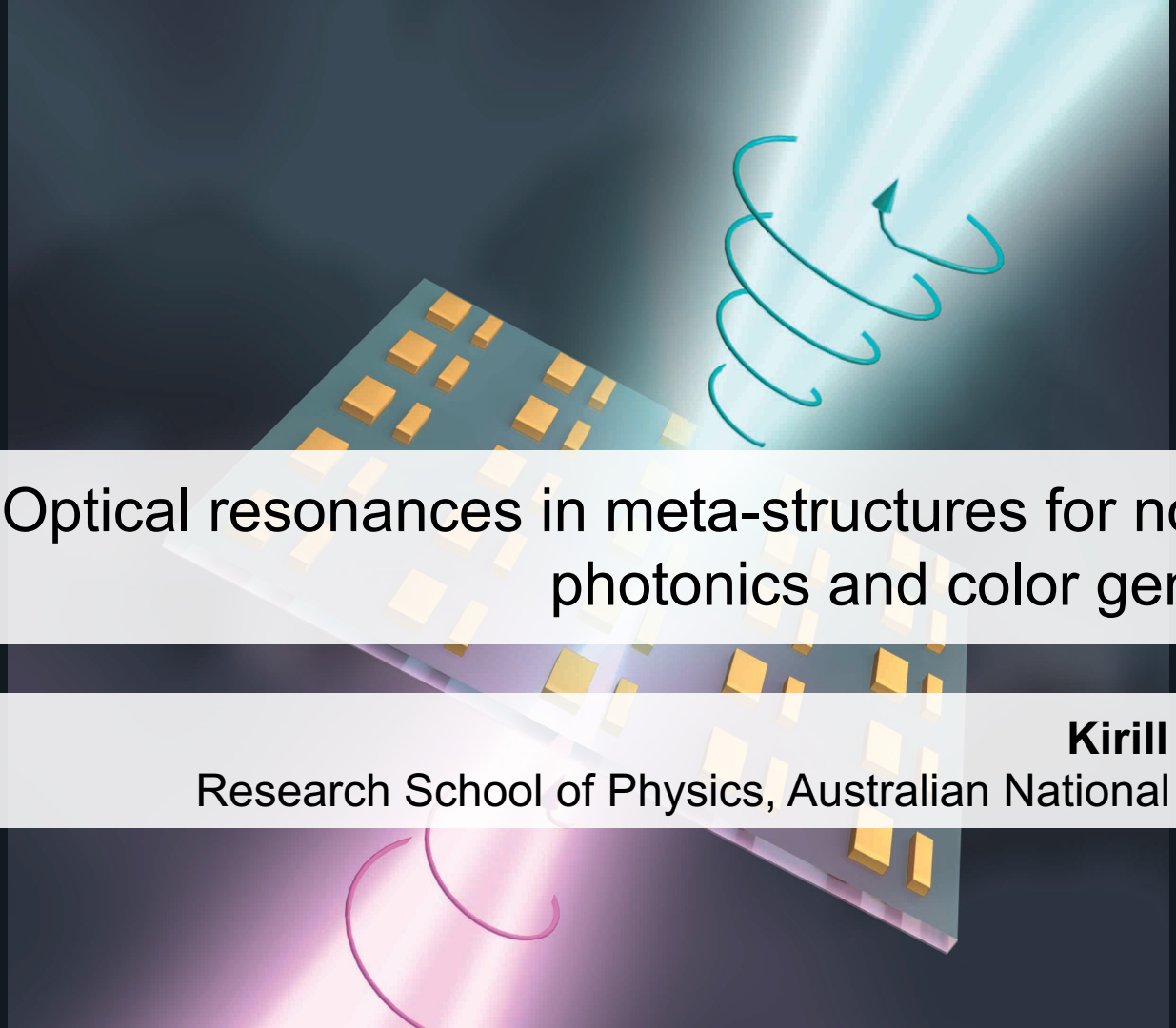

Optical resonances in meta-structures for nonlinear photonics and color generation

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08 April 2024

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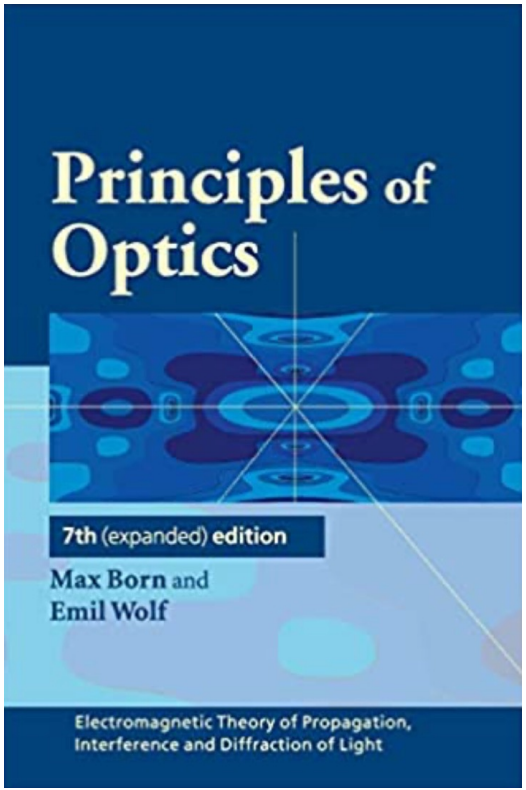
Pioneering experiments on interference



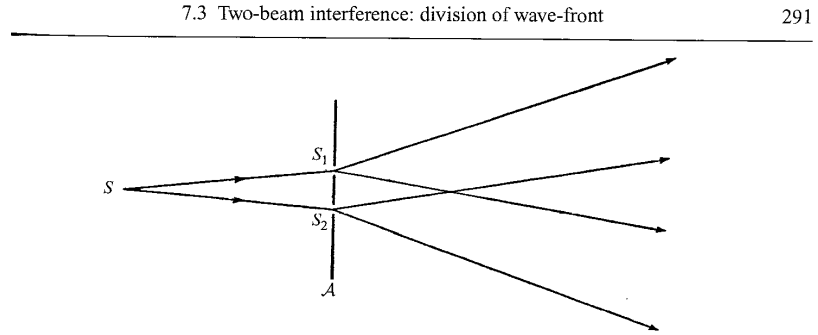


Fig. 7.2 Young's experiment.

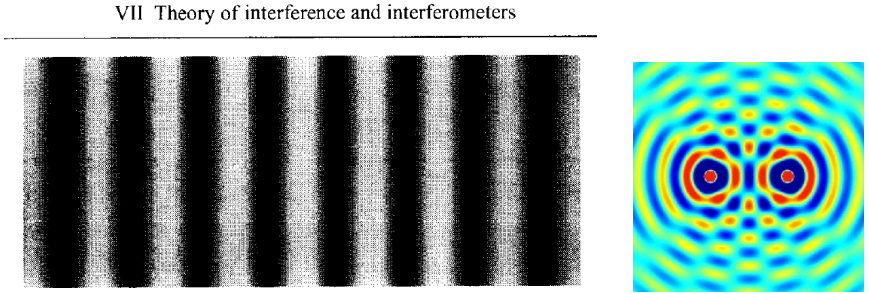


Fig. 7.4 Young's interference fringes.

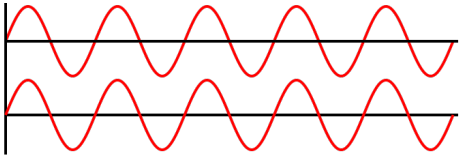
T. Young. Philosophical transactions of the Royal Society of London 92, 12-48 (1802)

Wave interference: fundamentals

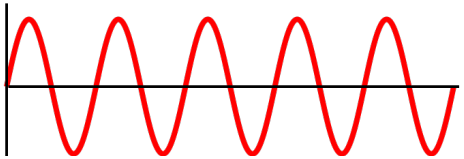
Coherent light beams

I_1 + I_2

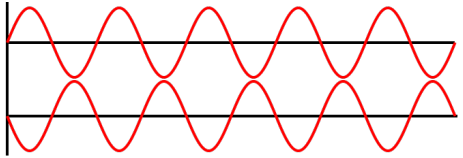
Constructive interference



$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}$$

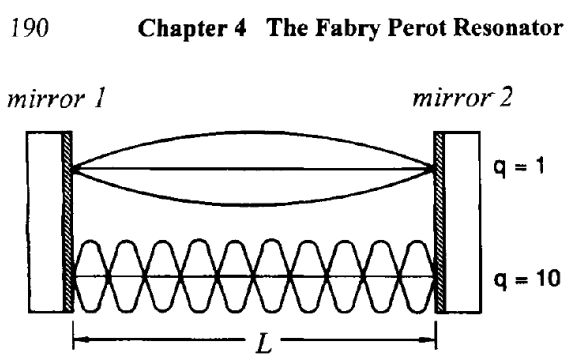


Destructive interference



$$I = I_1 + I_2 - 2\sqrt{I_1 I_2}$$

Optical resonators: fundamentals



Hodgson, N. and Weber, H., 2005. *Laser Resonators and Beam Propagation: Fundamentals, Advanced Concepts, Applications*

Wavelengths of optical resonances

$$\frac{\lambda_q}{2} = \frac{L}{q}$$

$$q = 1, 2, 3..$$

Standing wave = **interference** of contra-propagating waves

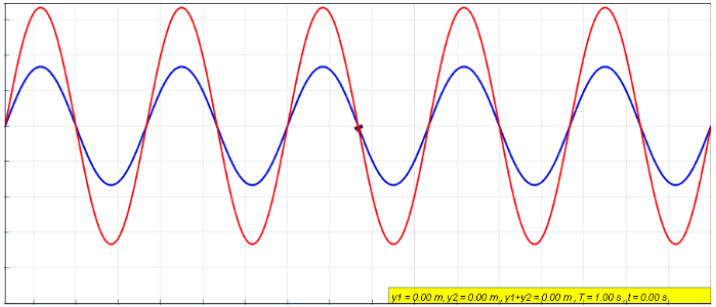


Image: wikipedia.org

Quality factor

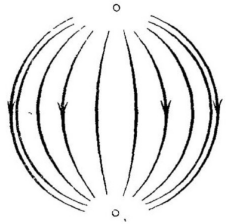
$$Q \overset{\text{def}}{=} \frac{\text{energy stored}}{\text{energy dissipated per cycle}}$$

$$1 < Q < \infty$$

Mie resonances: geometrical resonances

Gustav Mie., Annalen der physik, 330, 377-445 (1908)

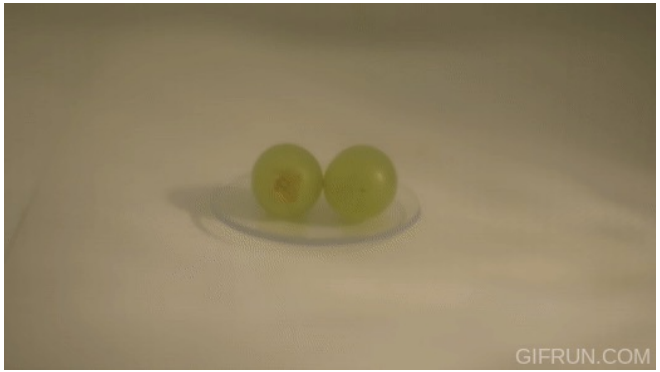
Resonances in spheres



$$\frac{\lambda}{\sqrt{\varepsilon}} \simeq \text{size}$$

Grapes in microwave

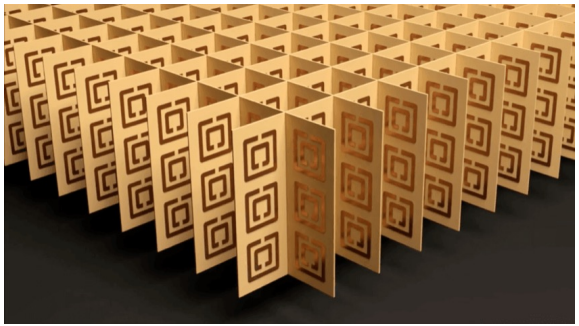
$$\frac{\lambda}{\sqrt{\varepsilon}} \sim 1.3\ \text{cm}$$



Khattak, H.K., et al. Soft matter, 15(29), 5804 (2019)

From metamaterials to metastructures

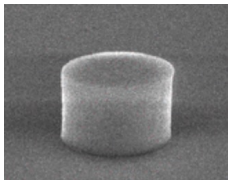
Metamaterials



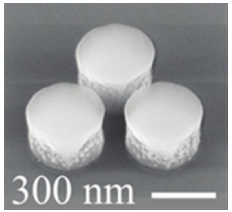
D. Smith et al. Science **305**, 788 (2004)

Metastructures

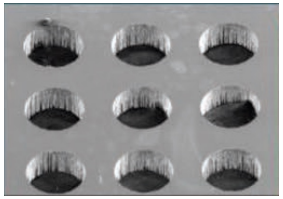
nanoresonators



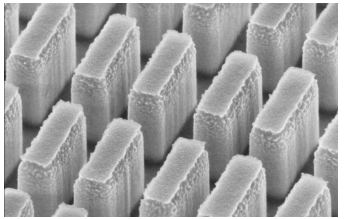
oligomers



membranes

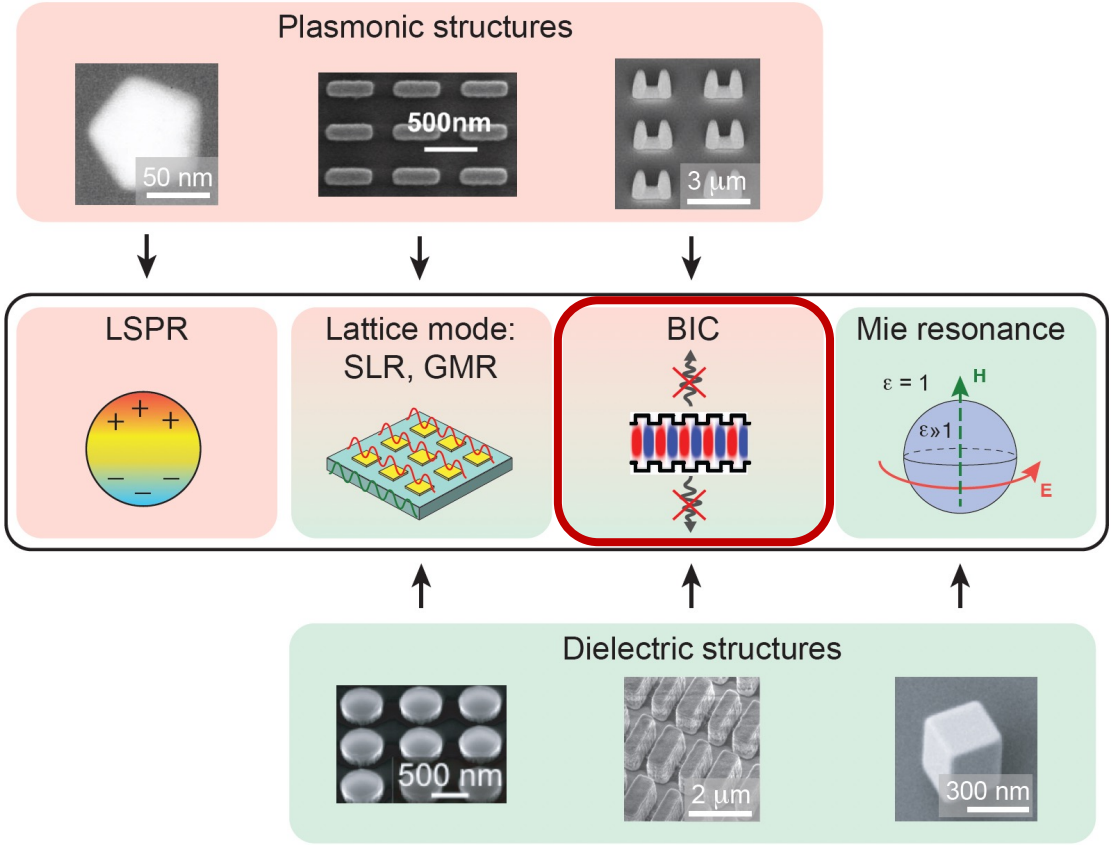


metasurfaces



K. Koshelev et al. ACS Photonics **8**, 102–112 (2021)

Meta-photonics with resonances



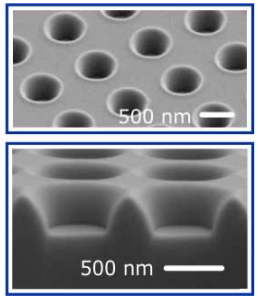
Outline

Quasi-BIC metasurfaces

- Designing a high-Q metasurface
- Experimental observation
- Harmonic generation
- High-harmonic generation

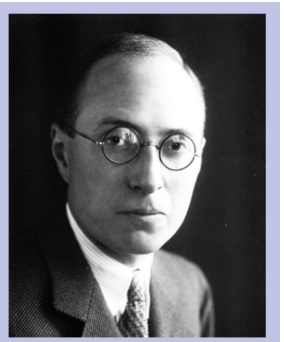
Mie voids

- High-Q modes in visible and UV
- Generation of structured colors



Bound state in the continuum (BIC): history

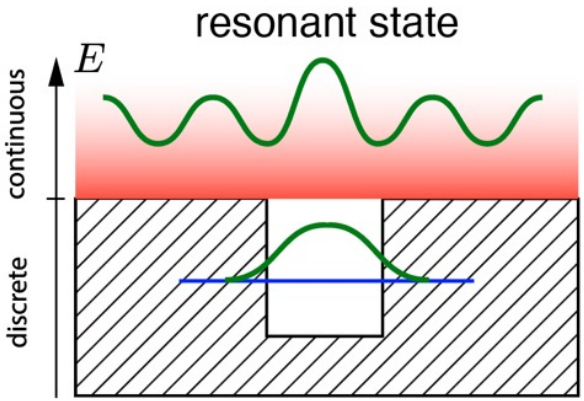

John von Neumann

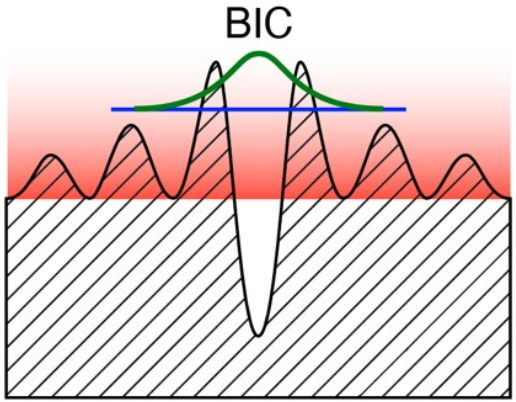

Eugene Wigner

Über merkwürdige diskrete Eigenwerte

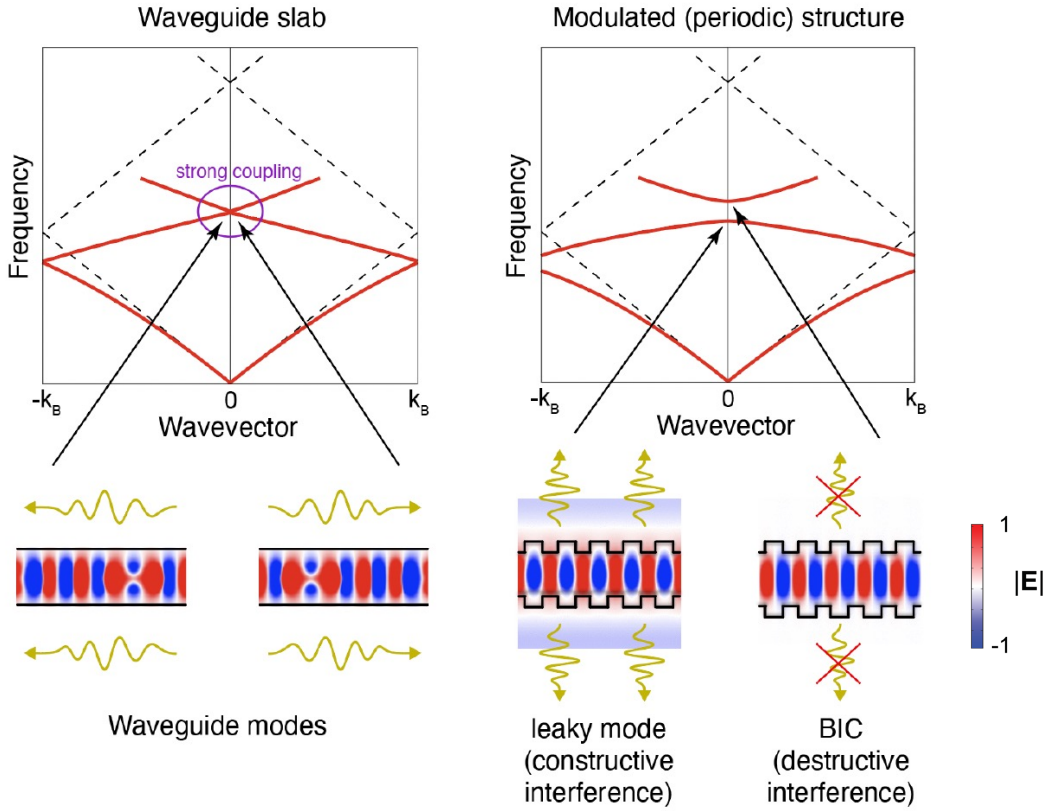
J. von Neumann and E. P. Wigner

Physikalische Zeitschrift *30*, 465–467 (1929)





BICs in photonics



Hamiltonian of mode interaction

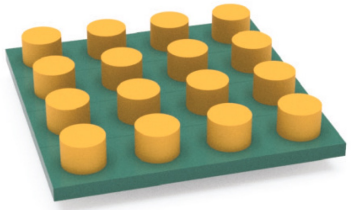
$$\hat{\mathcal{H}} = \begin{bmatrix} \omega_1 & \kappa \\ \kappa & \omega_2 \end{bmatrix} - i \begin{bmatrix} \gamma_1 & \pm\sqrt{\gamma_1\gamma_2} \\ \pm\sqrt{\gamma_1\gamma_2} & \gamma_2 \end{bmatrix}$$

BIC condition

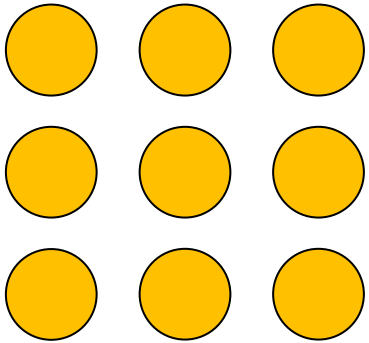
$$\kappa(\gamma_1 - \gamma_2) = \pm\sqrt{\gamma_1\gamma_2}(\omega_1 - \omega_2)$$

BICs in metasurfaces

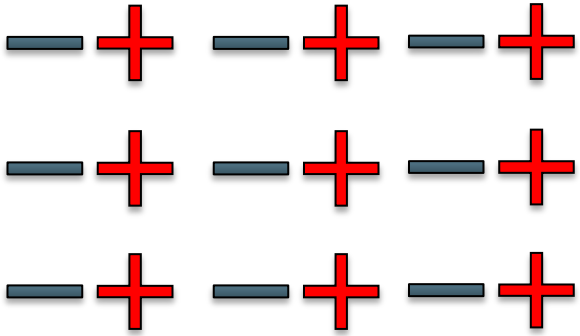
BICs can exist in symmetric structures



Symmetric unit cell
(meta-atom)



Polarization current density
(Electric field)



No radiation -> BICs $Q = \infty$

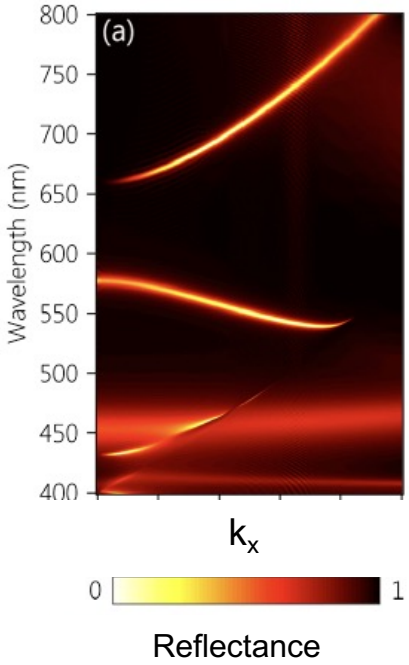


Fig. from S. Azzam et al. *PRL 121* (2018).

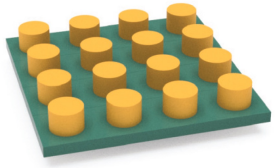
Losses in practical structures: quasi-BIC

Energy inside resonator $W(t) = W_0 \exp(-\gamma t)$

Lifetime $t = \frac{1}{\gamma}$

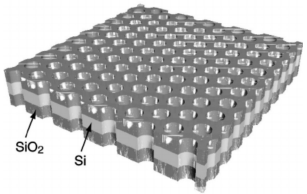
Radiation	Material absorption	Surface roughness	Radiation (sample edges)	Disorder effects

$$\gamma = \gamma_{\mathrm{rad}} + \gamma_{\mathrm{abs}} + \gamma_{\mathrm{surf}} + \gamma_{\mathrm{edg}} + \gamma_{\mathrm{dis}}$$



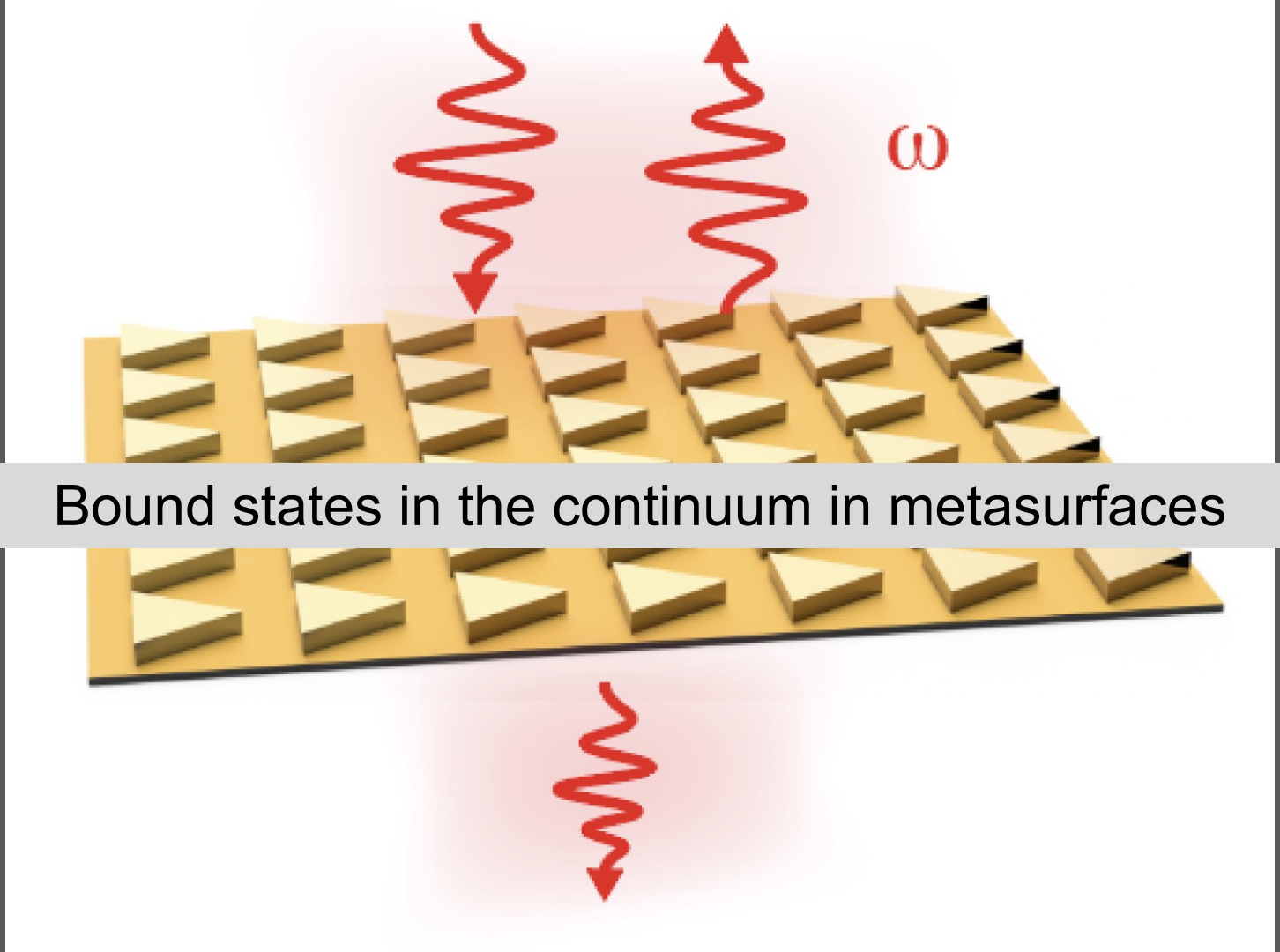
BIC Q factor = 10^2 - 10^4

Z. Liu *et al.*, *PRL* **123**, 253901 (2019)



BIC Q factor = 10^2 - 10^5

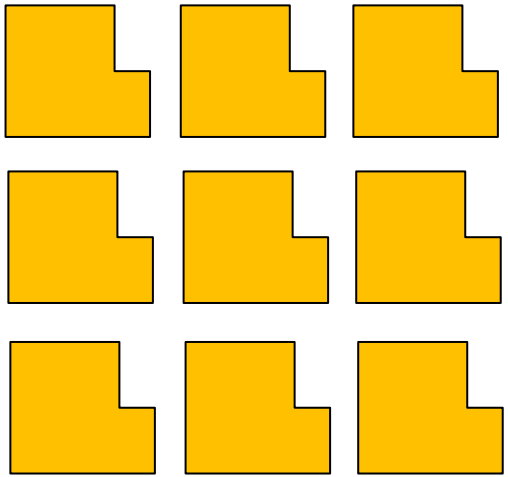
J. Jin *et al.,* Nature **574**, 501-504 (2019)



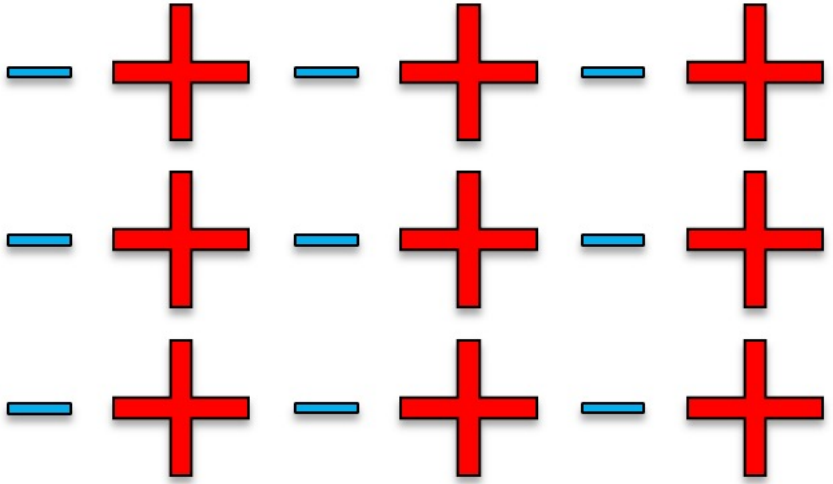
Bound states in the continuum in metasurfaces

BICs in asymmetric metasurfaces

Asymmetric unit cell
(meta-atom)

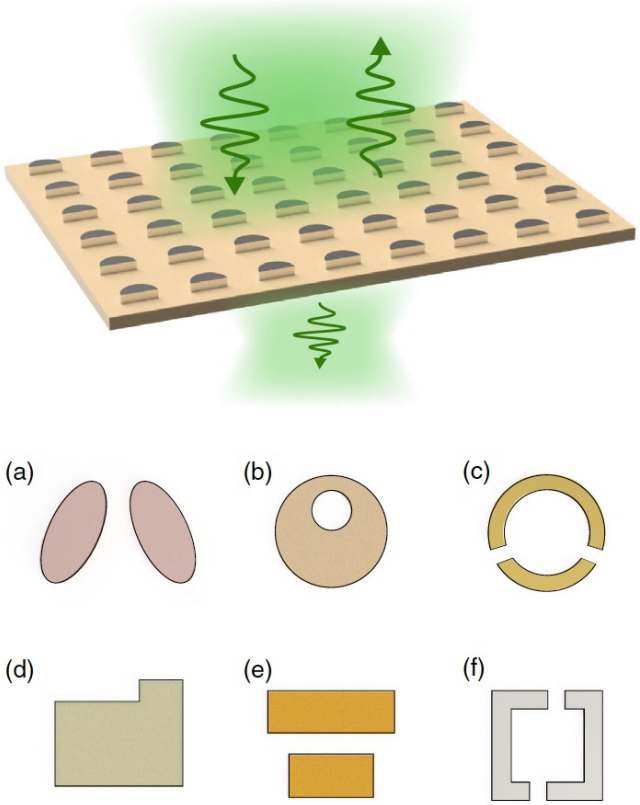


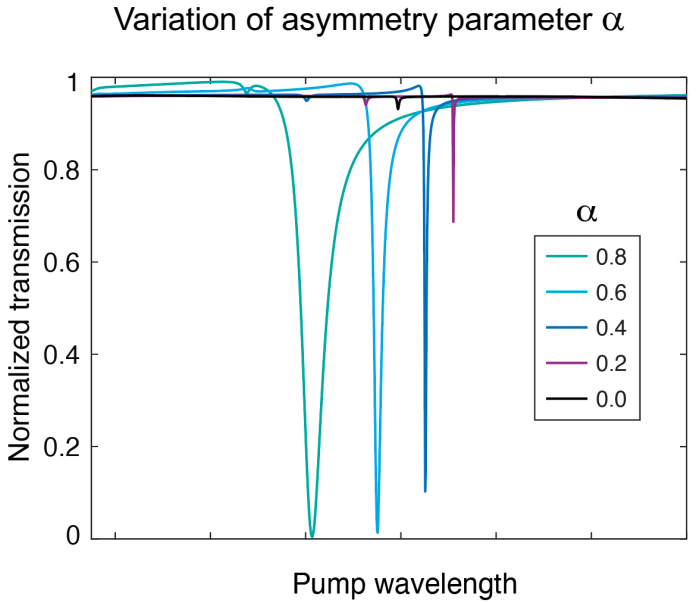
Polarization current density
(Electric field)



Imbalance -> radiation

BICs in asymmetric metasurfaces





$$Q_{\mathrm{rad}}(\alpha) \propto \alpha^{-2}$$

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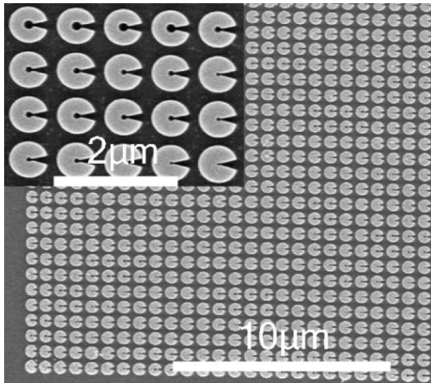
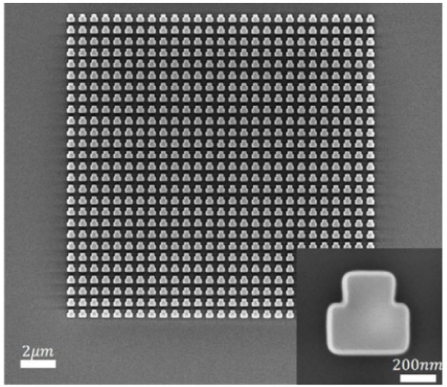
Examples of asymmetric metasurfaces

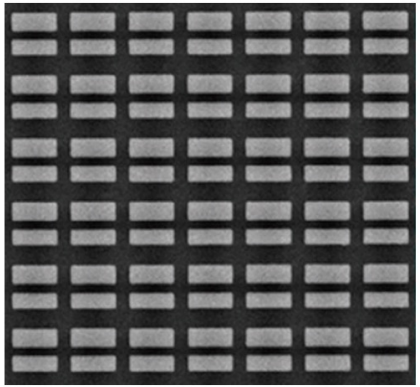


Y. Gao *et al.* Nano letters **18**, 8054-8061 (2018)



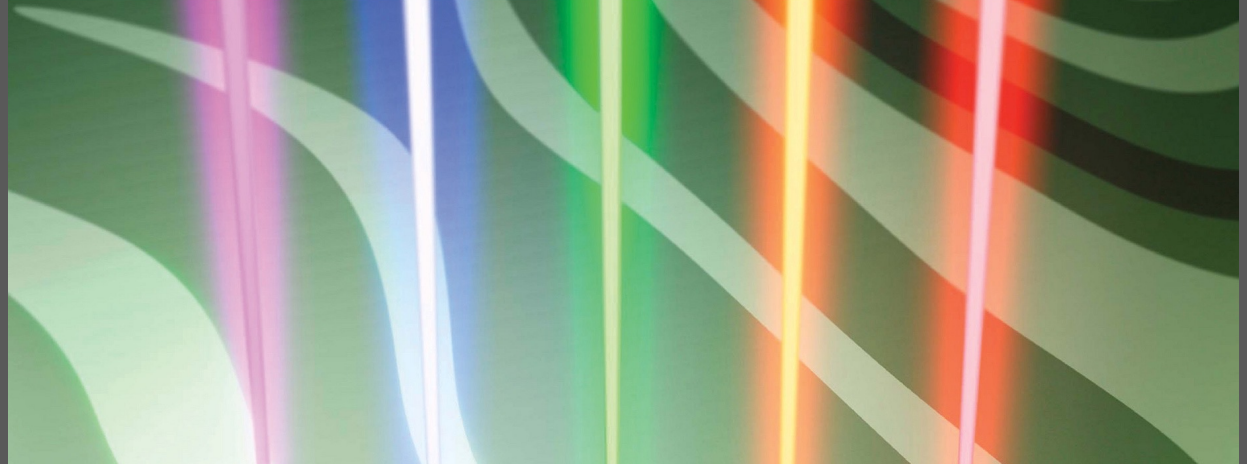
Z. Liu *et al.* Physical Review Letters **123**, 253901 (2019)

BIC Q factor = 18500

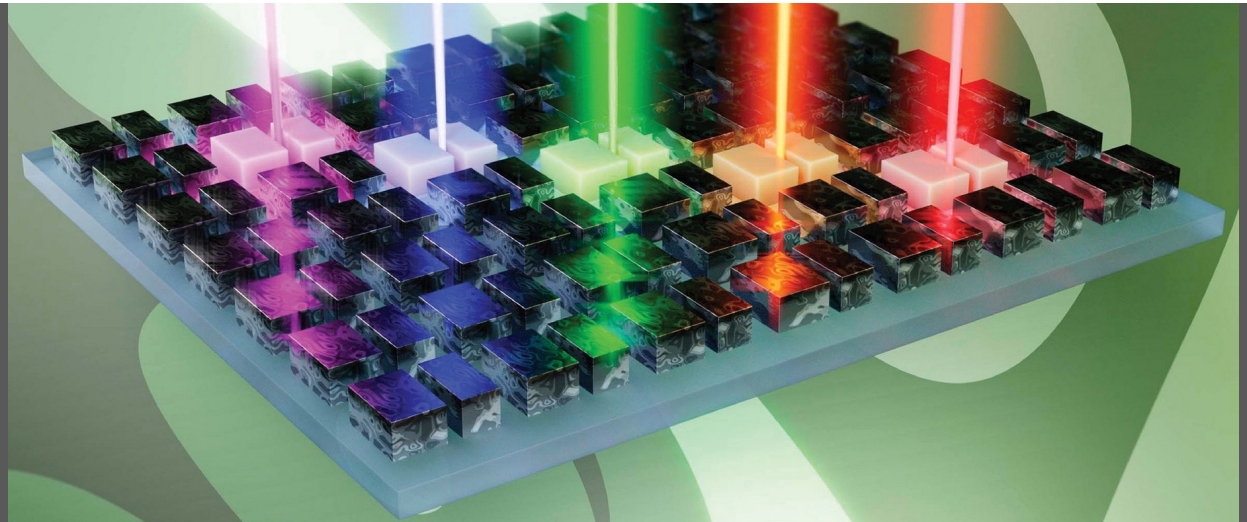


A. Ndao *et al.* Nanophotonics (2020) *10.1515/nanoph-2020-0008.*

BIC Q factor = 750

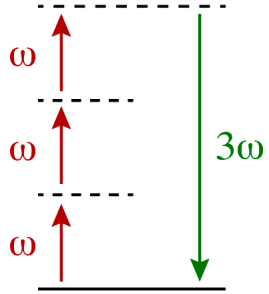


Nonlinear metasurfaces with BICs



Harmonic generation at the nanoscale

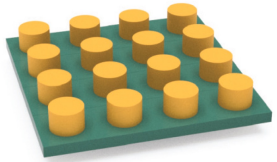
Nonlinear frequency generation in macroscopic media



$$n_\omega = n_{3\omega}$$
$$3k_\omega = k_{3\omega}$$

Phase-matching condition

Nonlinear generation in resonant nanostructures

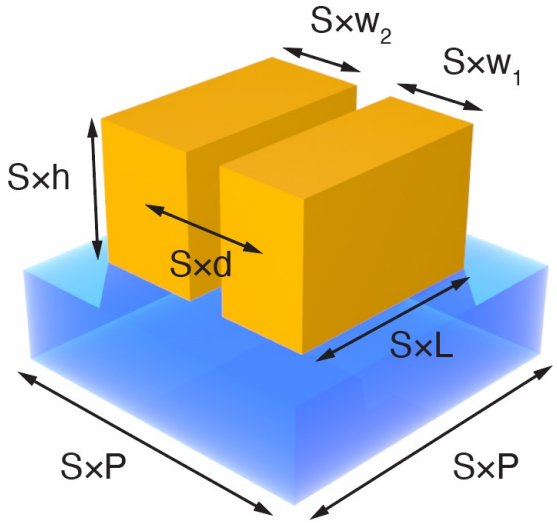


Resonances in metasurfaces

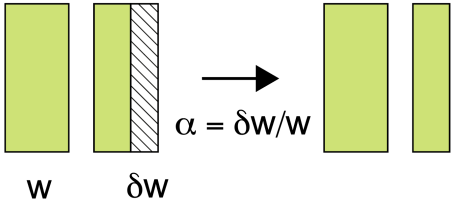
$$\frac{\text{generated nonlinear power}}{\text{pumn power}} \propto Q^3$$ **10^{-6} - 10^{-3} %**

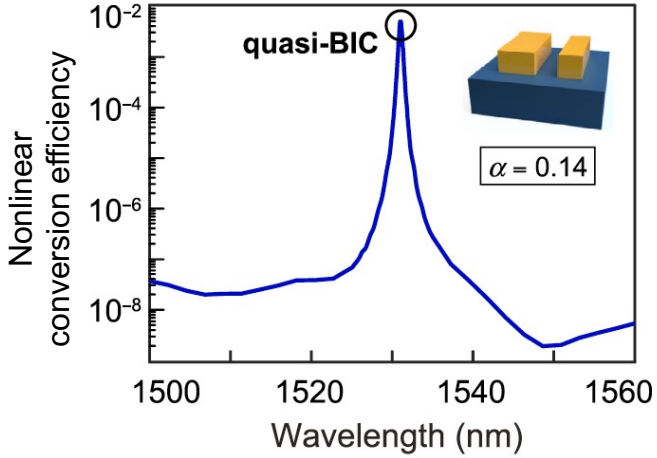
Nonlinear photonics with BICs: universal design

One universal design



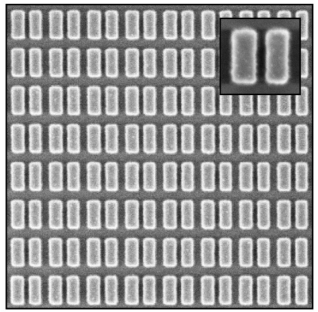
Breaking meta-atom symmetry



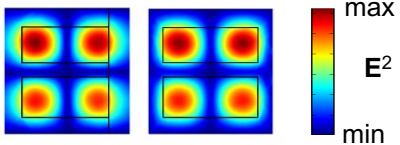


Third-harmonic generation with BICs

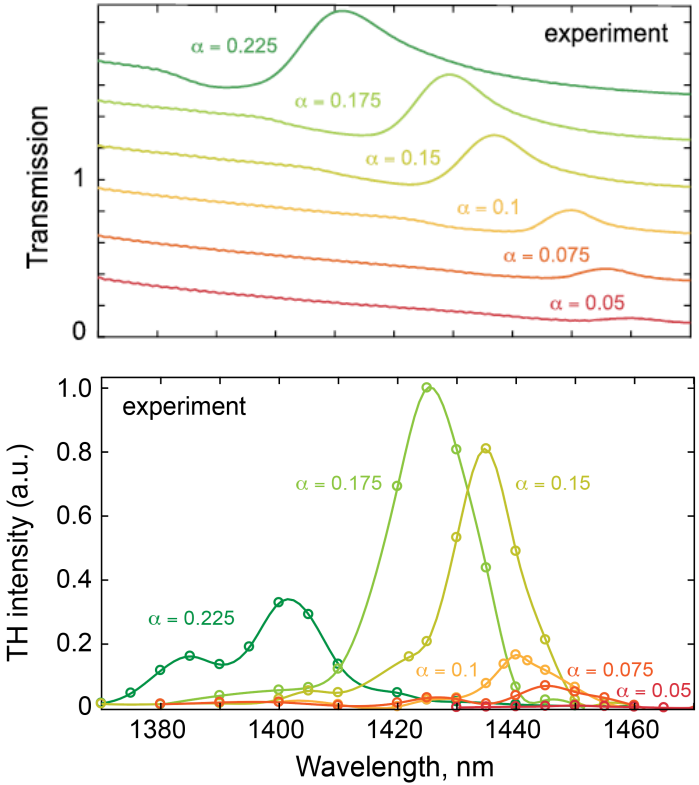
Si metasurface



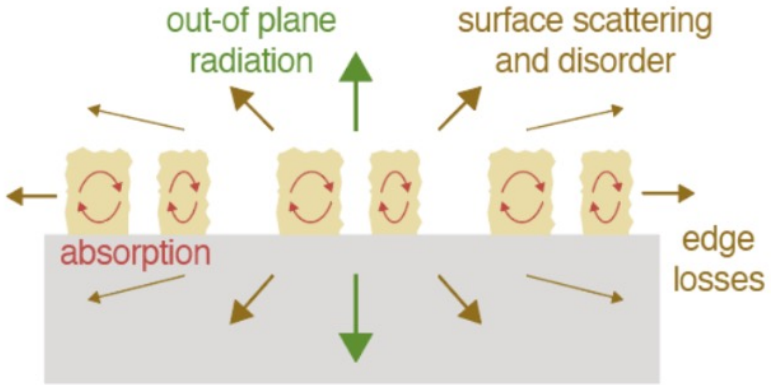
BIC resonance



Q ~ 100



Critical coupling



Field enhancement

$$|\mathbf{E}|^2, |\mathbf{H}|^2 \propto \frac{Q_{\mathrm{rad}} Q_{\mathrm{par}}}{(Q_{\mathrm{rad}} + Q_{\mathrm{par}})^2}$$

$$Q_{\mathrm{tot}}^{-1} = \underbrace{Q_{\mathrm{rad}}^{-1} + Q_{\mathrm{par}}^{-1}}_{\text{radiative}} + \underbrace{Q_{\mathrm{abs}}^{-1}}_{\text{non-radiative}}$$

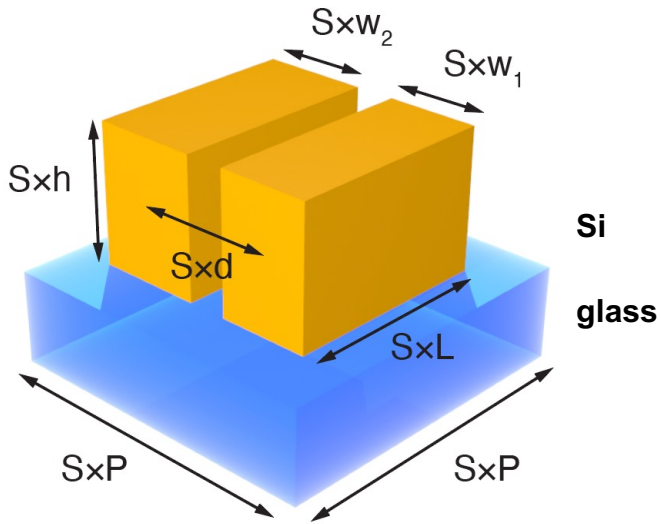
$$Q_{\mathrm{par}}^{-1} = Q_{\mathrm{surf}}^{-1} + Q_{\mathrm{dis}}^{-1} + Q_{\mathrm{size}}^{-1} + Q_{\mathrm{sub}}^{-1}$$

Critical coupling

$$Q_{\mathrm{rad}} = Q_{\mathrm{par}}$$

Nonlinear photonics with BICs: universal design

One universal design



High-Q metasurface

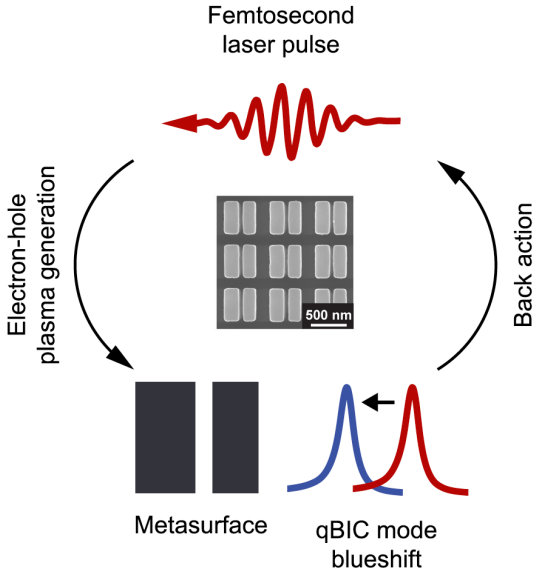
- Geometric scaling: S = 0.5 ↔ 3
- Radiative Q factor: asymmetry

$$Q_{\mathrm{rad}}(\alpha) \propto \alpha^{-2}$$

- Field enhancement: critical coupling

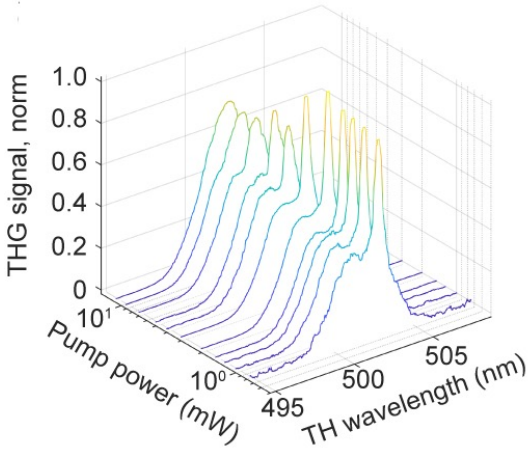
$$Q_{\mathrm{rad}} = Q_{\mathrm{par}}$$

Self-action with BICs

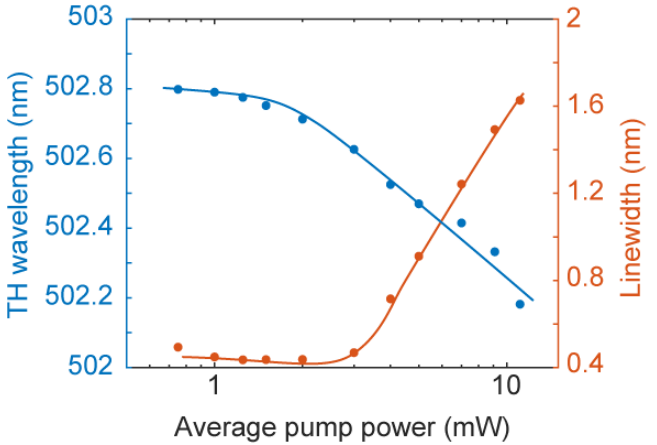


Q ~ 900

THG signal



Self-action



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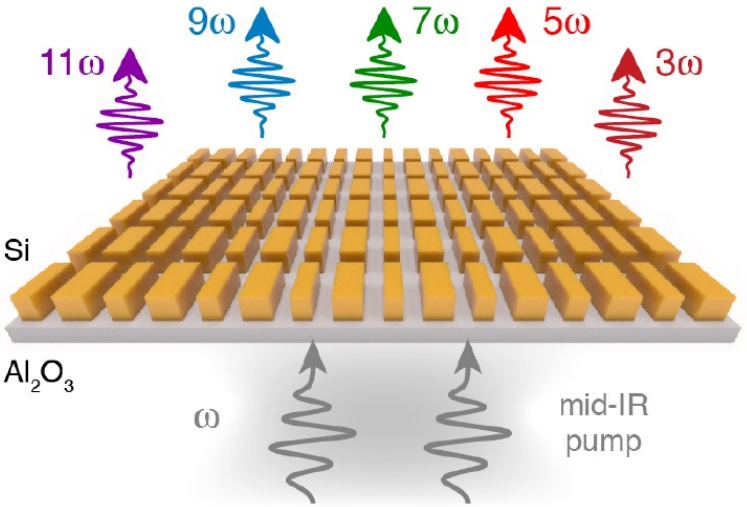
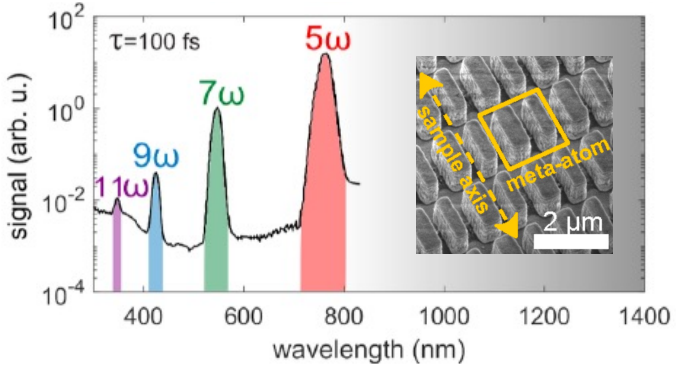
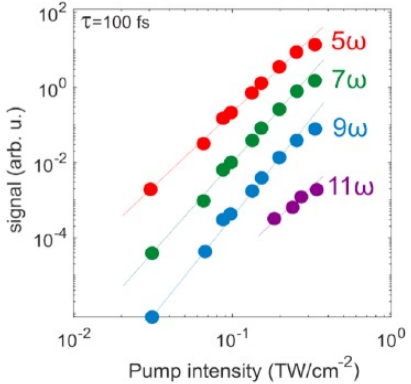
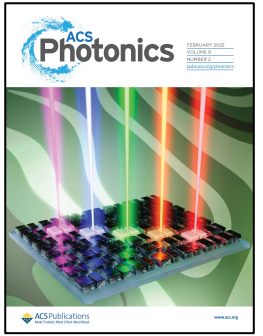
High-harmonic generation with BICs



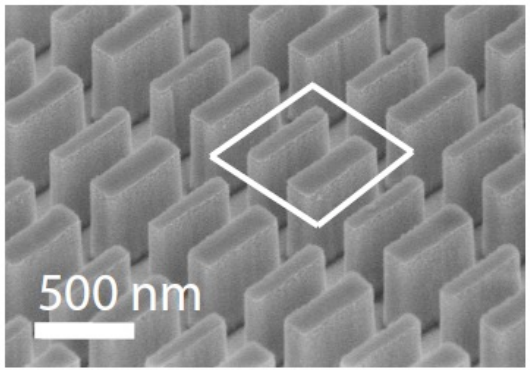


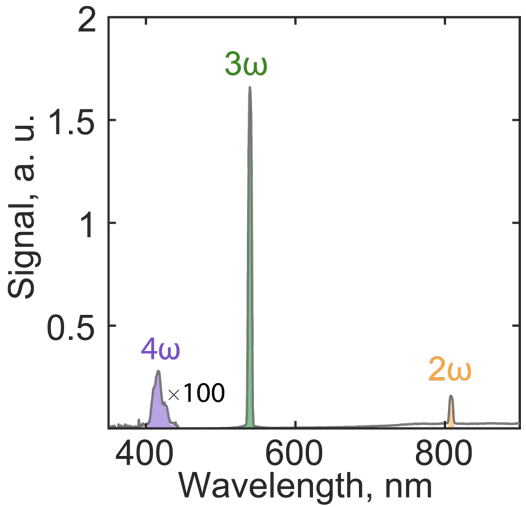




SHG and 4HG from Si metasurfaces

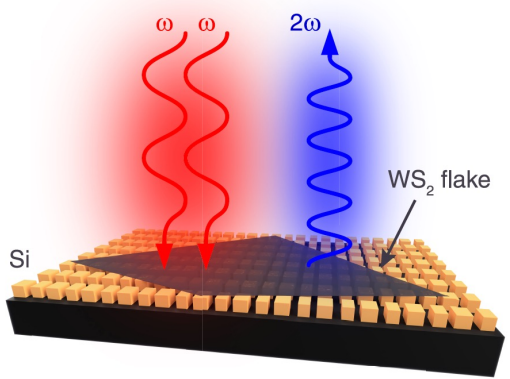
Si metasurface



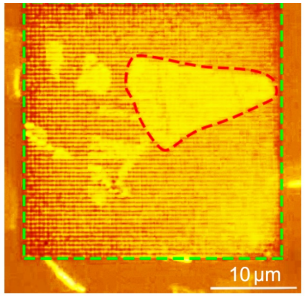


SHG with BICs and TMD monolayers

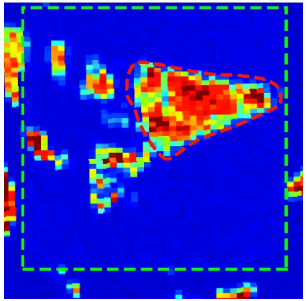
Exfoliated WS_2

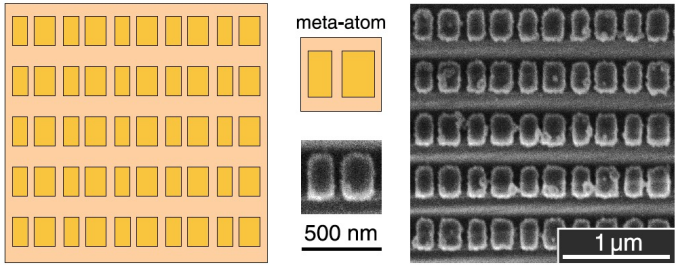


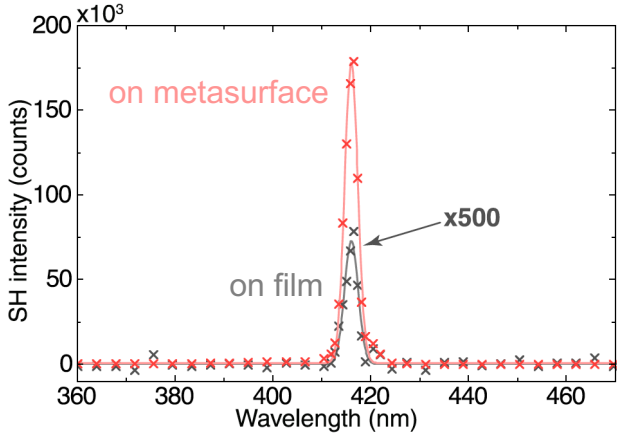
Optical image



PL map

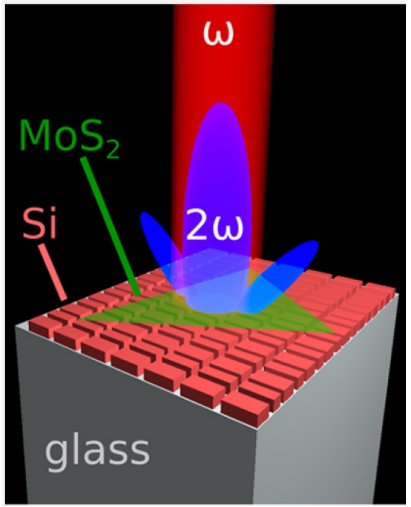


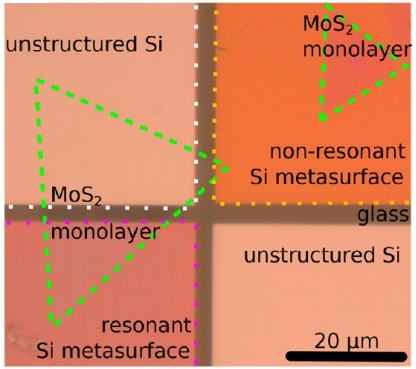


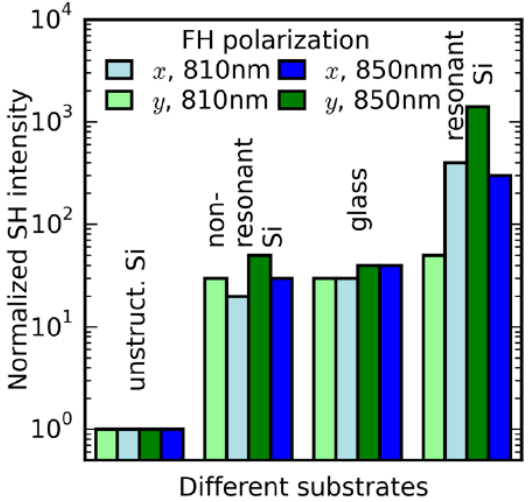


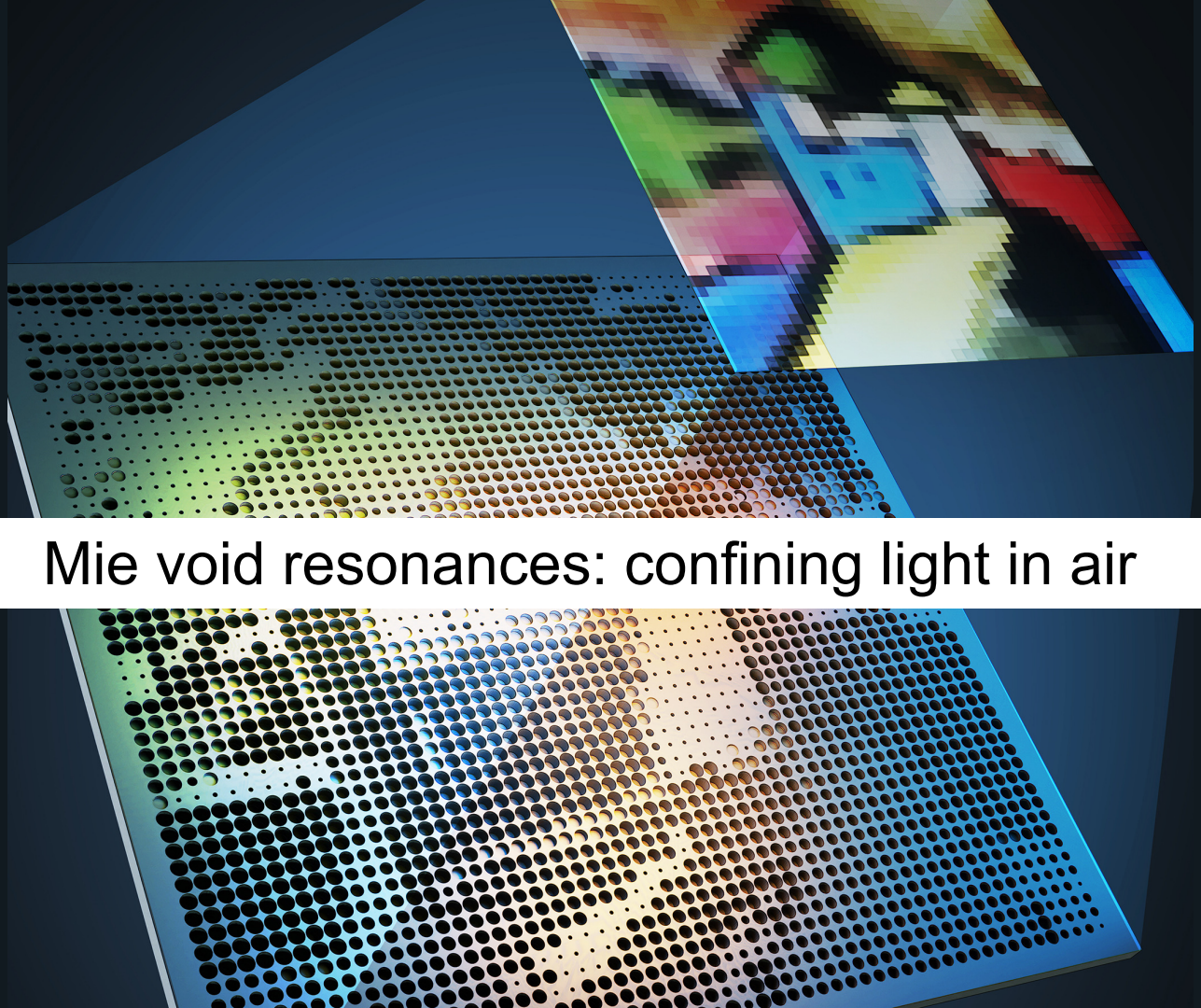
SHG with BICs and TMD monolayers

CVD-grown MoS_2



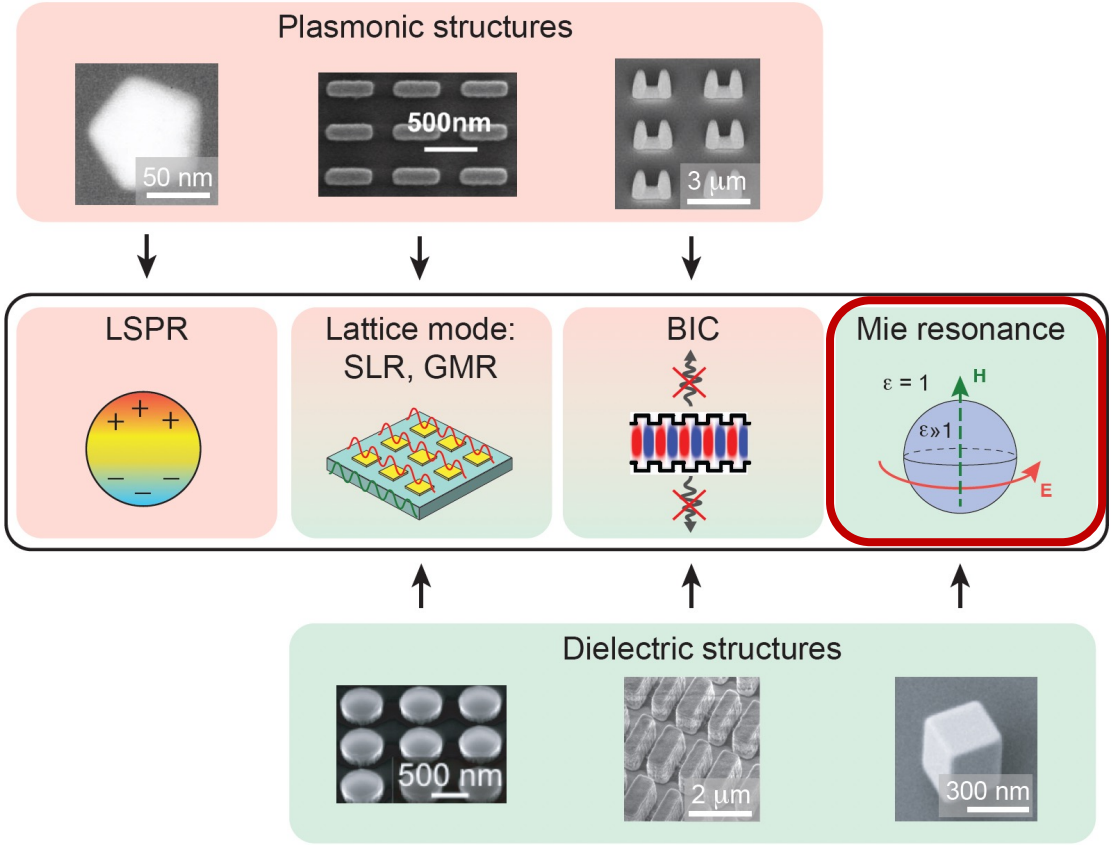




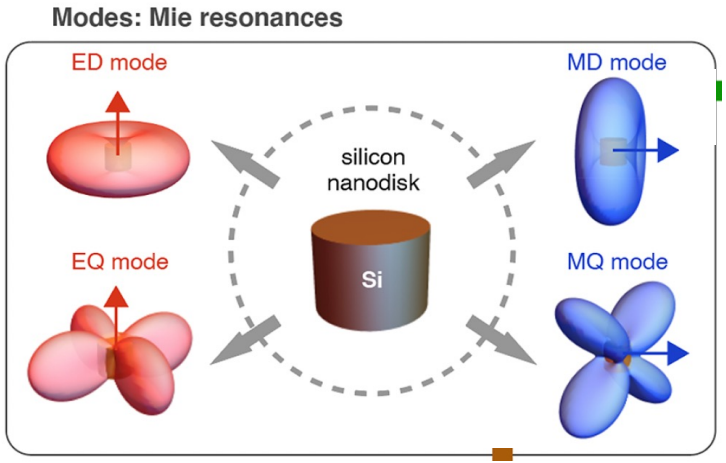


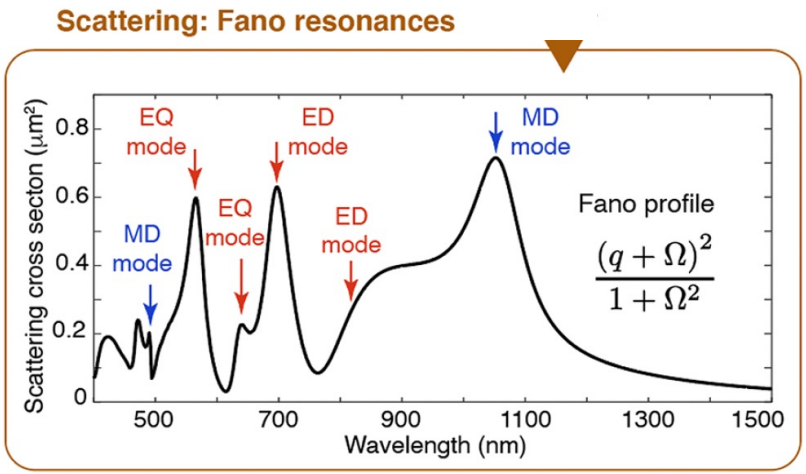
Mie void resonances: confining light in air

Meta-photonics with resonances



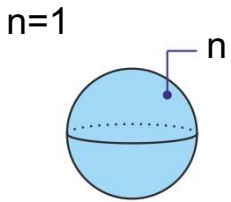
Mie resonances





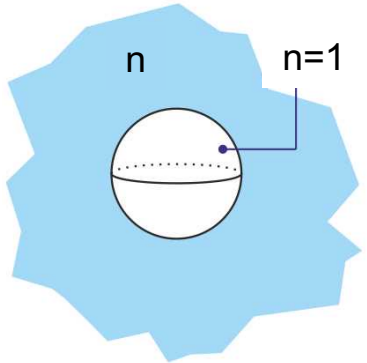
Concept of Mie voids vs. Mie resonators

Mie sphere



G. Mie, Ann. Phys. **4**, 377 (1908)

Mie void



Maxwell‘s equations (TM)

$$\frac{\psi_l'(nk_0R)}{\psi_l(nk_0R)} = n\frac{\xi_l'(k_0R)}{\xi_l(k_0R)}$$

Can we solve the same Maxwell‘s equations?

$$\frac{\psi_l'(k_0R)}{\psi_l(k_0R)} = \frac{1}{n}\frac{\xi_l'(nk_0R)}{\xi_l(nk_0R)}$$

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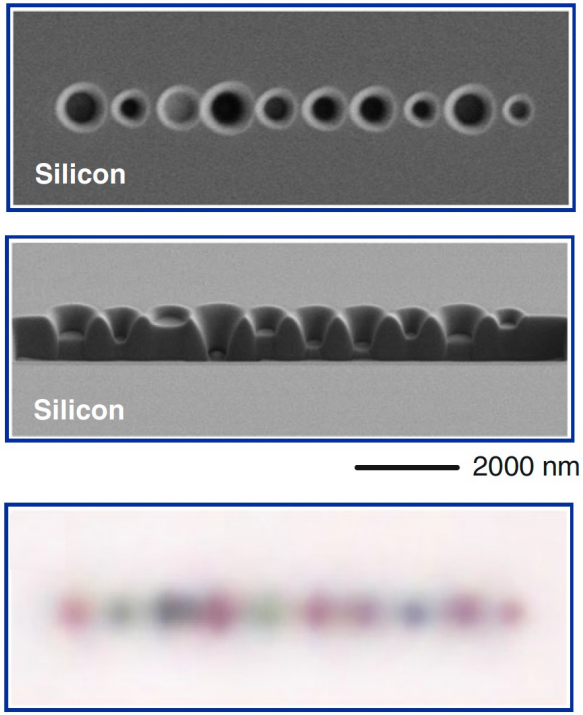
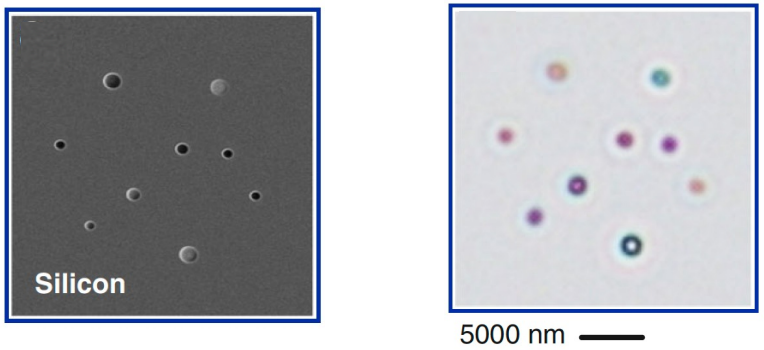
Experimental observation of void modes

First observation of resonances in surface carvings
(Dr Mario Hentschel, Prof Harald Giessen)

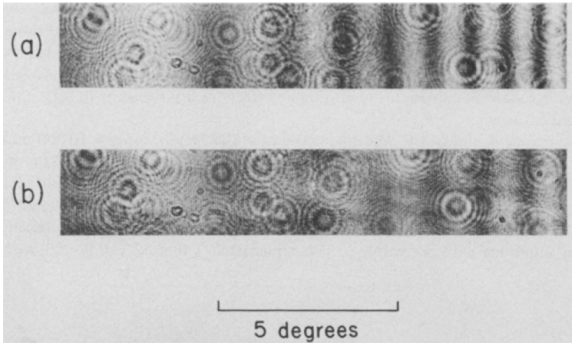


Individual nanoresonators!



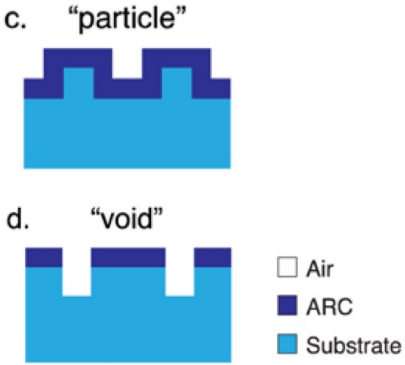
History of void structures in optics

Air bubbles in water



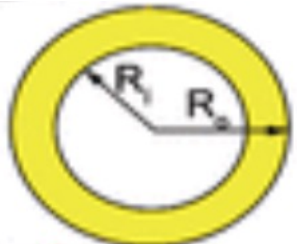
Marston, P. L. et al,
Appl. Sci. Res. 38, 373 (1982).

Cylindrical voids
with anti-reflection coatings



Mann, S.A. et al.
Optics Express 19, 25729 (2011)

Plasmonic nanoshells



Prodan, E., Nordlander, P.,
Nano Letters 3, 543 (2003)

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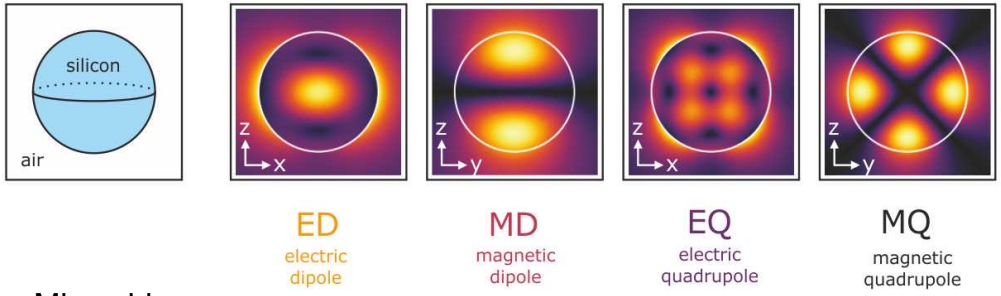
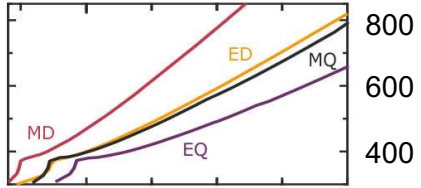
Mie modes in spherical geometry

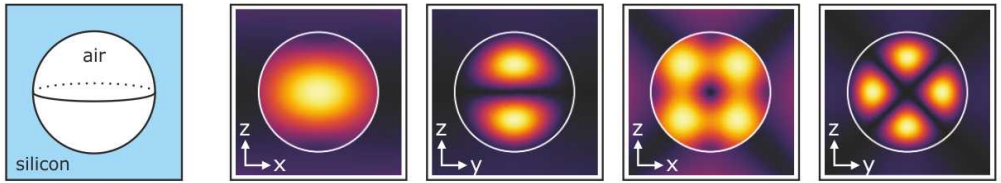
Mie sphere

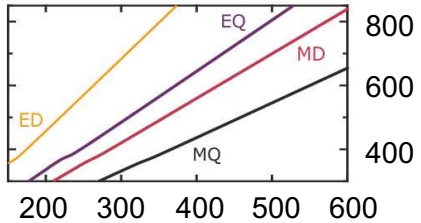




Resonant wavelength (nm)

Mie void





Resonant wavelength (nm)

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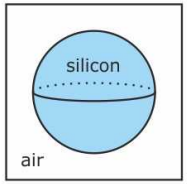
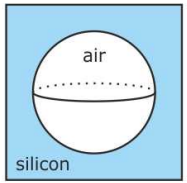
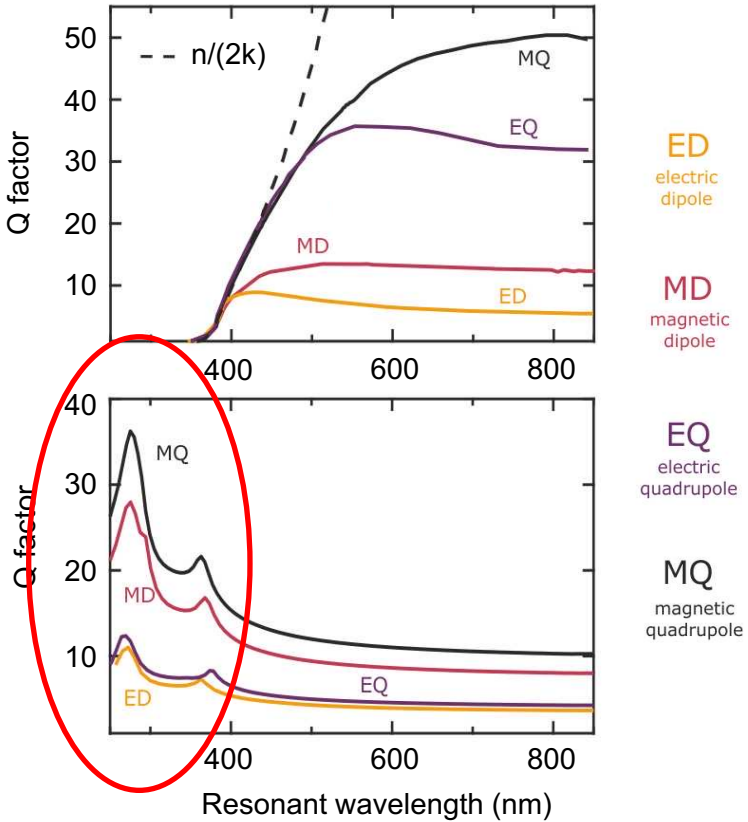
Mie modes in spherical geometry

Mie sphere



Mie void





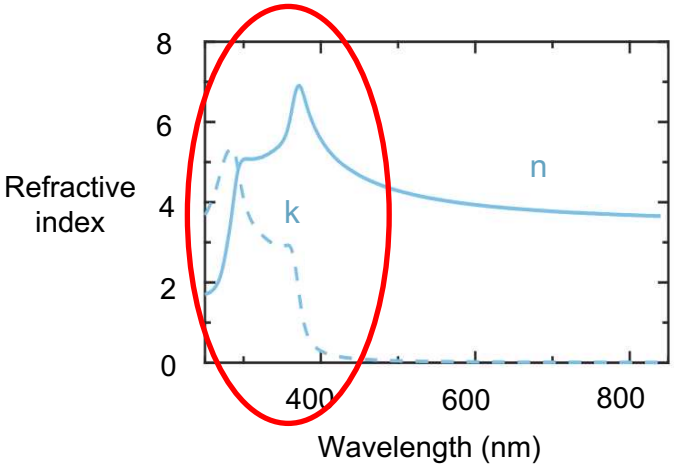
ED
electric dipole

MD
magnetic dipole

EQ
electric quadrupole

MQ
magnetic quadrupole

Si refractive index data



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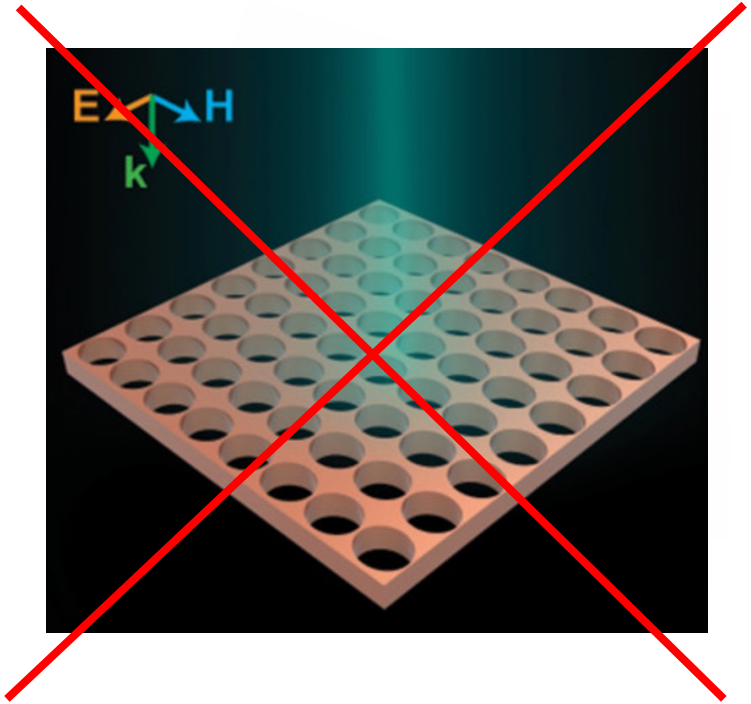
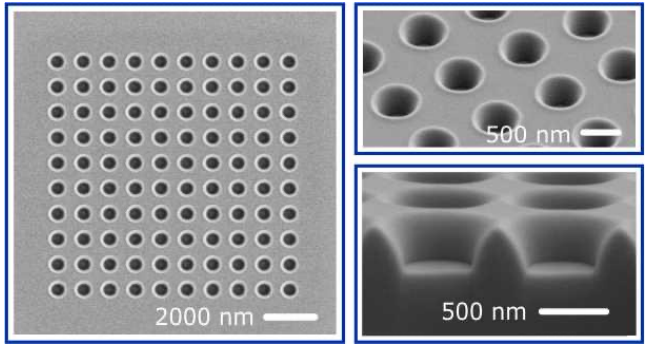
Experimental realization of Mie voids





Minimal thickness is several wavelengths to prevent coupling to guided modes

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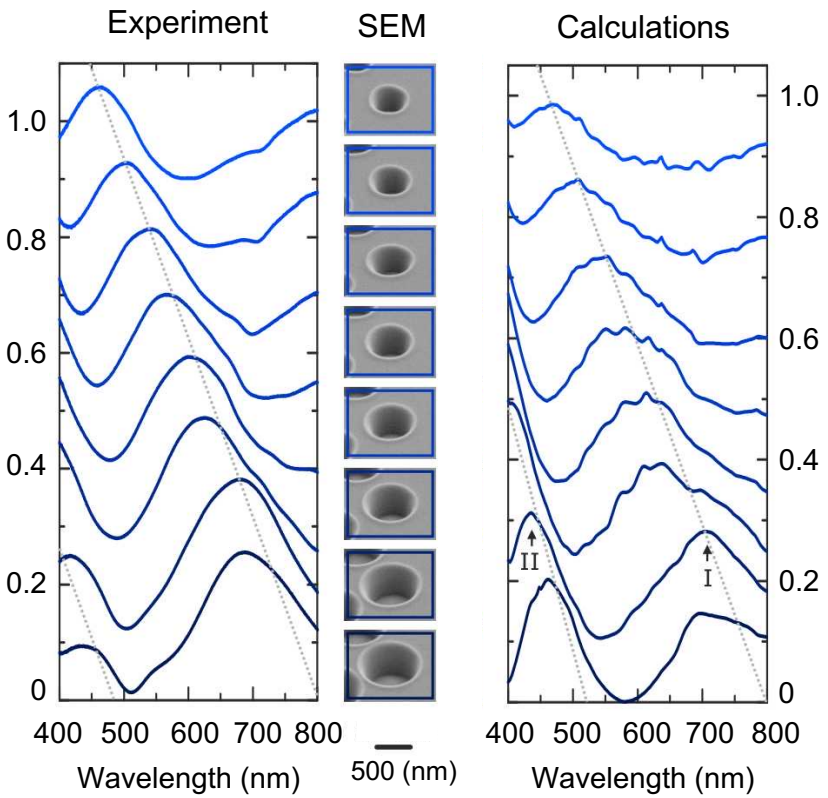
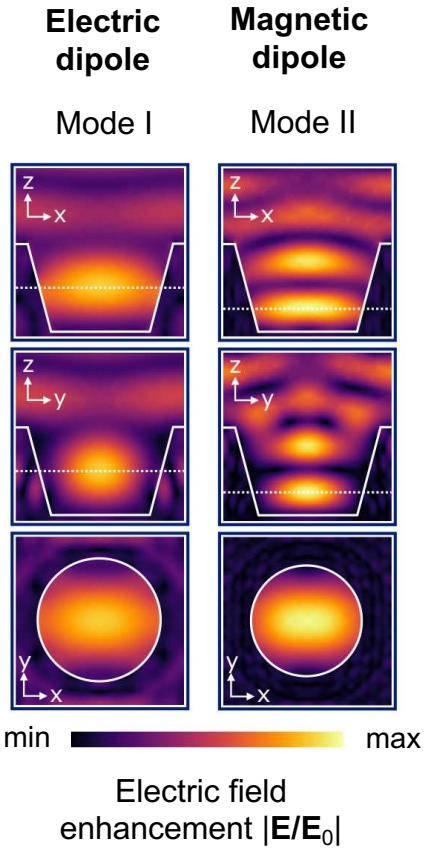
Mie voids in scattering





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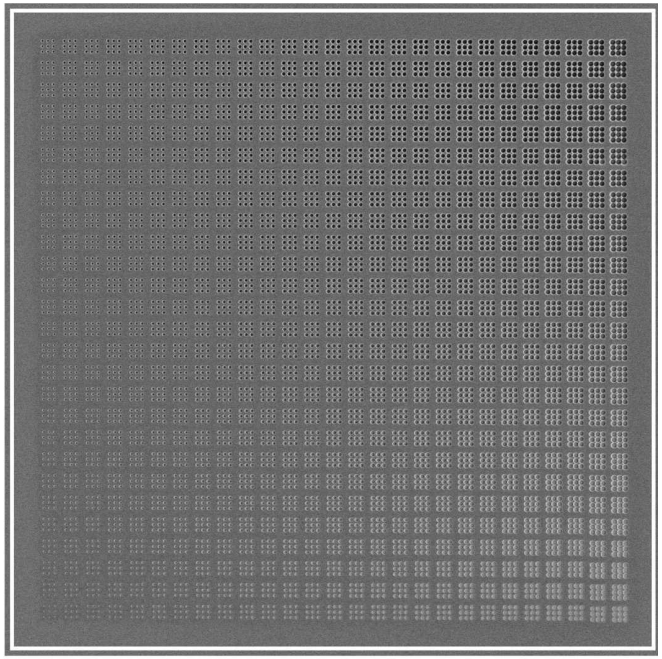
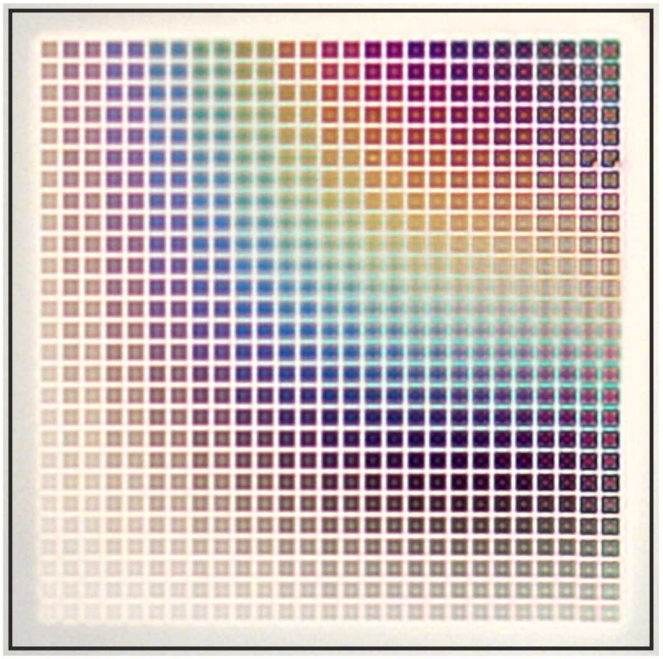
Mie voids imaging: experiment

SEM



Optical microscope (white light)



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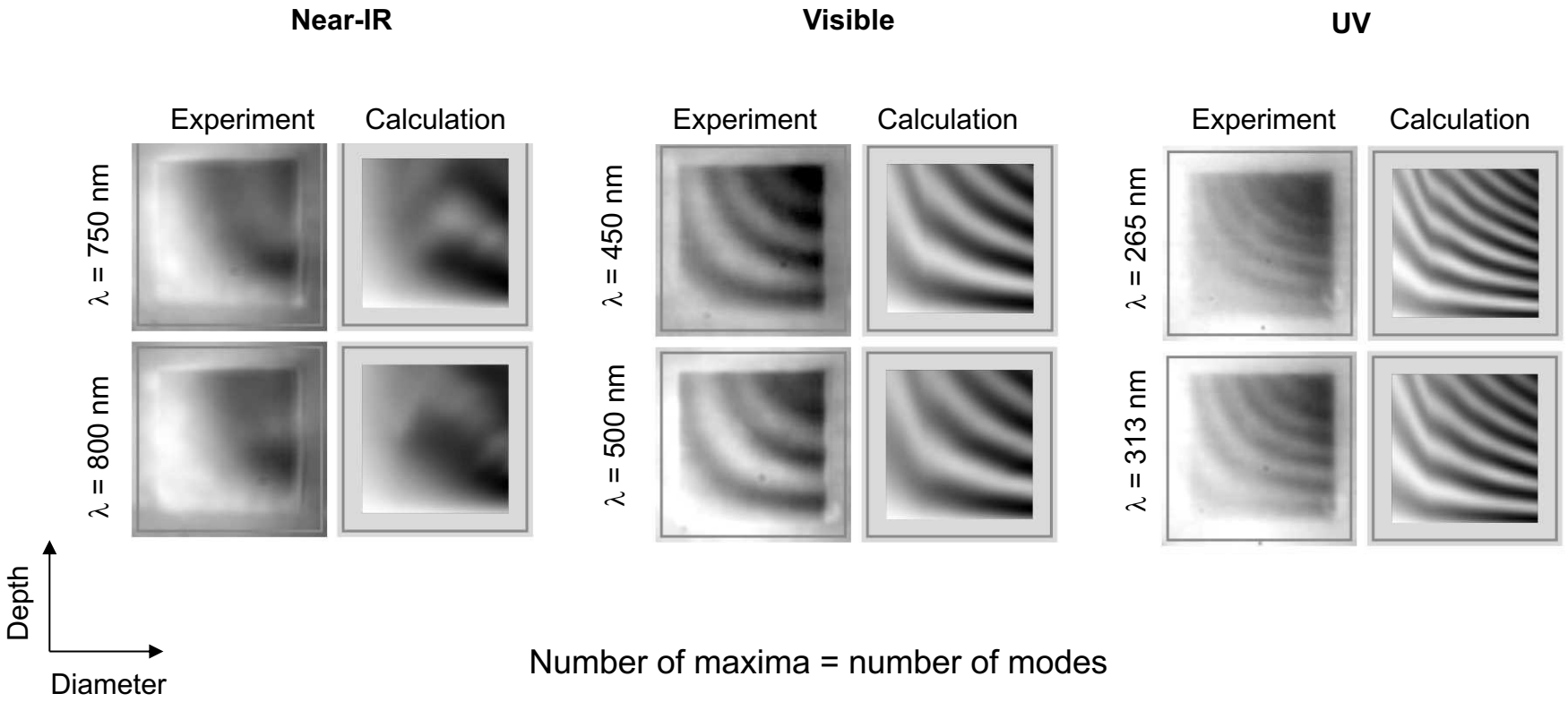
Mie voids in the UV: imaging



Number of maxima = number of modes

Mie voids for color generation

Wassily Kandinsky
Painting: Improvisation 9 (1910)

Video by M. Hentschel

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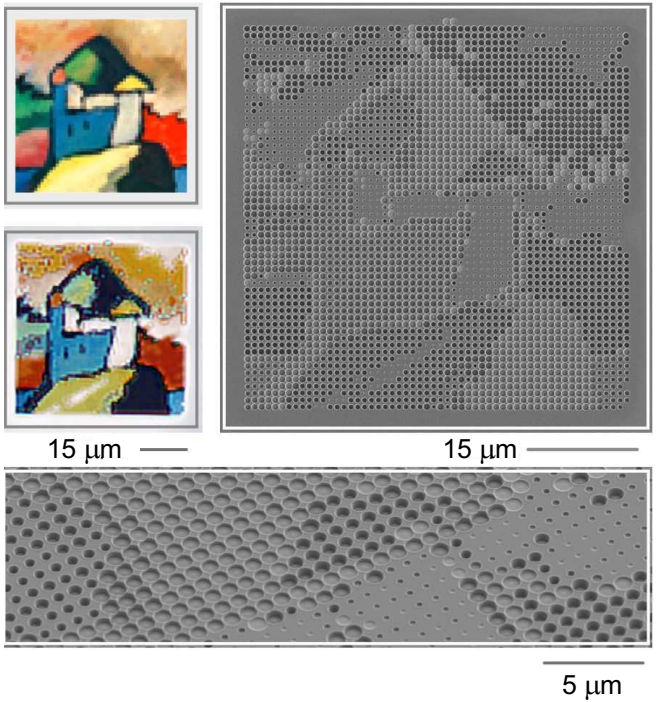
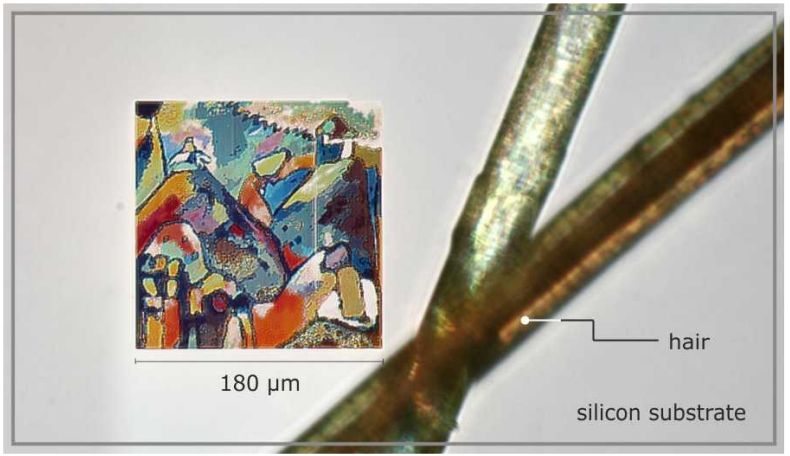
Mie voids for color generation

Original image

Experiment





Resolution - 36000 dpi

Editorial: Oliver Graydon. Mie voids generate miniature artworks. Nature Photonics 17, 133 (2023)

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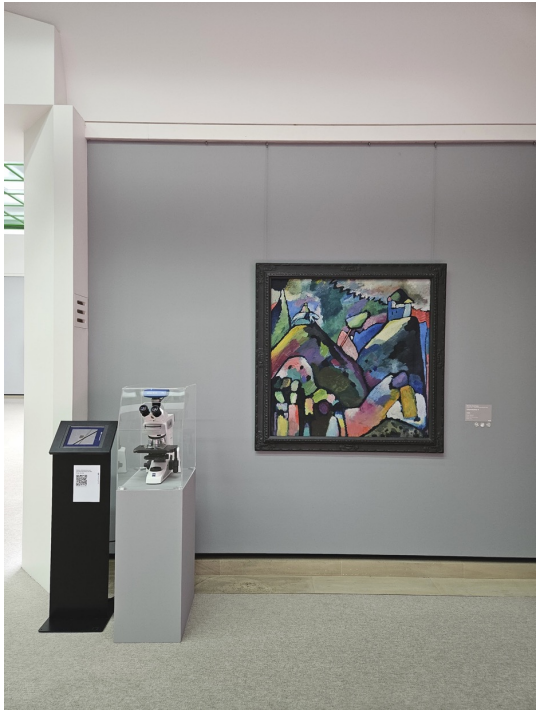
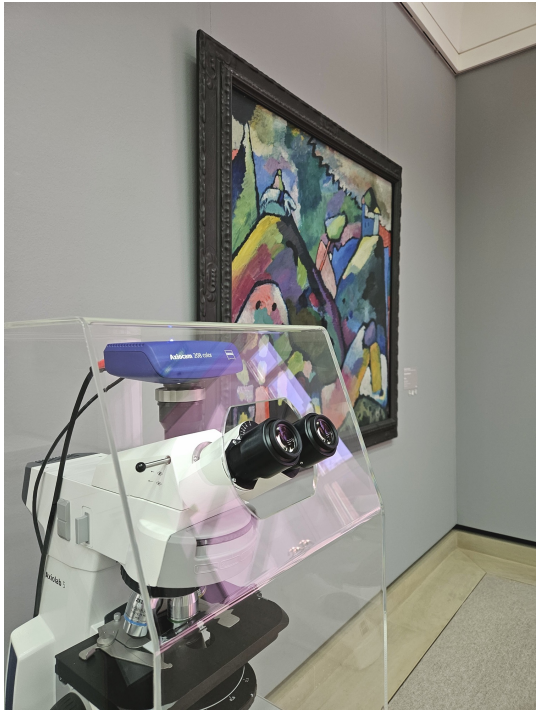
Nano-Kandinsky in Stuttgart Gallery

Staatsgalerie Stuttgart, Germany





Exposition was open September – December 2023

Conclusions

- BIC in meta-structures – versatile platform for engineering resonances
- Design of BIC in metasurfaces: asymmetry & critical coupling
- Harmonic generation enhancement: >1000 times stronger
- Mie voids: new platform for dielectric nanophotonics

Relevant papers

K. Koshelev et al., Optics and Photonics News 31, 38 (2020)

K. Koshelev et al., ACS Photonics 8, 102–112 (2021)

K. Koshelev et al., Physics-Uspekhi 66, 494 (2023)

M. Hentschel, K. Koshelev et al. Light: Sci. Appl. 12, 3 (2023)