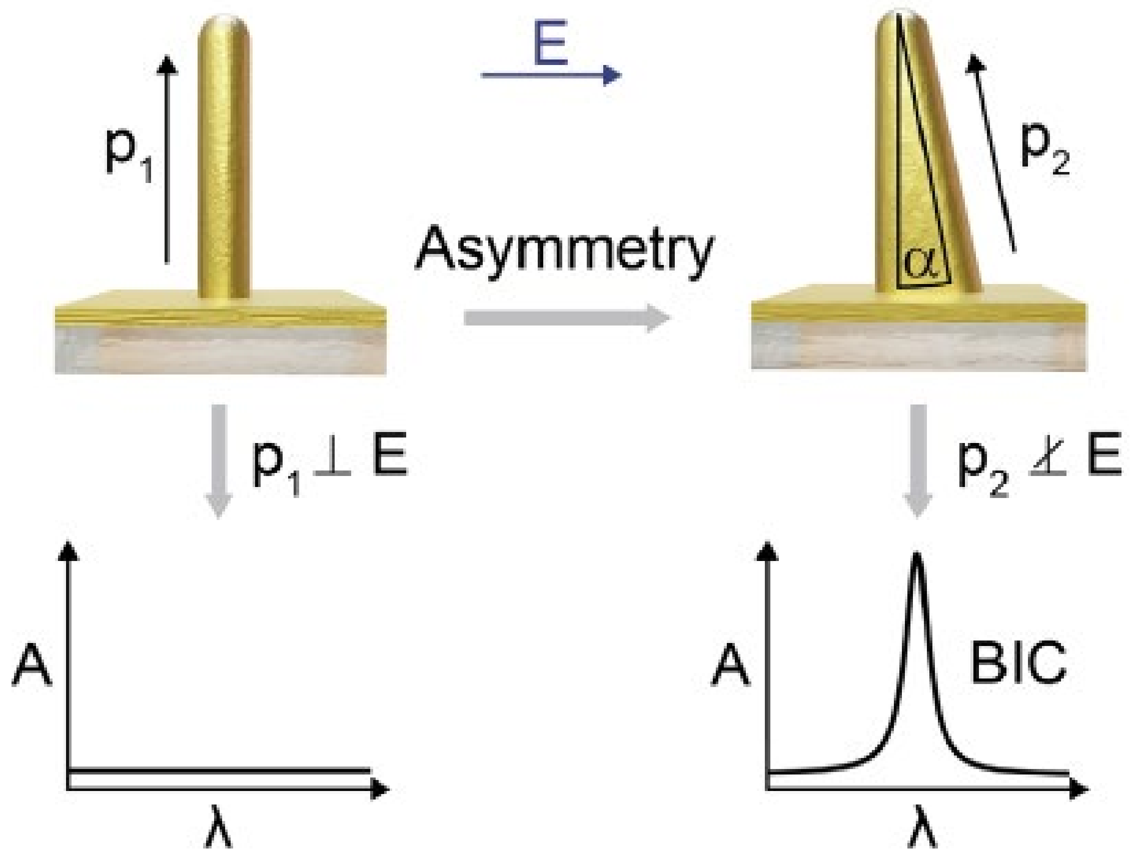
*arXiv:***2210.05339**

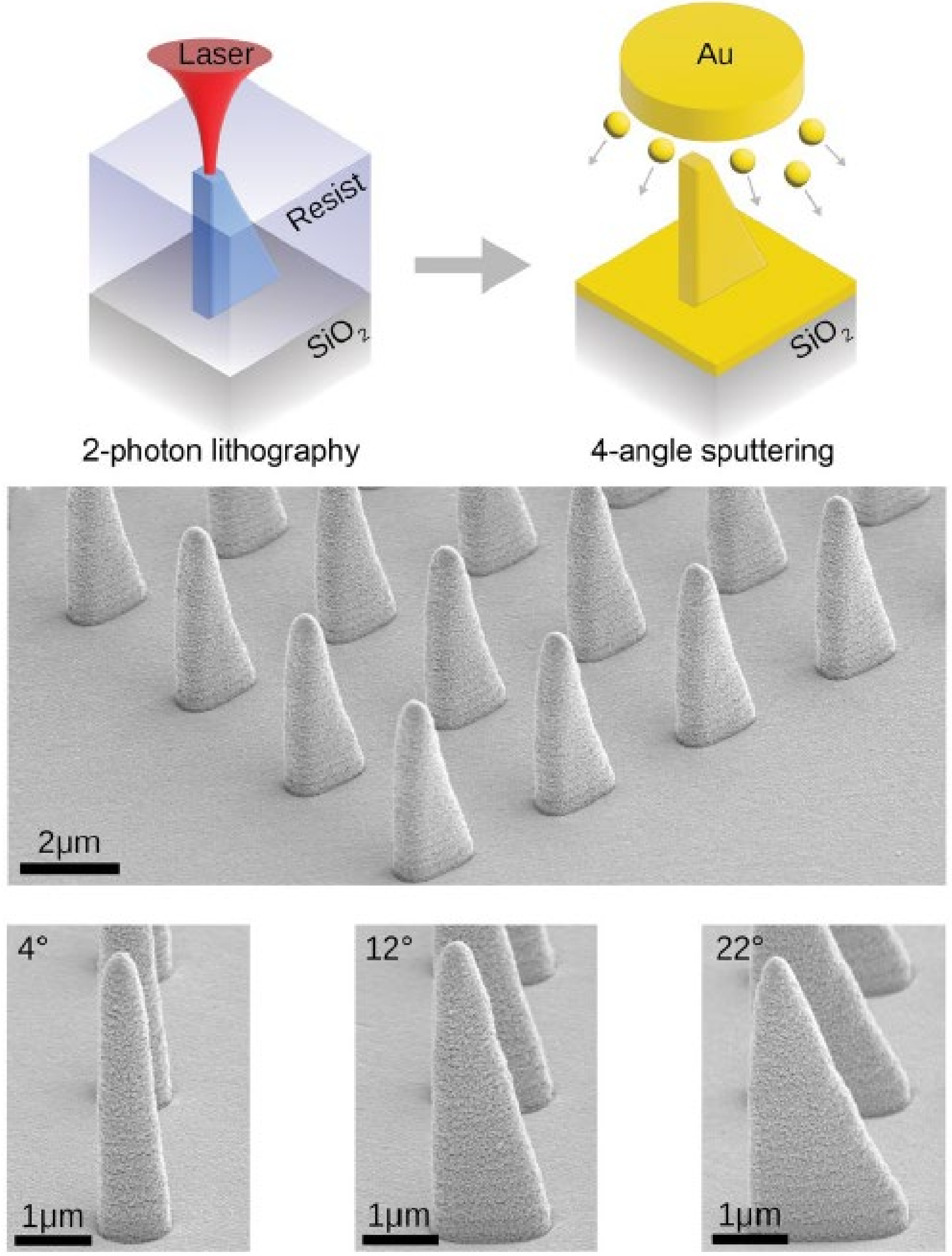


Mid-IR metasurfaces based on nanoantenna engineering



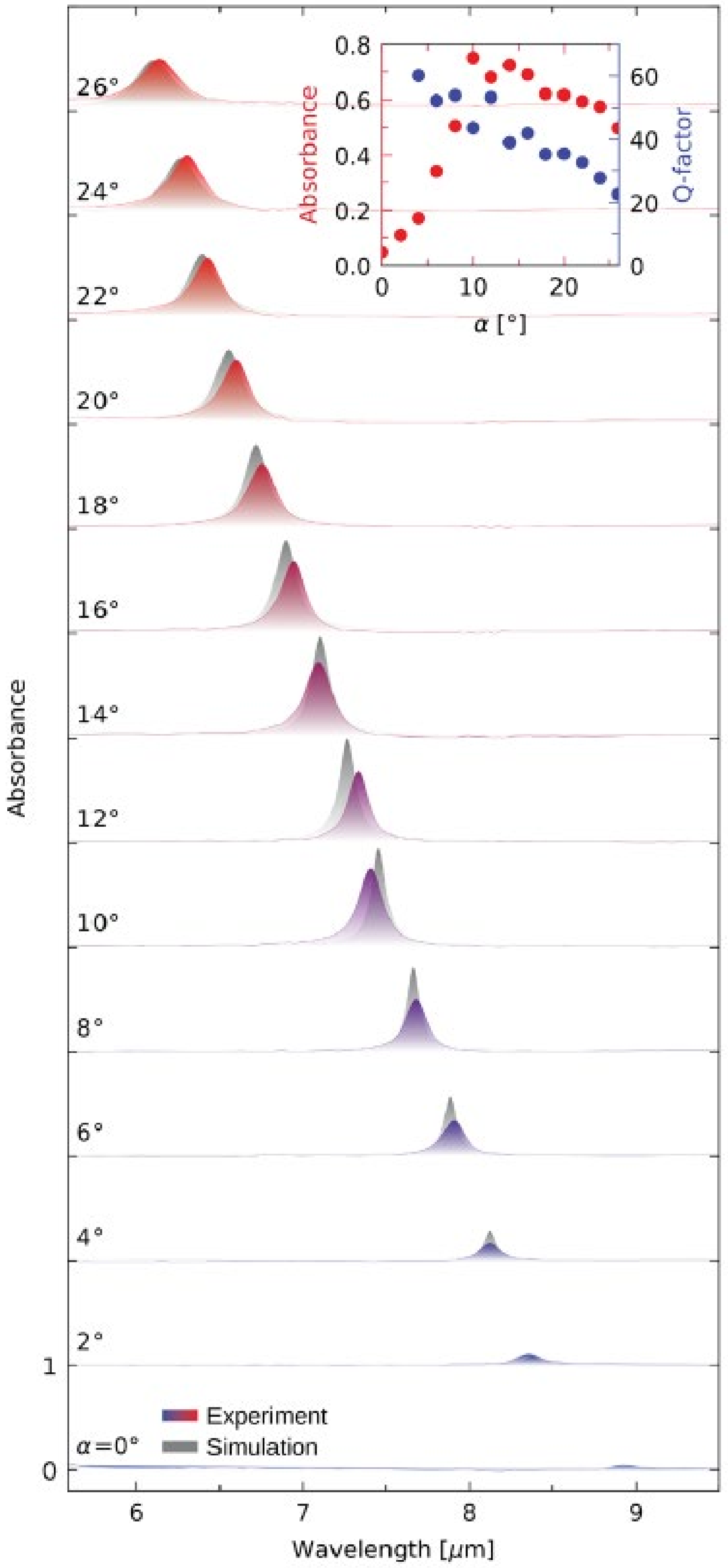
Arrays of gold coated standing triangles

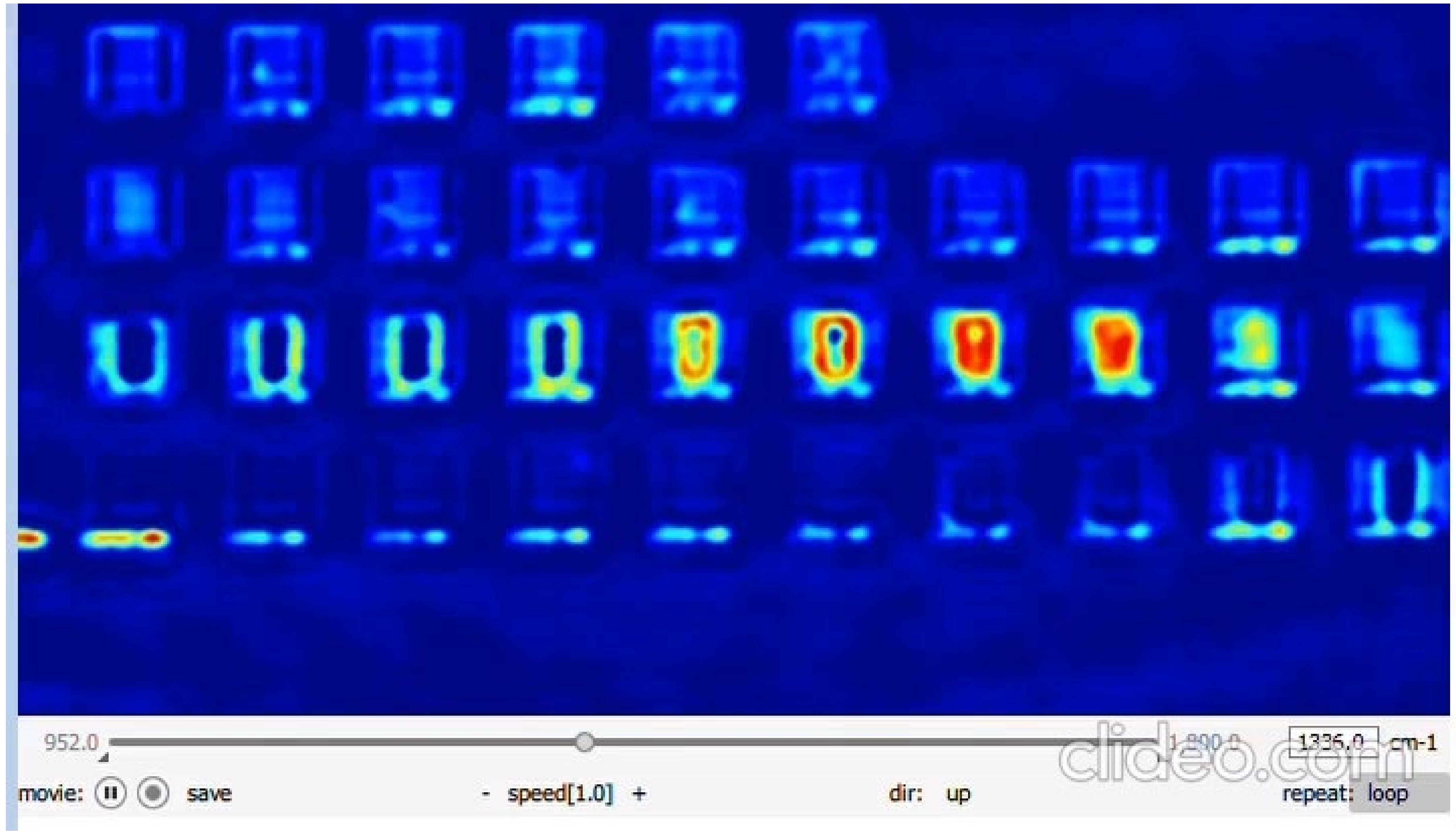




Example of a symmetry-broken "nanofin" bound states in the continuum metasurface

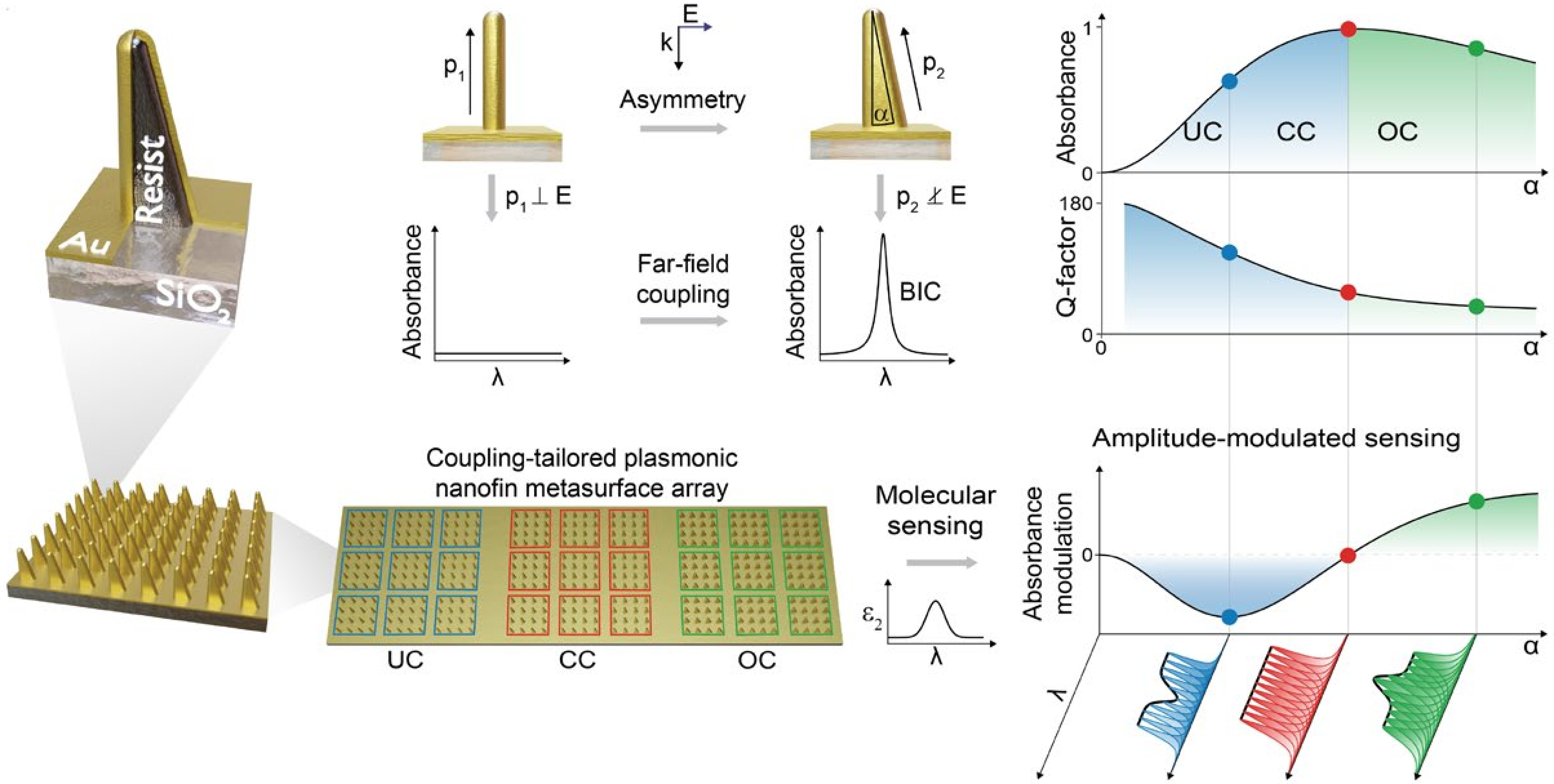
Bound states in the continuum generate sharp resonances

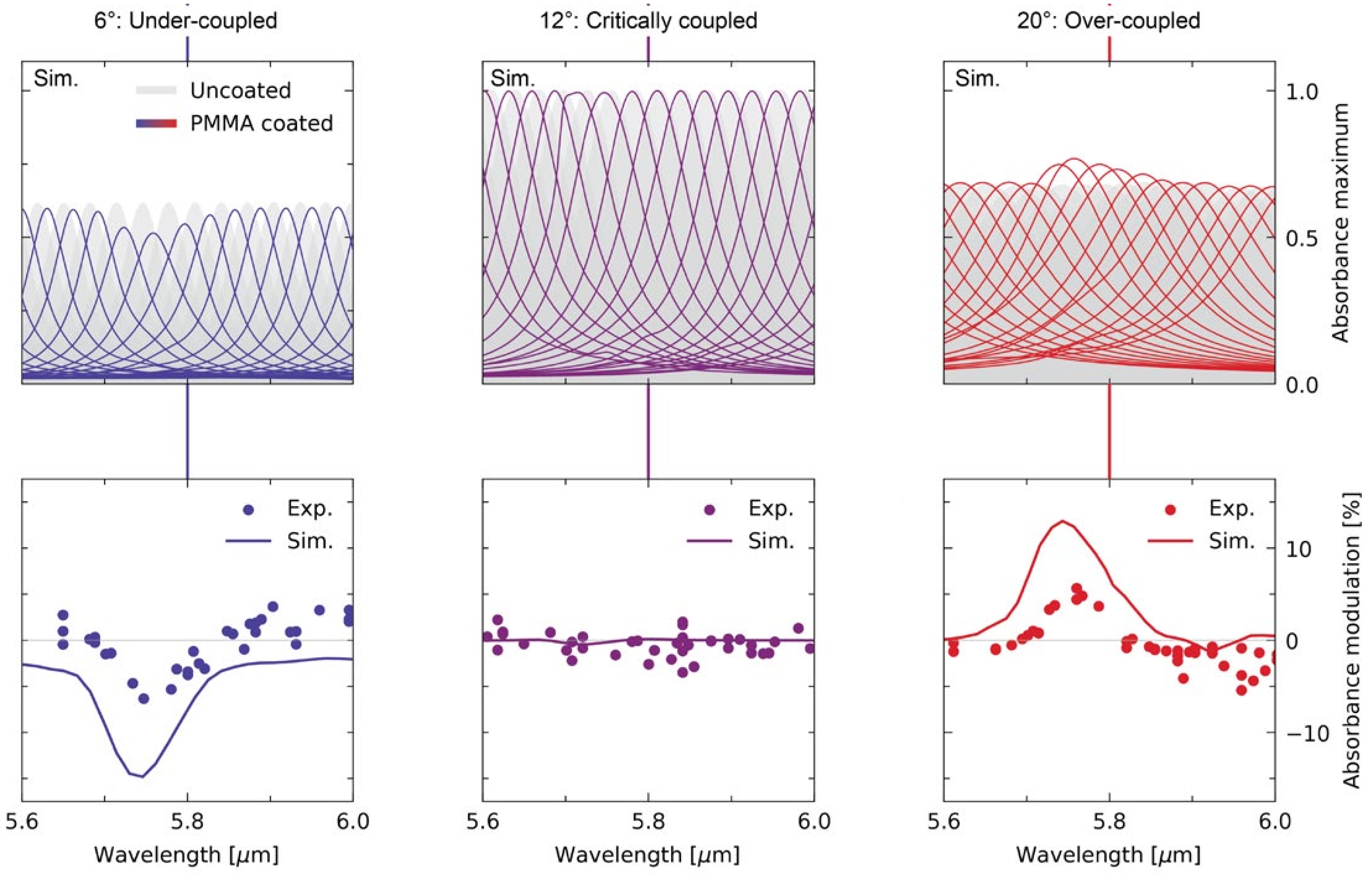




Pixelated sensing arrays

Coupling-tailored molecular sensing in the mid-IR



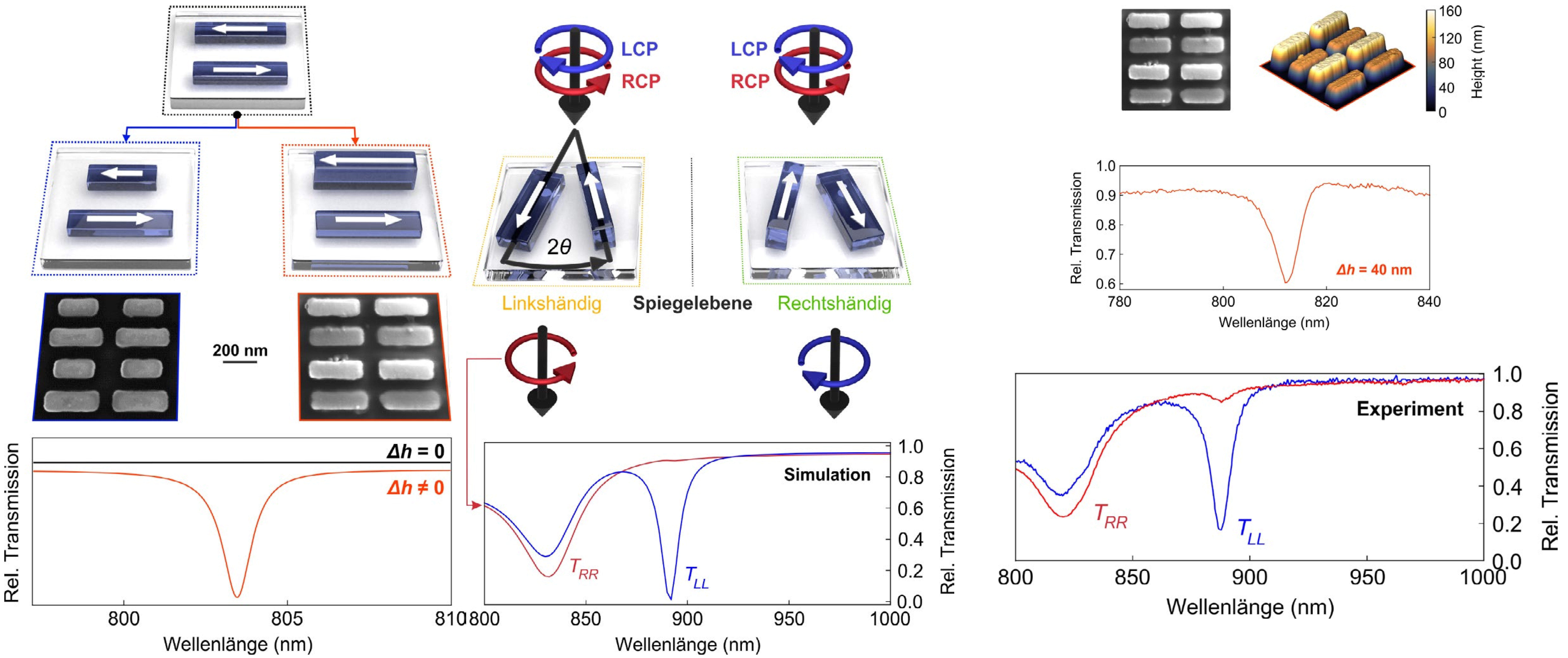


Symmetry-breaking tunes ratio of radiative to intrinsic losses

Surface-enhanced infrared absorption spectroscopy (SEIRA) in different coupling regimes

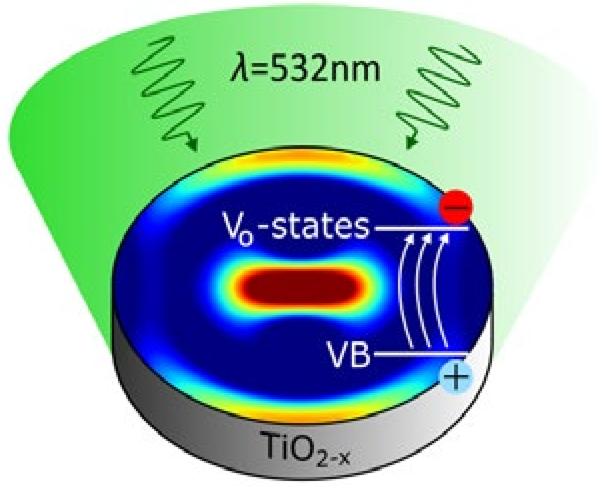
Chiral BIC Metasurfaces

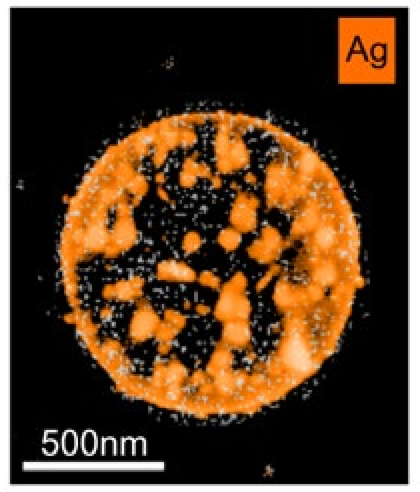
arXiv:2210.05339



Height degree of freedom enables new chiral BIC designs

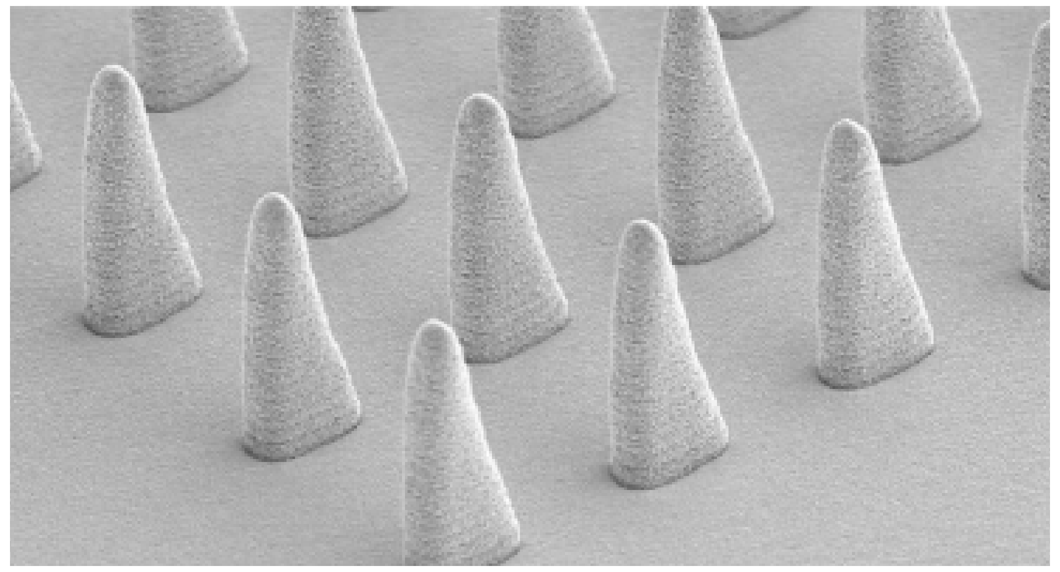
Closing credits





Emiliano Cortés
Andreas Tittl
Ian Sharp
Markus Becherer

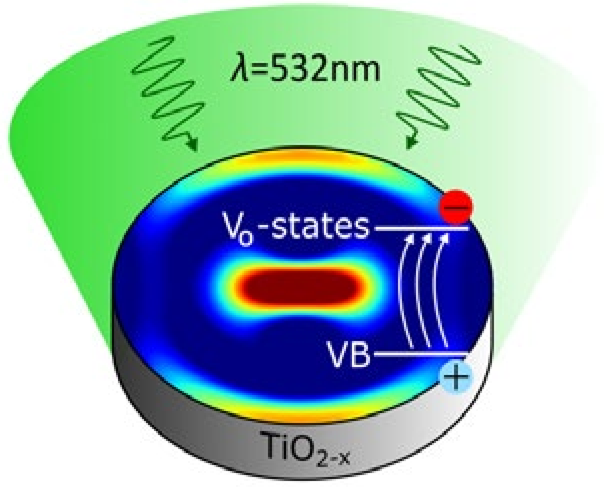
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
TECHNISCHE UNIVERSITÄT MÜNCHEN

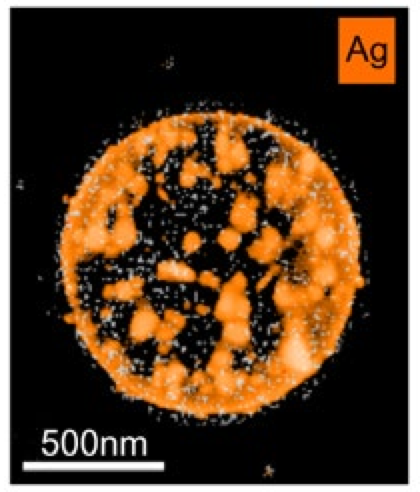


Andreas Tittl
Haoran Ren
Yuri Kivshar

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
THE AUSTRALIAN NATIONAL UNIVERSITY

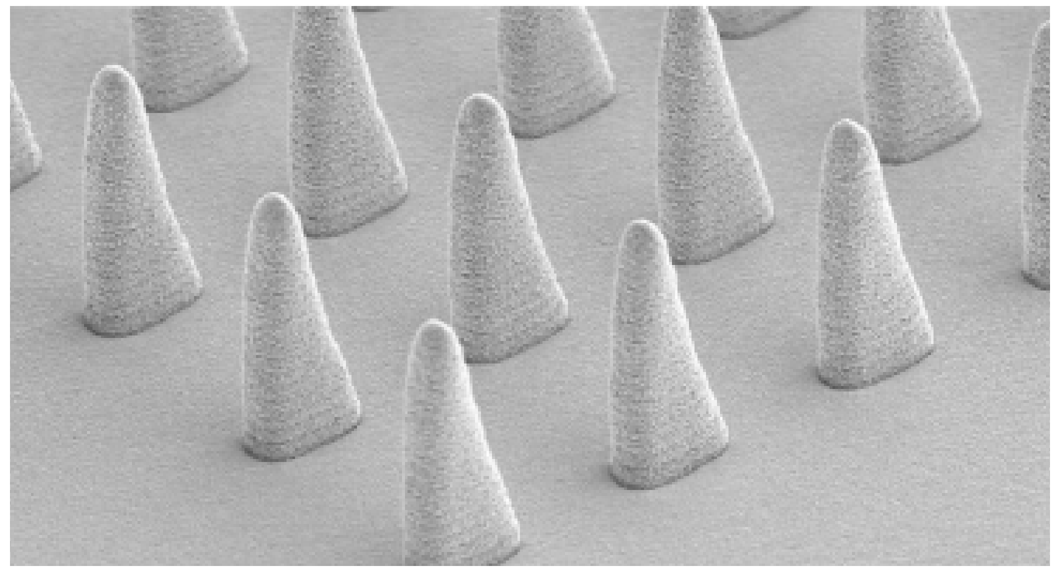
Thanks for your attention :-)





Anapoles and BICs for energy con-version

ACS Nano **16,** 13057 (2022)
Adv Energy Mater **11,** 2102877 (2021)
ACS Photonics **8,** 1469 (2021)
ACS Nano **14,** 2456 (2020)



BICs for infrared absorption and chirality

*arXiv:***2210.05339**