Metaphotonics and metasurfaces with Mie resonances

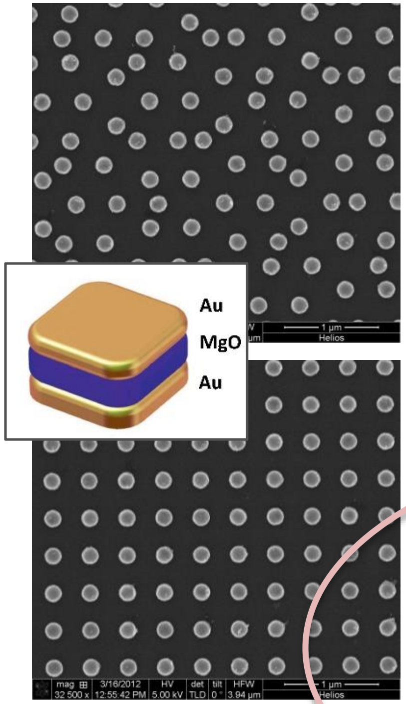
Yuri Kivshar

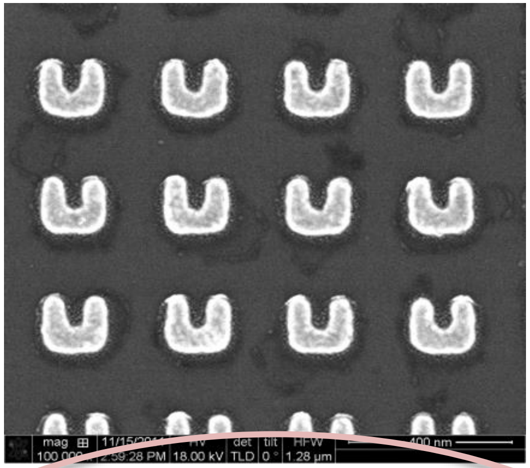
Australian National University

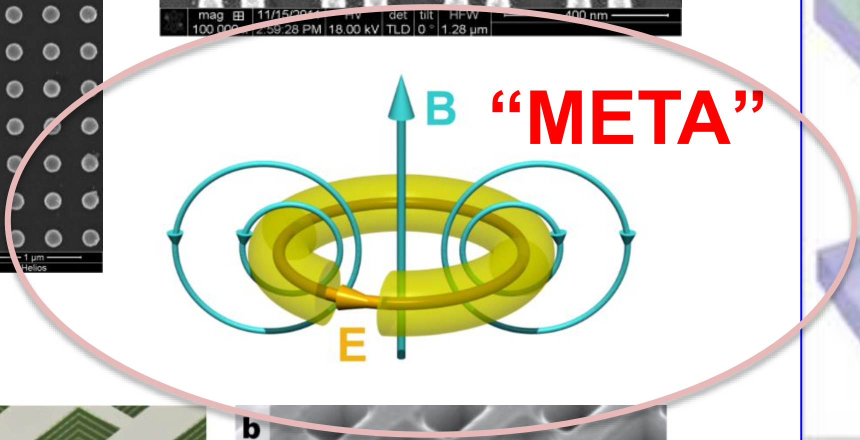
The Hong Kong Polytechnic University
香港理工大學

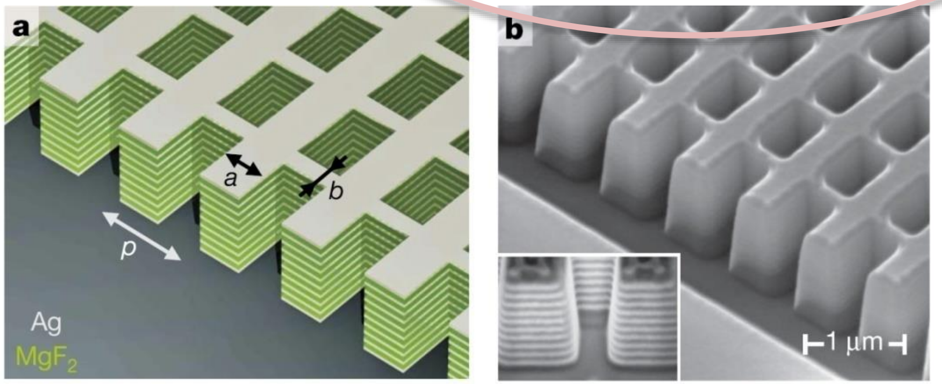
ITMO University

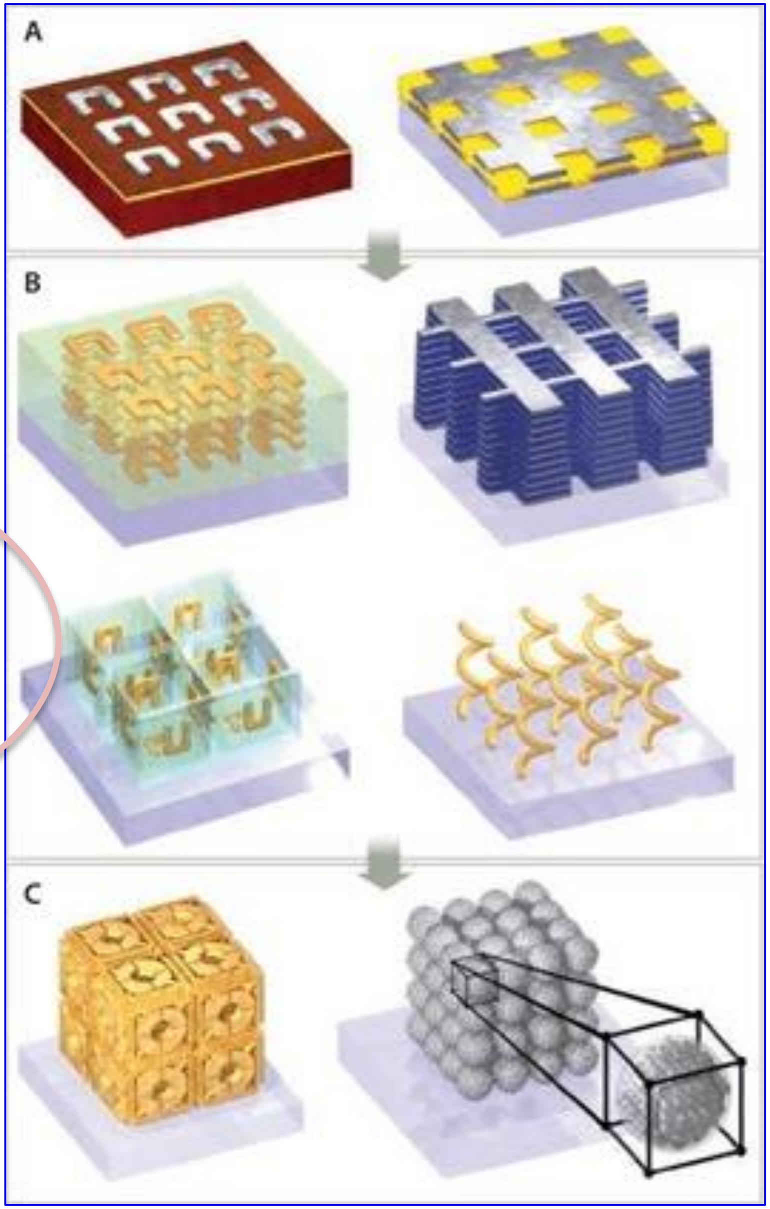
Metamaterials: Electric and magnetic resonances











Mie-resonant metaphotonics

NATURE PHOTONICS | VOL 13 | SEPTEMBER 2019 | 585–587 |

meeting report

VIEW FROM… ICMAT2019

Into the 'Mie-tronic' era

Dielectric antennas and metasurfaces open up new opportunities for future applications in advanced optoelectronics, light detection and ranging for autonomous vehicles, fluorescence-enhancing substrates for bioimaging and many more.

See our review paper: Science **354**, 2472 (2016)

Australian National University

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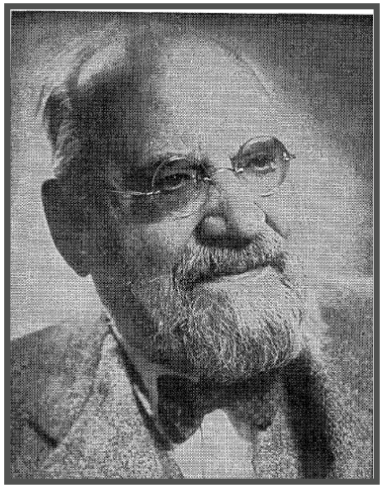
1908: Mie theory



Gustav Mie

$$x = \frac{2\pi r}{\lambda}$$

- x << 1 : Rayleigh scattering
- x ~ 1 : Mie scattering
- x >>1 : Geometric scattering

1908. № 3.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 25.

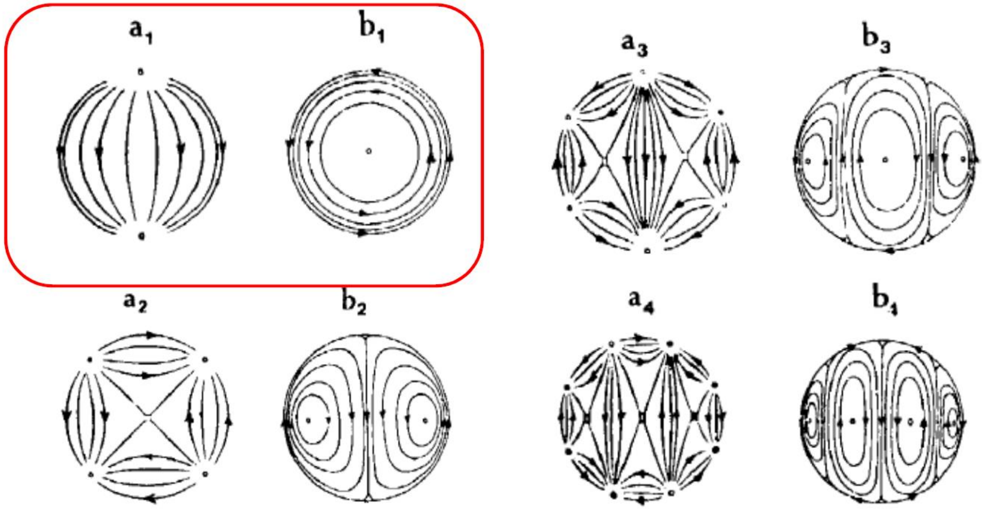
1. *Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösungen;*
von Gustav Mie.

$$\mathbf{E}_r = E_0 e^{-i\omega t} \sum_{n=1}^{\infty} i^n \frac{2n+1}{n(n+1)} \left(a_n^r \mathbf{m}_{o1n}^{(3)} - i b_n^r \mathbf{n}_{e1n}^{(3)}\right),$$

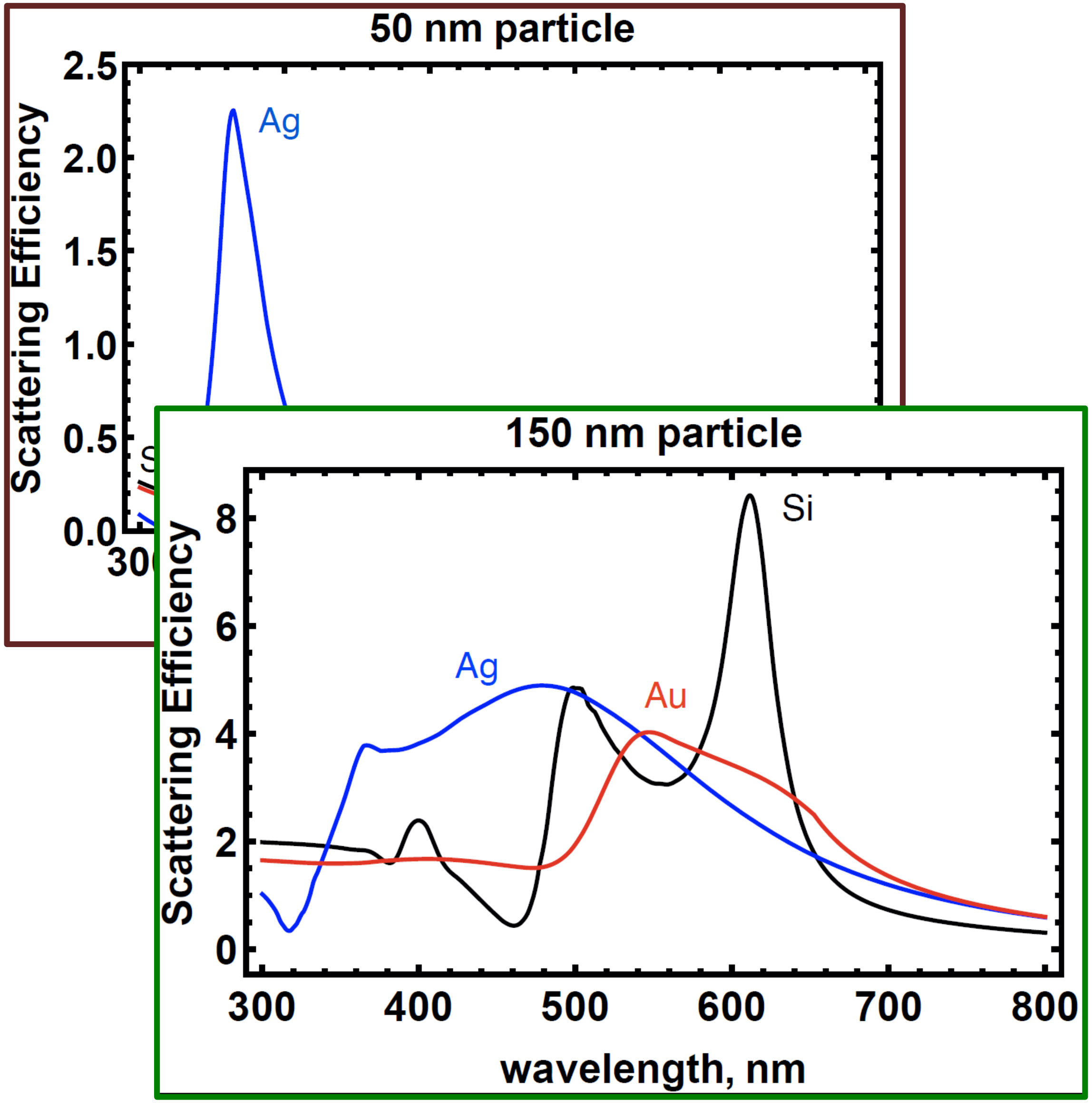
$$\mathbf{H}_r = -\frac{k_2}{\omega\mu_2} E_0 e^{-i\omega t} \sum_{n=1}^{\infty} i^n \frac{2n+1}{n(n+1)} \left(b_n^r \mathbf{m}_{e1n}^{(3)} + i a_n^r \mathbf{n}_{o1n}^{(3)}\right),$$

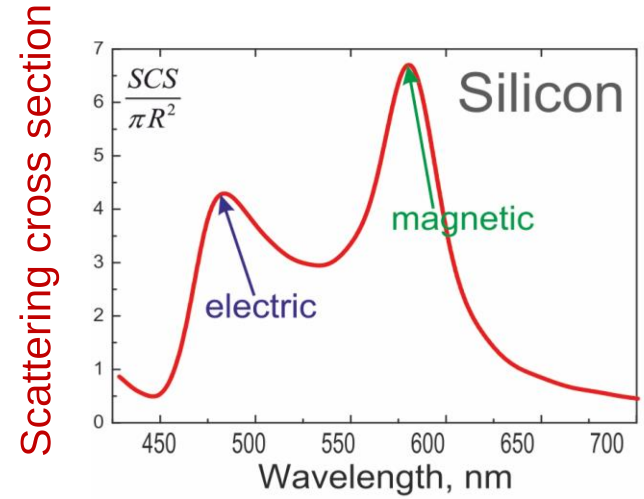
$$a_n^r = -\frac{\mu_1 j_n(N\rho)\,[\rho j_n(\rho)]' - \mu_2 j_n(\rho)\,[N\rho j_n(N\rho)]'}{\mu_1 j_n(N\rho)\,[\rho h_n^{(1)}(\rho)]' - \mu_2 h_n^{(1)}(\rho)\,[N\rho j_n(N\rho)]'}$$

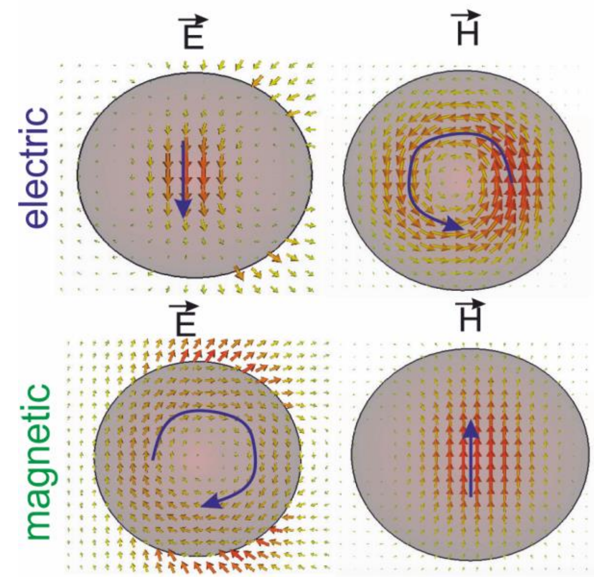
$$b_n^r = -\frac{\mu_1 j_n(\rho)\,[N\rho j_n(N\rho)]' - \mu_2 N^2 j_n(N\rho)\,[\rho j_n(\rho)]'}{\mu_1 h_n^{(1)}(\rho)\,[N\rho j_n(N\rho)]' - \mu_2 N^2 j_n(N\rho)\,[\rho h_n^{(1)}(\rho)]'}$$



Electromagnetic response of a sphere







Multipoles and interferences

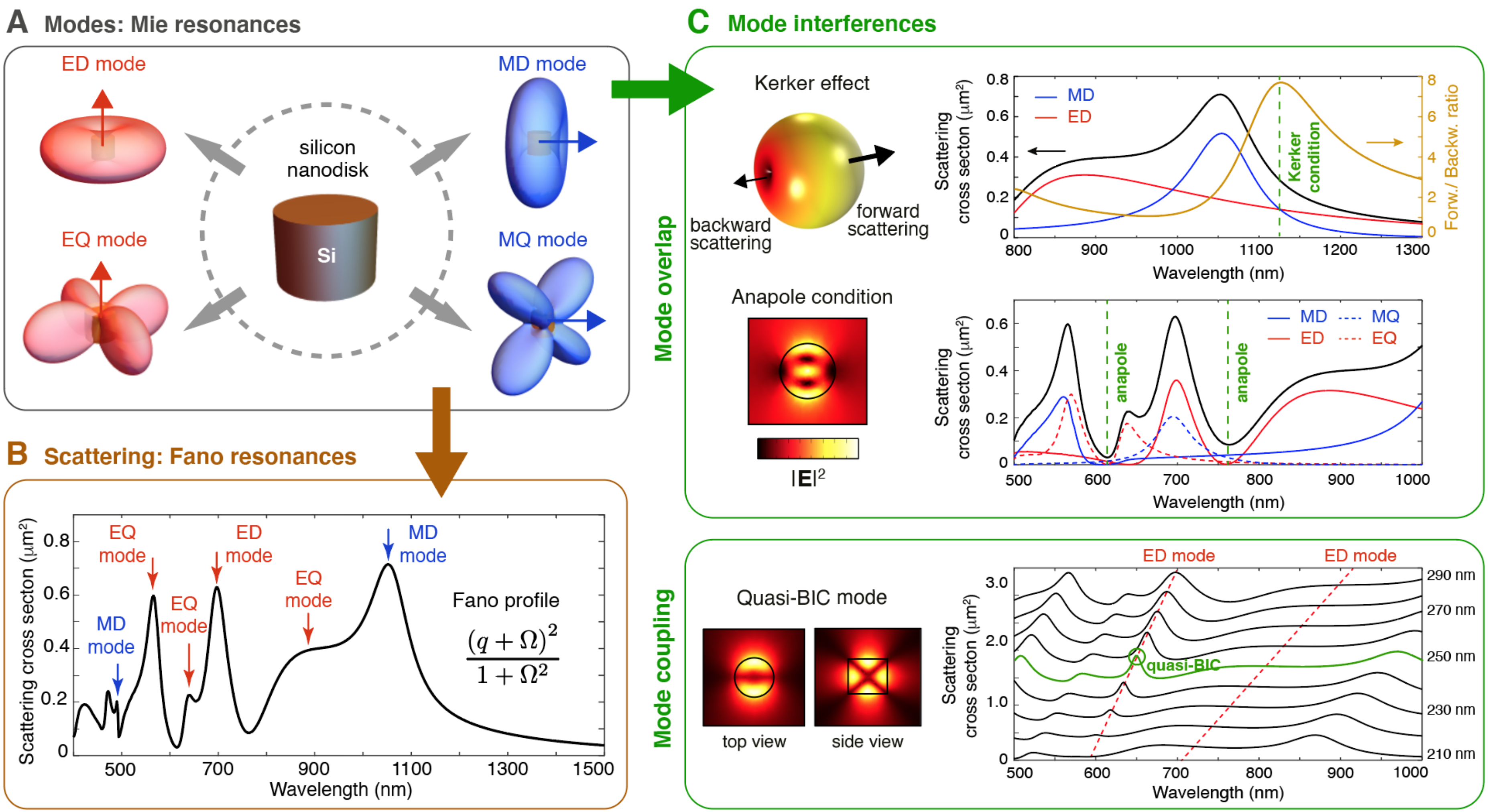


Figure from K. Koshelev and Y. Kivshar, Dielectric resonant metaphotonics, ACS Photonics, Special issue “Photonics 2020”, submitted (2020)

Bound state in the continuum (BIC)

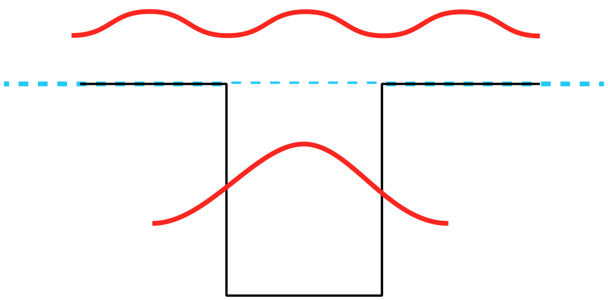
J. von Neumann

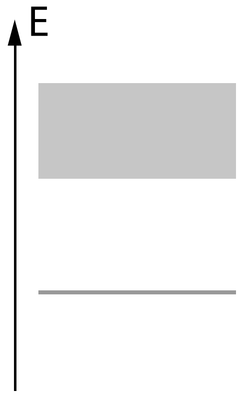
E.P. Wigner

Über merkwürdige diskrete Eigenwerte

J. von Neumann and E. P. Wigner

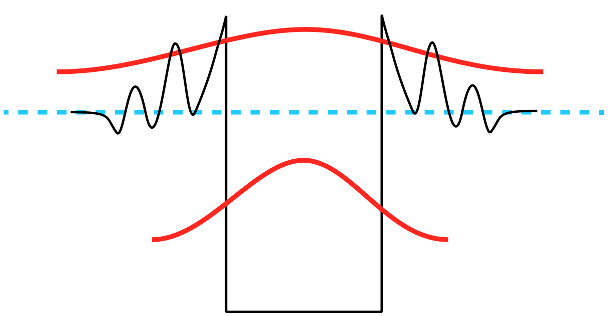
Physikalische Zeitschrift *30*, 465–467 (1929)

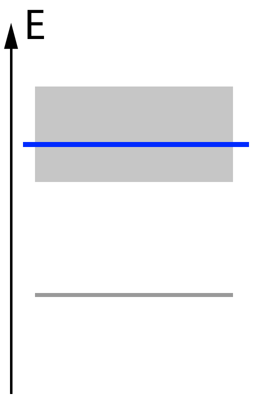




Continuum

Discrete level





Bound state in the continuum

Discrete level

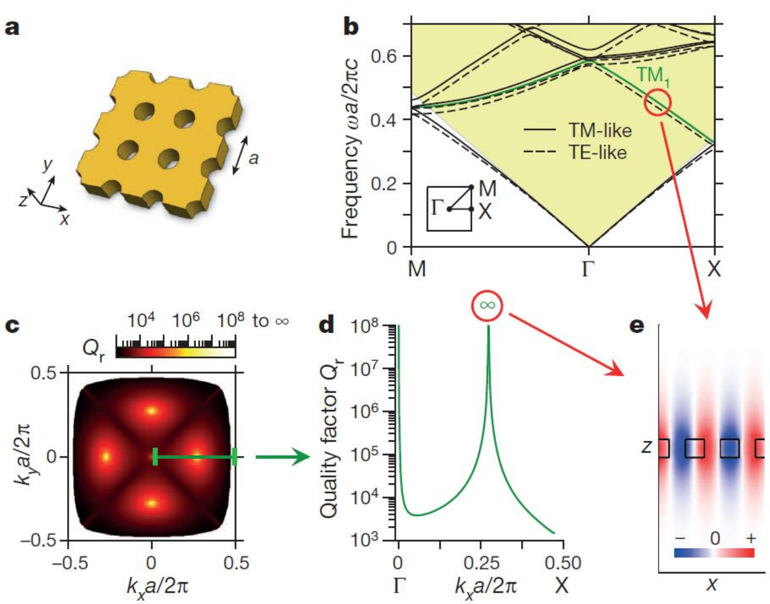
Observation of bound states in the continuum

Observation of an electronic bound state above a potential well **Nature, 1992**

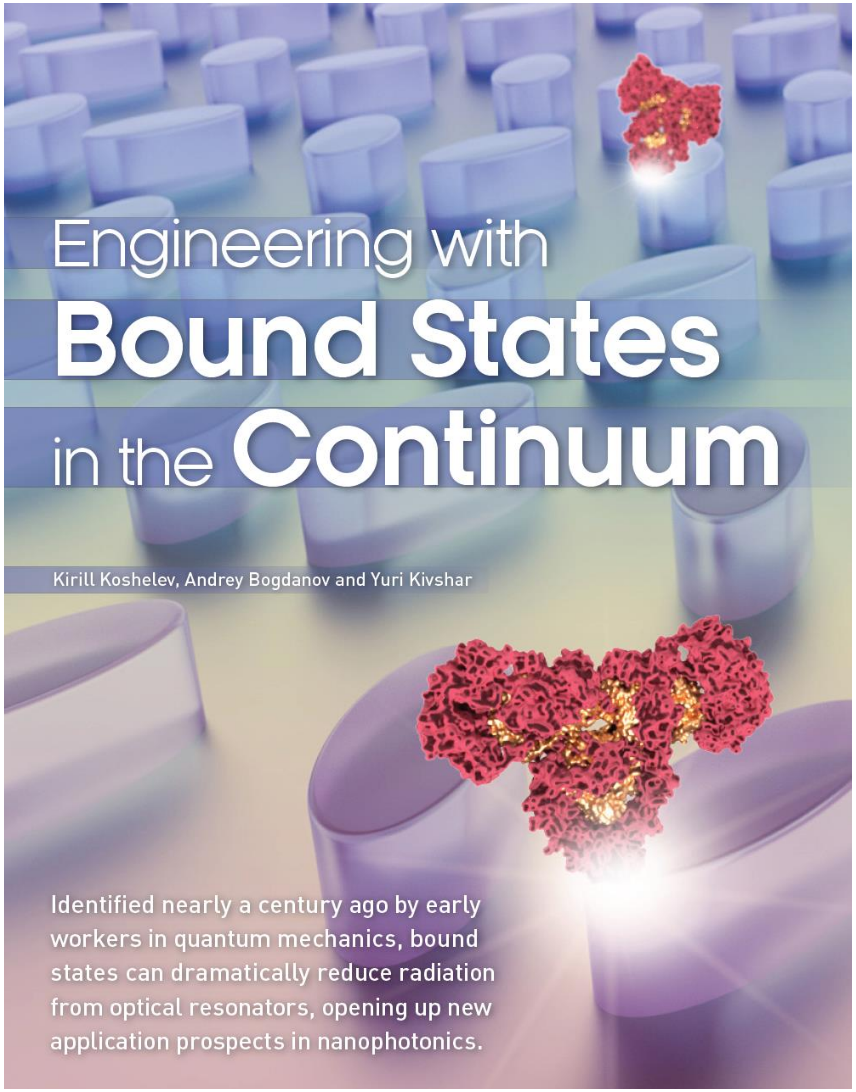
Federico Capasso, Carlo Sirtori, Jerome Faist, Deborah L. Sivco, Sung-Nee G. Chu & Alfred Y. Cho

AT&T Bell Laboratories, Murray Hill, New Jersey 07974, USA

Photonic crystal slabs



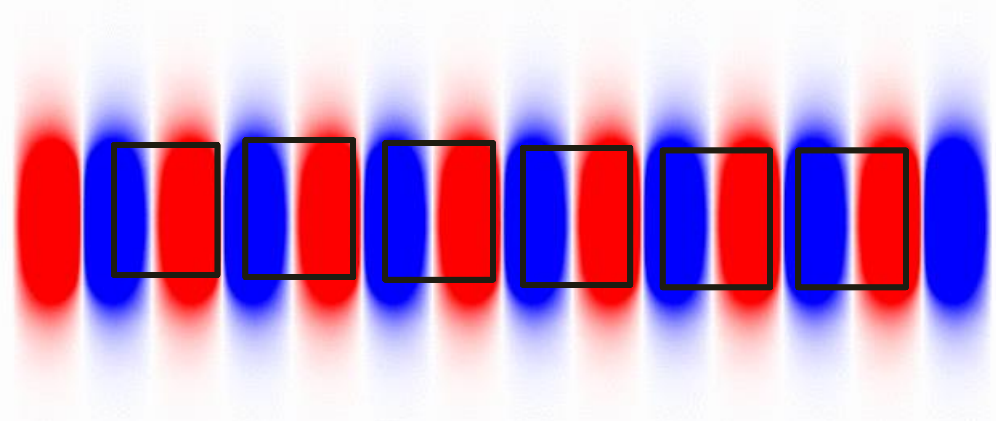
Hsu et al, Nature 2013



OPN, January 2020

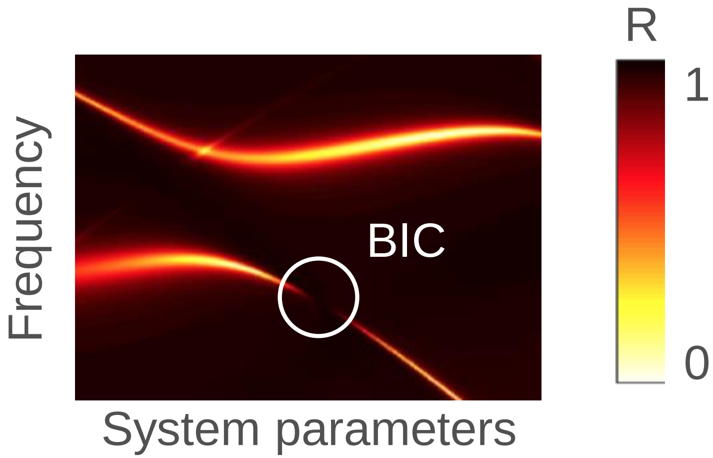
Classification of BICs

Symmetry-protected (conventional)



in-plane inversion symmetry
time reversal symmetry

Accidental (Friedrich-Wintgen)



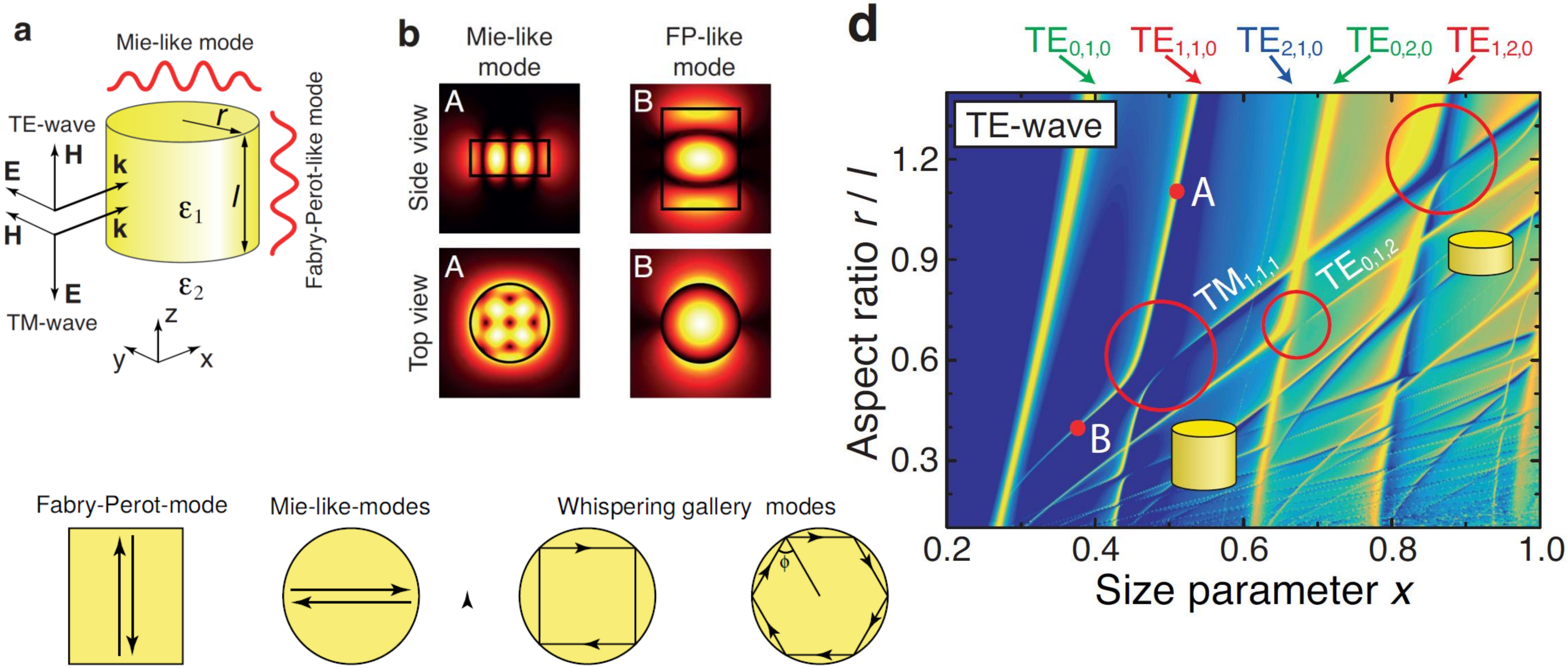
in-plane inversion symmetry
time reversal symmetry
up-down symmetry

PHYSICAL REVIEW A VOLUME 32, NUMBER 6 DECEMBER 1985

Interfering resonances and bound states in the continuum

H. Friedrich and D. Wintgen
Physik Department, Technische Universität München, D-8046 Garching, West Germany
(Received 24 June 1985)

BIC in a subwavelength resonator



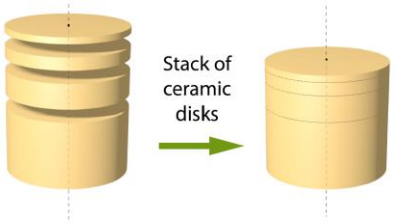
PRL **119,** 243901 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

High-*Q* Supercavity Modes in Subwavelength Dielectric Resonators

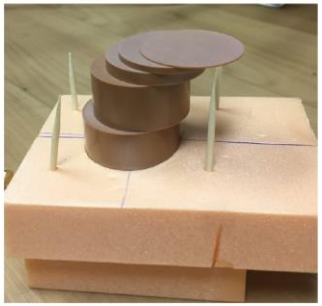
Mikhail V. Rybin,[1,2,*] Kirill L. Koshelev,[1,2] Zarina F. Sadrieva,[2] Kirill B. Samusev,[1,2] Andrey A. Bogdanov,[1,2] Mikhail F. Limonov,[1,2] and Yuri S. Kivshar[2,3]

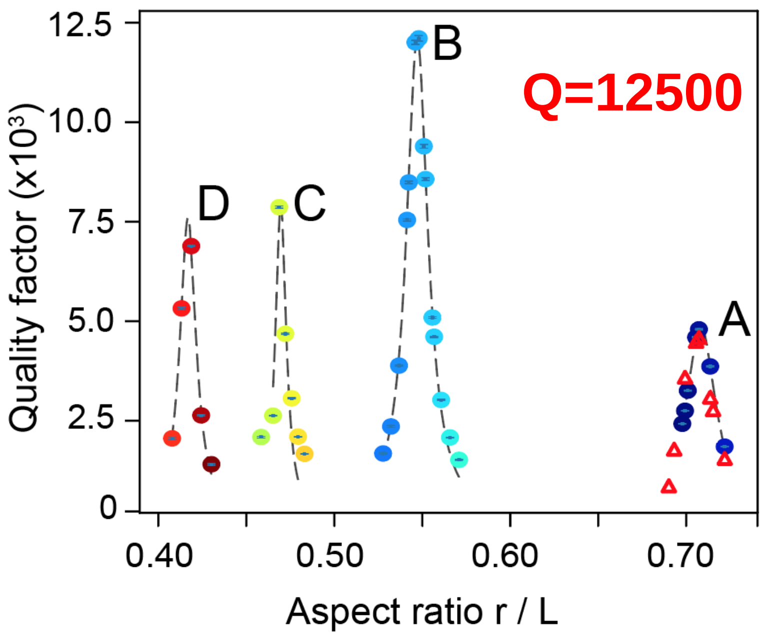
Recent experimental demonstrations

RF experiment



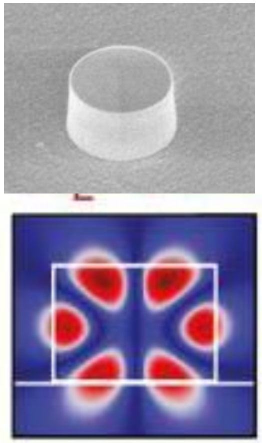
$\varepsilon = 45$
$\tan\delta = 10^{-4}$

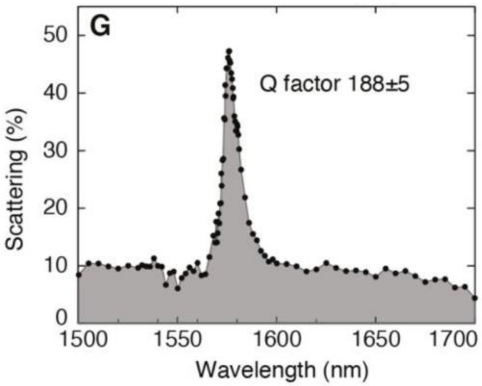


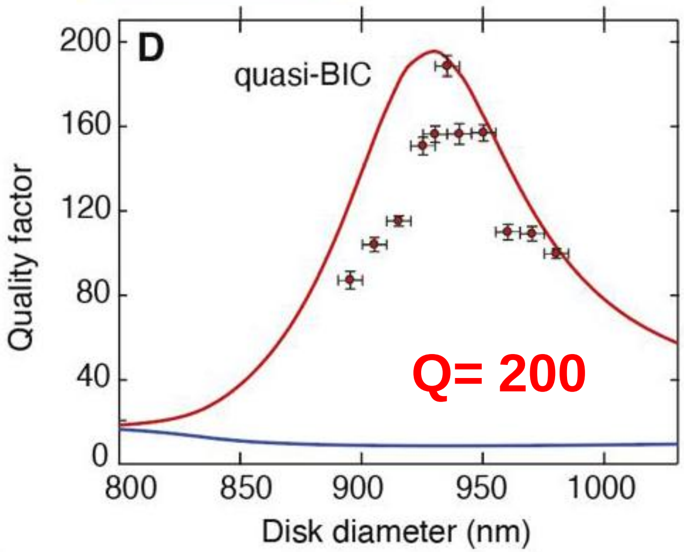


M. Odit et al, submitted (2020)

Near-IR experiment

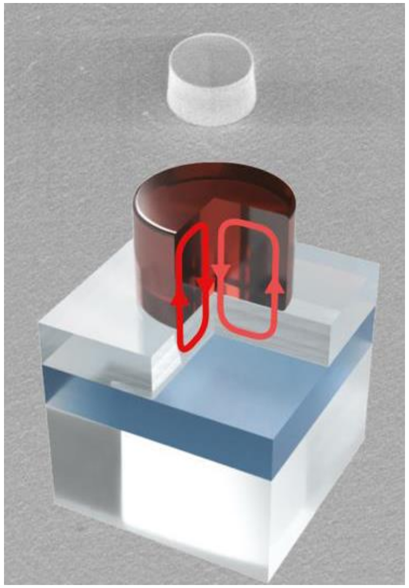


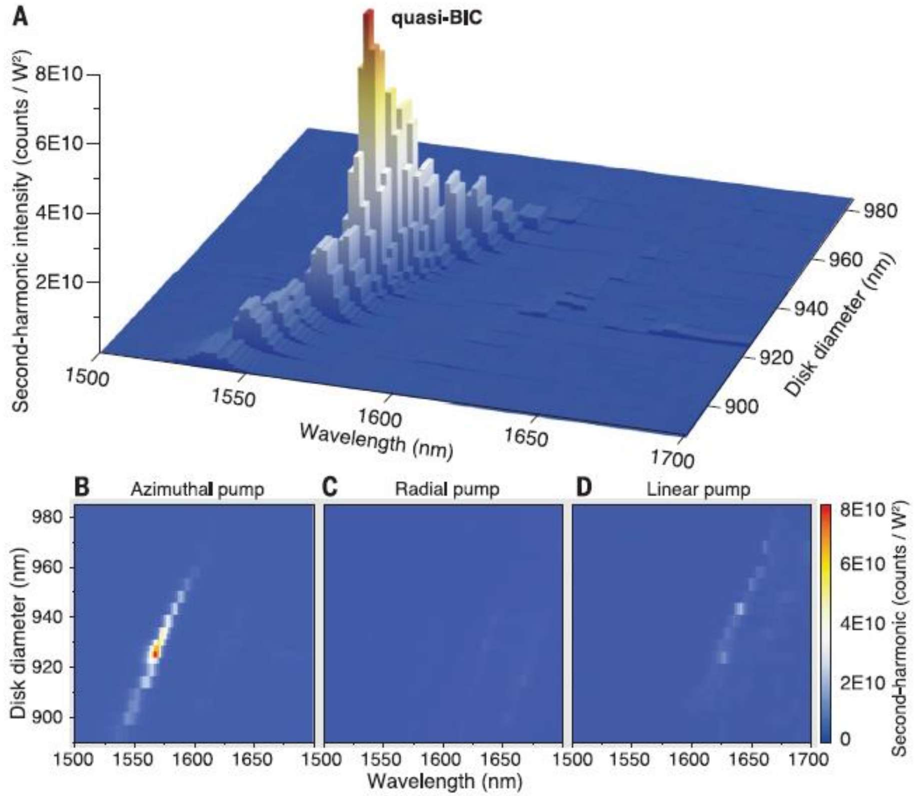




K. Koshelev et al, Science **367**, 288 (2020)

SHG from quasi-BIC states: Recent experiment





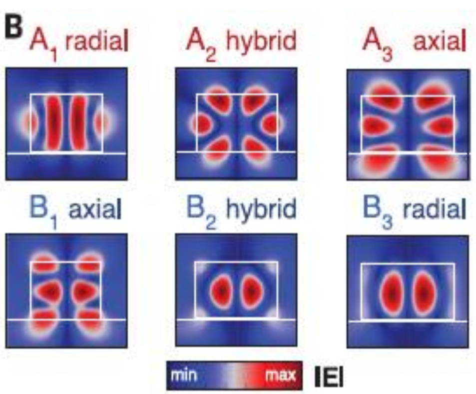
RESEARCH

Science 367, 288 (2020)

OPTICS

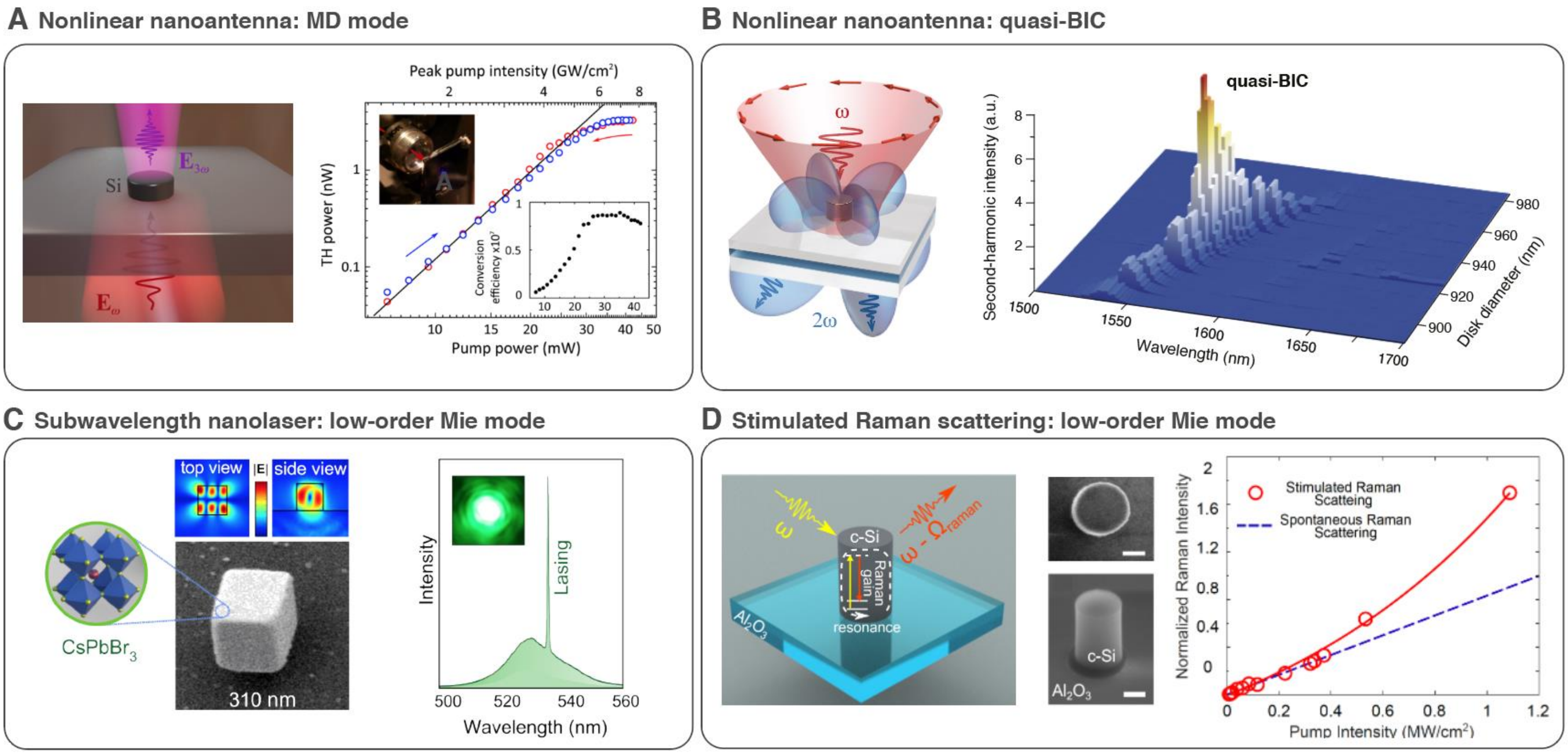
Subwavelength dielectric resonators for nonlinear nanophotonics

Kirill Koshelev[1,2], Sergey Kruk[1], Elizaveta Melik-Gaykazyan[1,3], Jae-Hyuck Choi[4], Andrey Bogdanov[2], Hong-Gyu Park[4]*, Yuri Kivshar[1,2]*



Examples of “Mie-tronics” effects

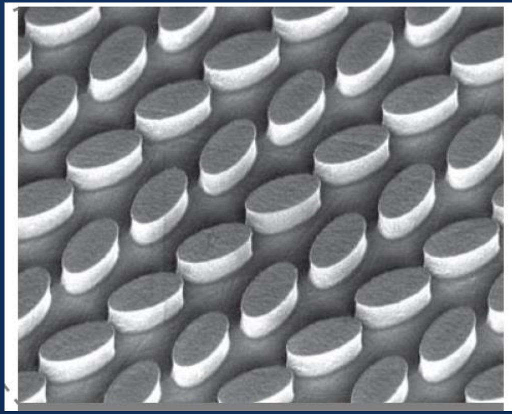
Nano Letters (2014) Science (2020)

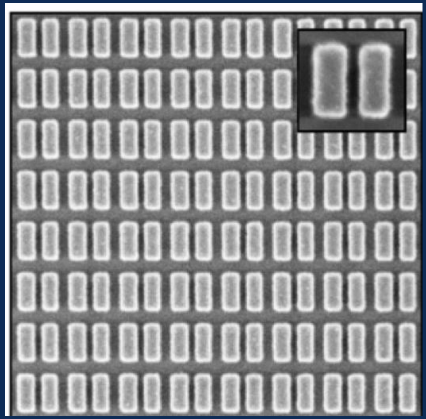


ACS Nano (2020) online Nano Letters (2020) under review

Figure from K. Koshelev and Y. Kivshar, Dielectric resonant metaphotonics, ACS Photonics, Special issue “Photonics 2020”, submitted (2020)

Dielectric metasurfaces





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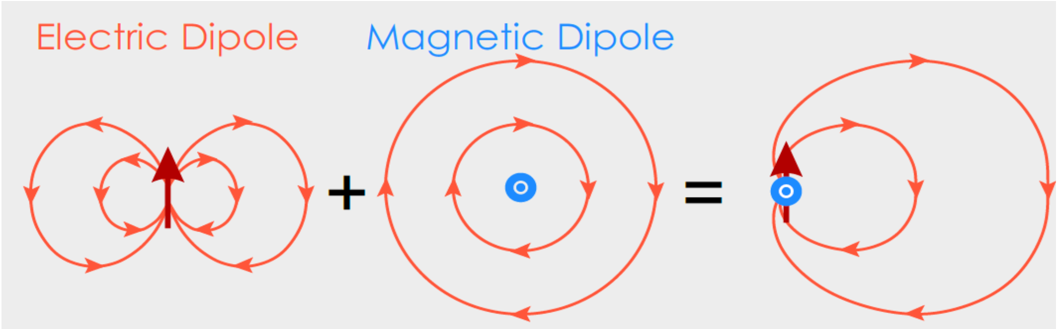
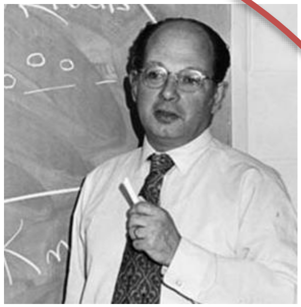
Two strategies for metasurface engineering

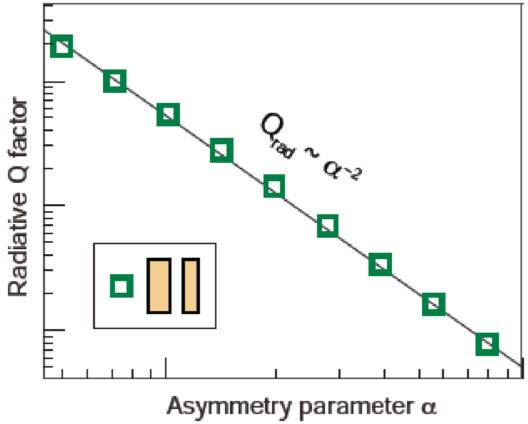
Multipoles for highly efficient transmission

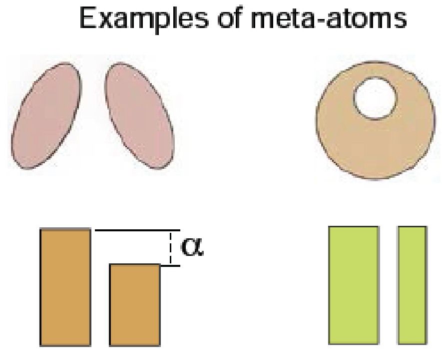




Milton Kerker

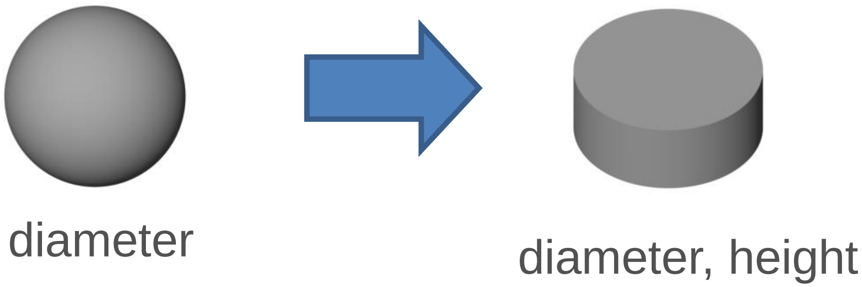
Resonances with bound states in the continuum

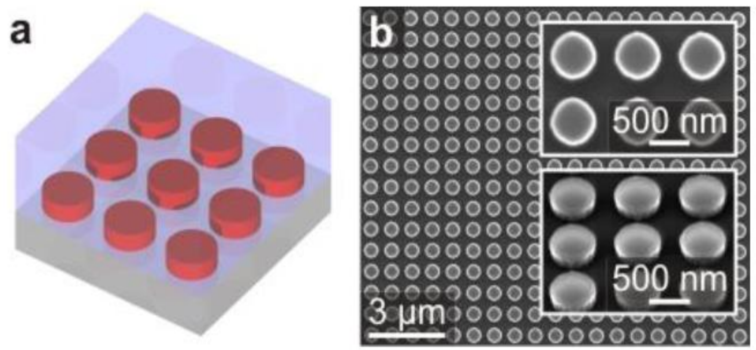


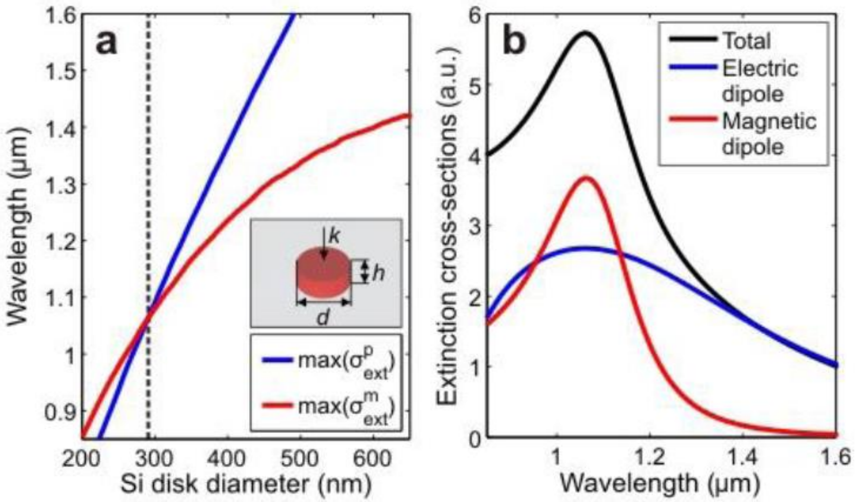


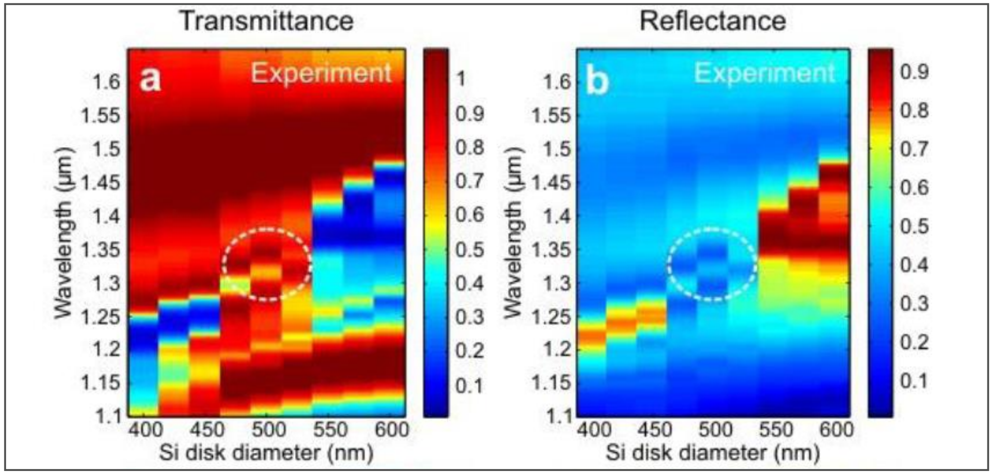
J. von Neumann E. Wigner

Tailoring magnetic response





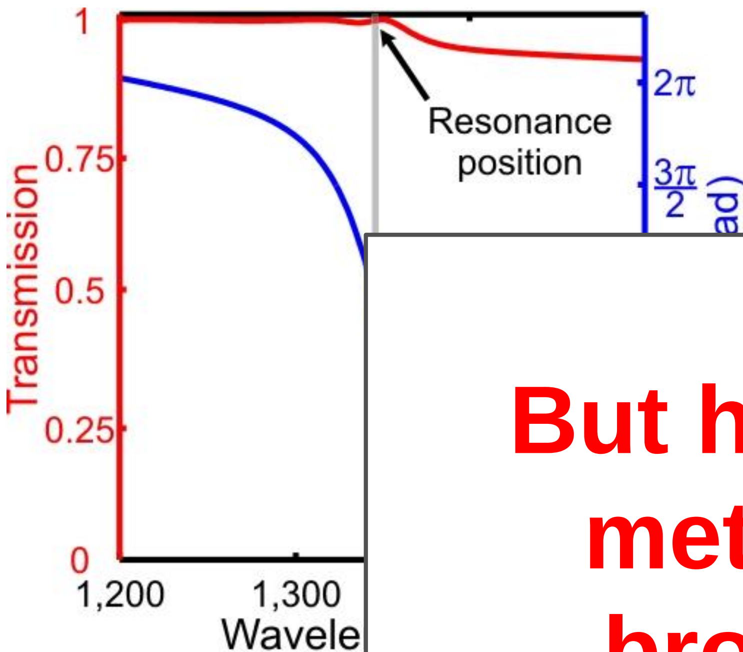




I. Staude et al, ACS Nano 7, 7824 (2013)

Huygens‘ metasurfaces

Silicon nanodisks embedded in n = 1.66 medium



- Complete 2π phase coverage
- → Near-unity transmittance: T > 91% for embedded disks

s (NIR)

version losses

lar

But how to make metasurfaces broadband ?

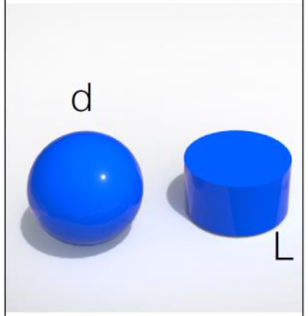
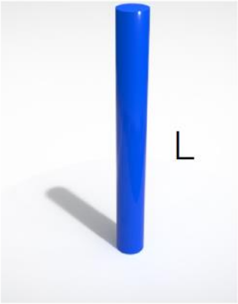
www.MaterialsViews.com

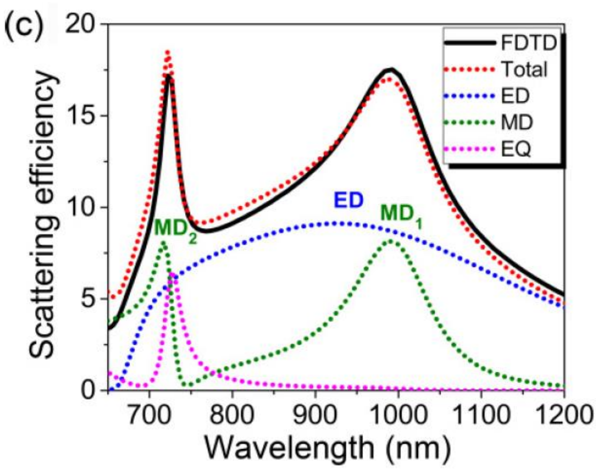
ADVANCED OPTICAL MATERIALS
www.advopticalmat.de

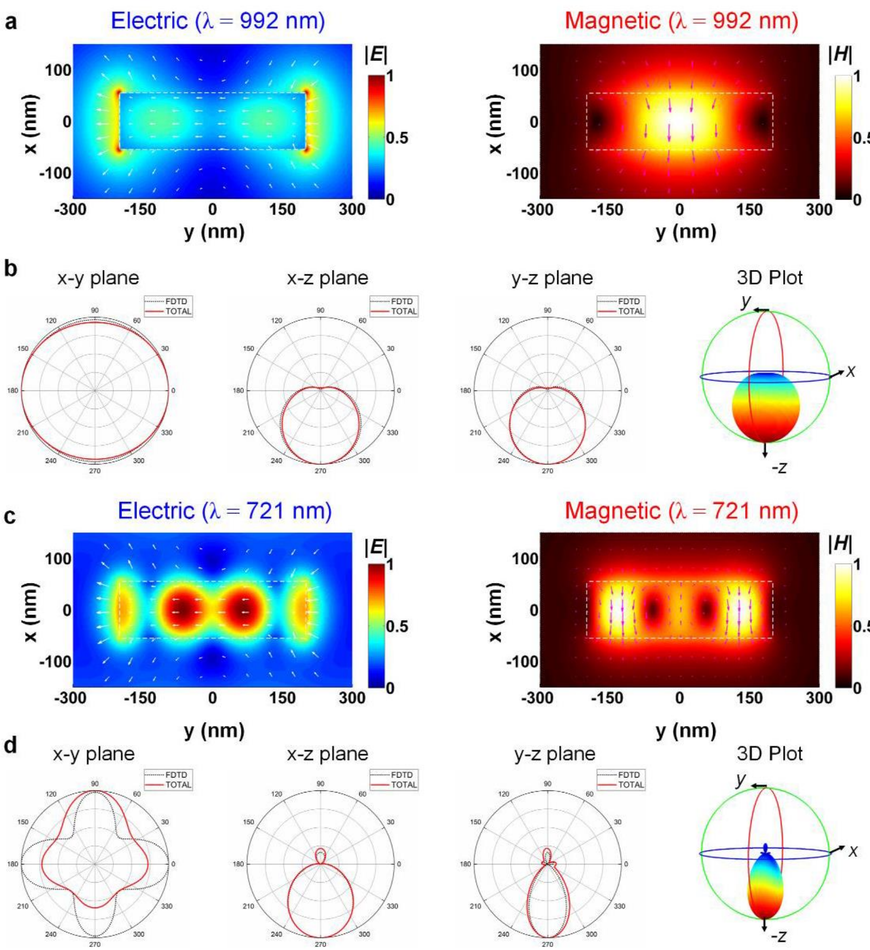
High-Efficiency Dielectric Huygens’ Surfaces

Manuel Decker, Isabelle Staude, Matthias Falkner, Jason Dominguez, Dragomir N. Neshev, Igal Brener, Thomas Pertsch, and Yuri S. Kivshar*

Mie + Fabry-Perot resonances

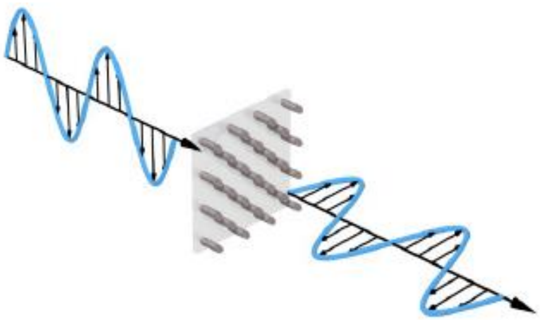
3D Mie		2D Mie
 d,L<<λ		 L>>λ

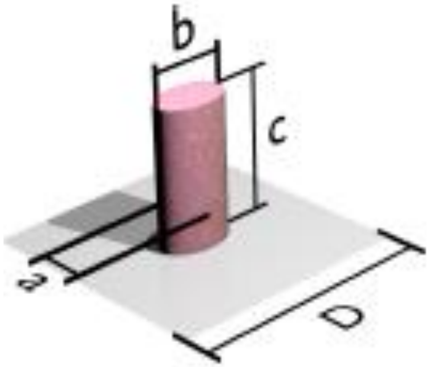


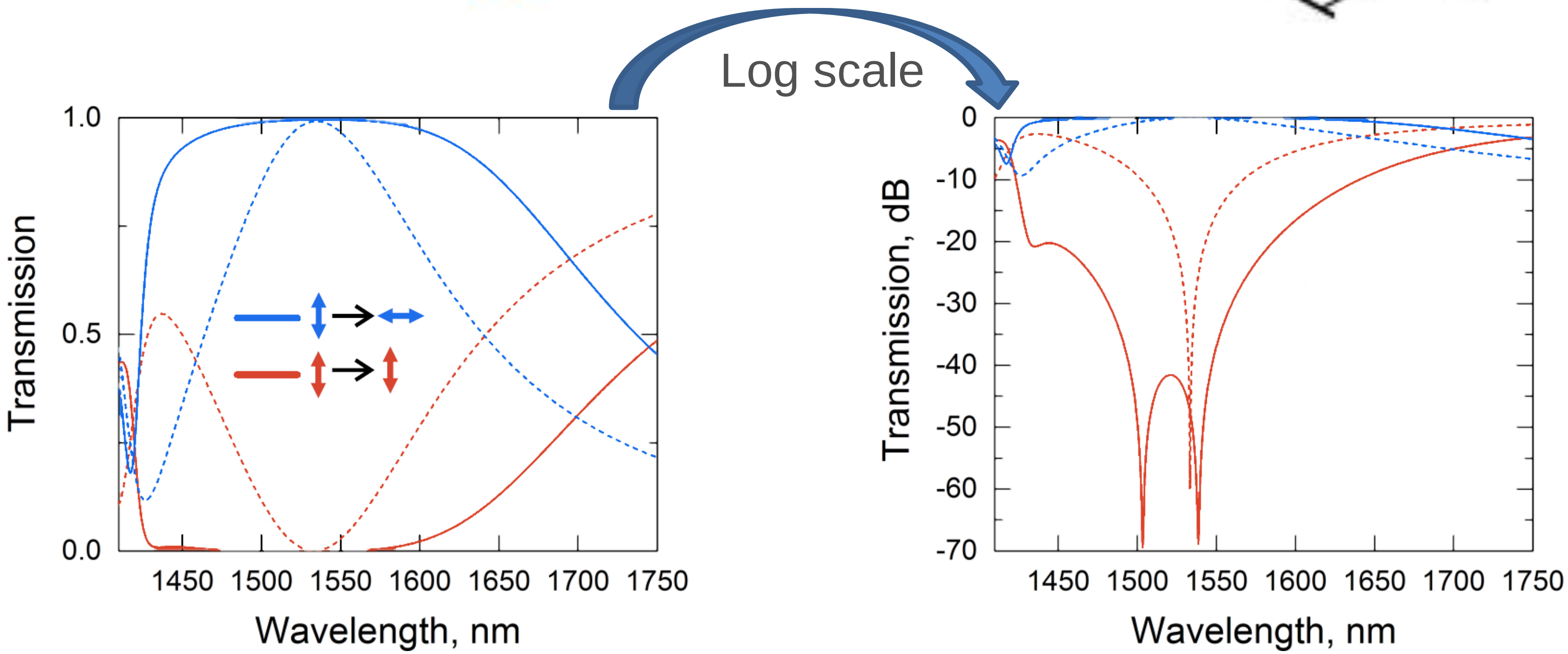


Y. Yang et al, Phys Rev B **95**,165426 (2017)

How to make a metasurface broadband ?

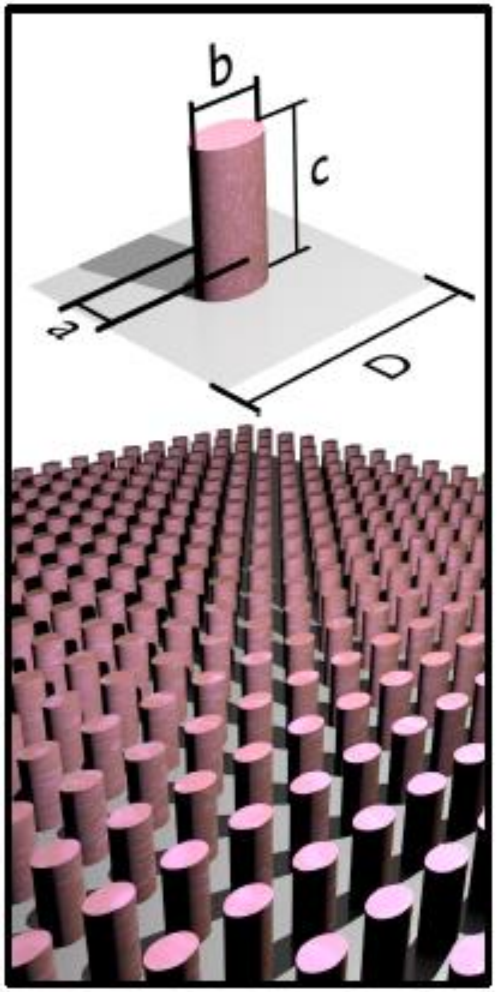


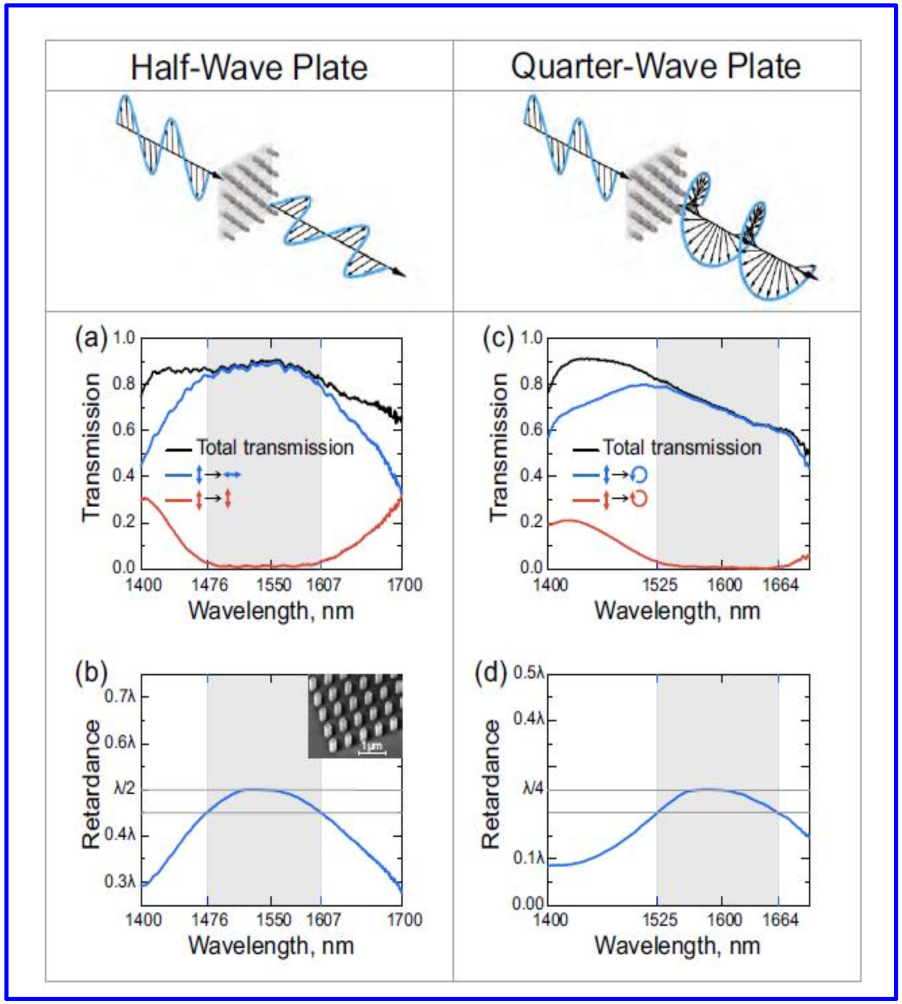


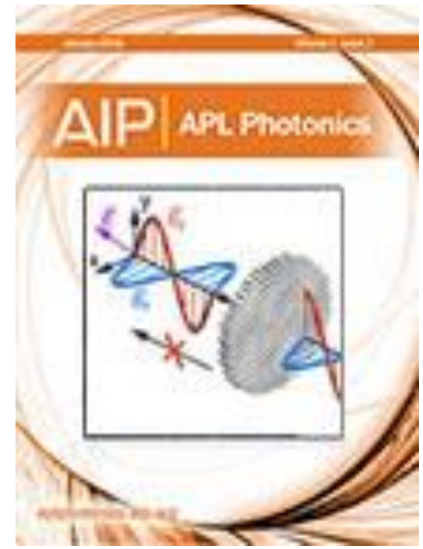


Broadband operation via multipolar response

Broadband highly-efficient dielectric metasurfaces







S. Kruk et al, APL Photonics 1, 030801 (2016)

Transmission efficiencies of metadevices

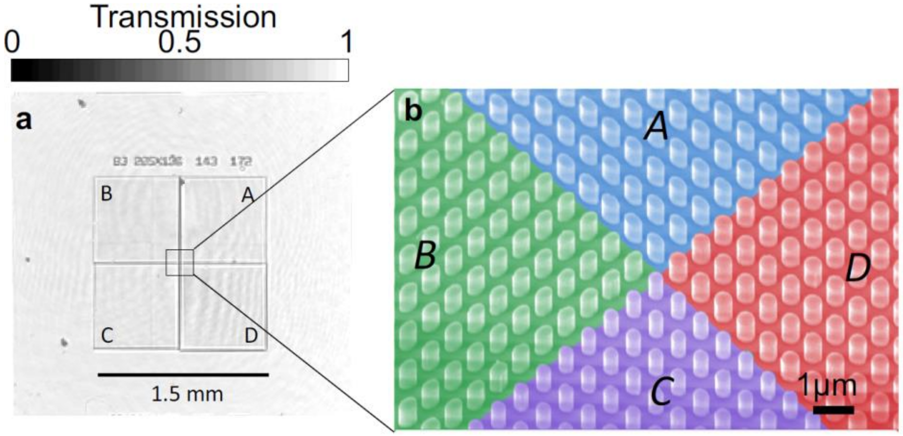
Year	Functionality	Efficiency	Ref
2012	lens, axicon	1%	Aieta 2012
2013	hologram	0.2%	Zhou 2013
2013	lens	10%	Ni 2013
2013	hologram	2%	Huang 2013
2014	lens, axicon, beam deflector	75%	Lin 2014
2015	lens	59%	Matsui 2015
2015	lens	82%	Arbabi 2015
2015	beam deflector	45%	Yu 2015
2015	vortex	70%	Chong 2015
2015	vortex, beam deflector	45%	Shalaev 2015
2015	lens, hologram,Q-plate	83%	Arbabi 2015
2015	lens, vortex	36%	Zhan 2015
2016	hologram	75%	Khorasaninejad 2016
2016	lens	86%	Khorasaninejad 2016
2016	lens	65%	Arbabi2016
2016	waveplate, Q-plate	90%	Kruk 2016
2016	holograms	91%	Wang 2016
2017	beam deflector	67%	zhou 2017
2017	lens	53%	Chen 2017
2017	beam deflector	75%	Sell 2017

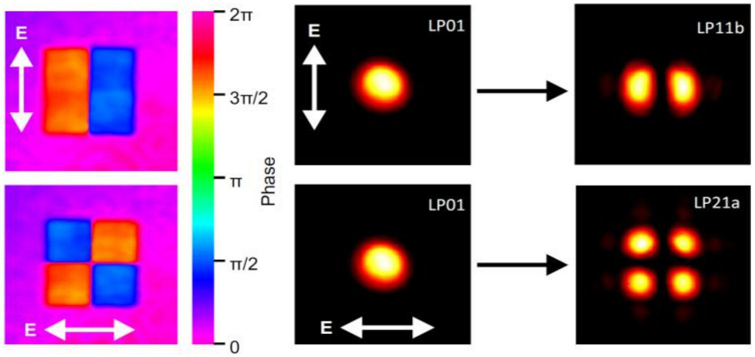
Efficiency axis: 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

Transparency of a glass plate

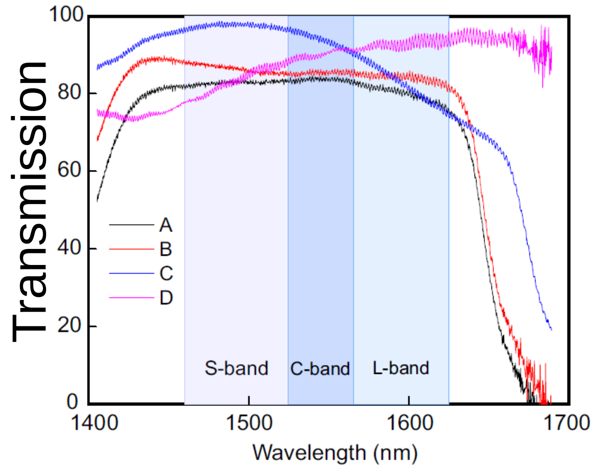
ANU

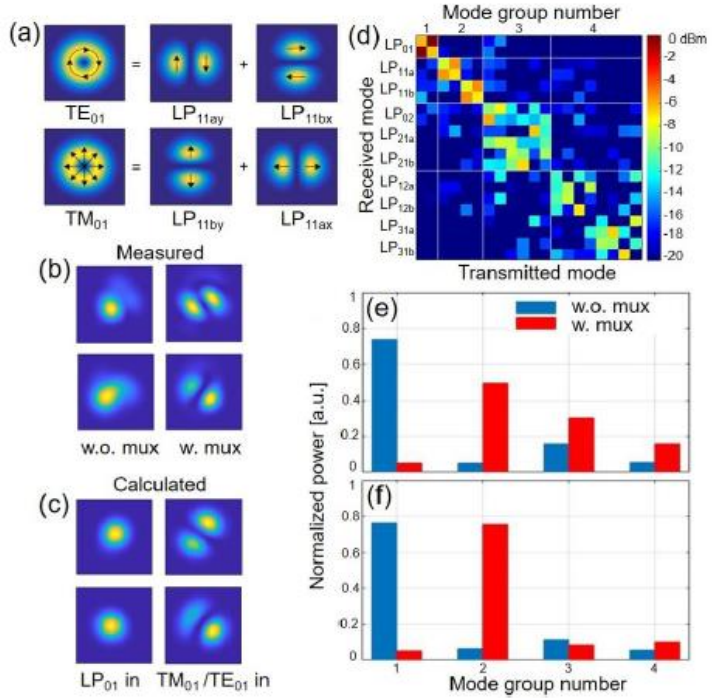
Metasurfaces and optical communications



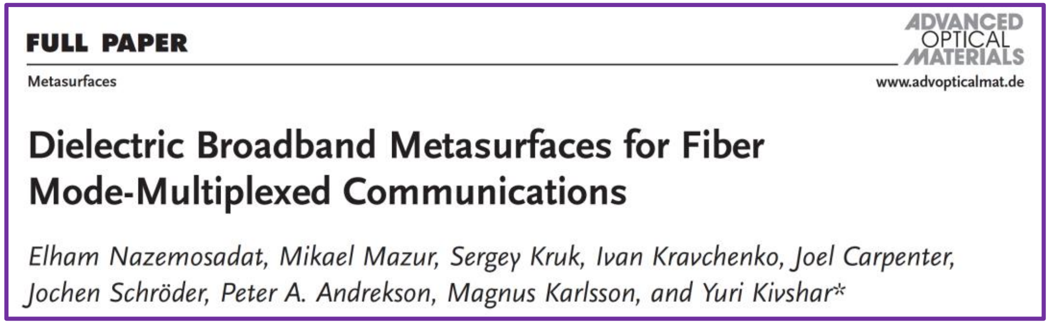


S. Kruk et al, Laser & Photonics Reviews (2018)





Multimode fiber transmission



FULL PAPER

ADVANCED OPTICAL MATERIALS

Metasurfaces

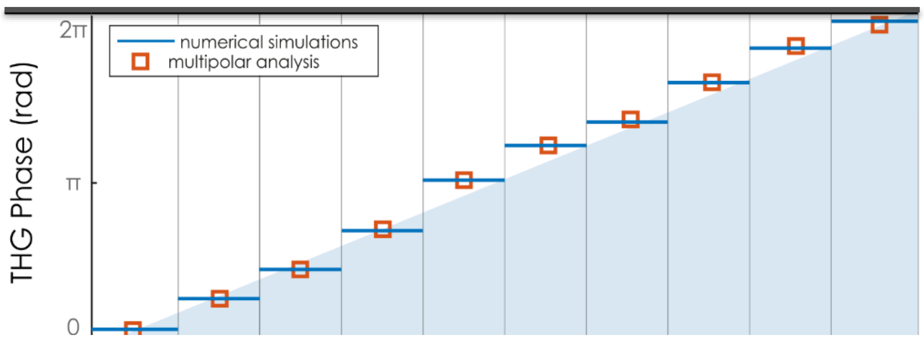
www.advopticalmat.de

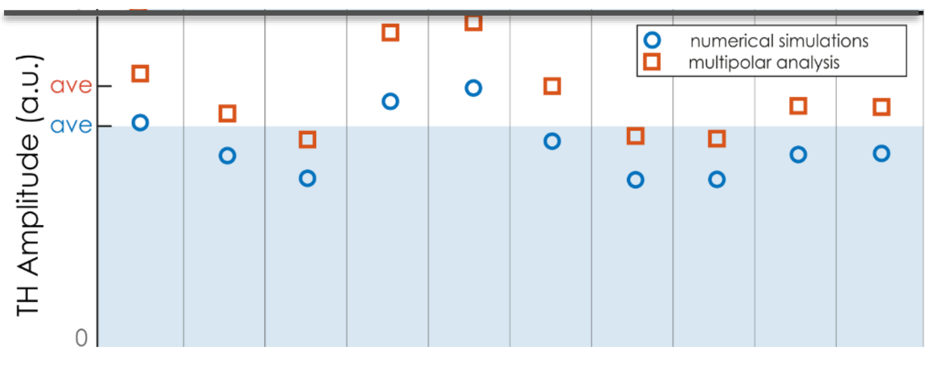
Dielectric Broadband Metasurfaces for Fiber Mode-Multiplexed Communications

*Elham Nazemosadat, Mikael Mazur, Sergey Kruk, Ivan Kravchenko, Joel Carpenter, Jochen Schröder, Peter A. Andrekson, Magnus Karlsson, and Yuri Kivshar**

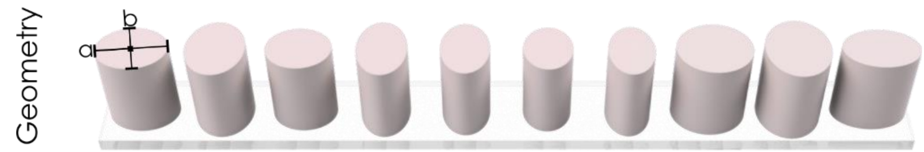
Nonlinear dielectric metasurfaces

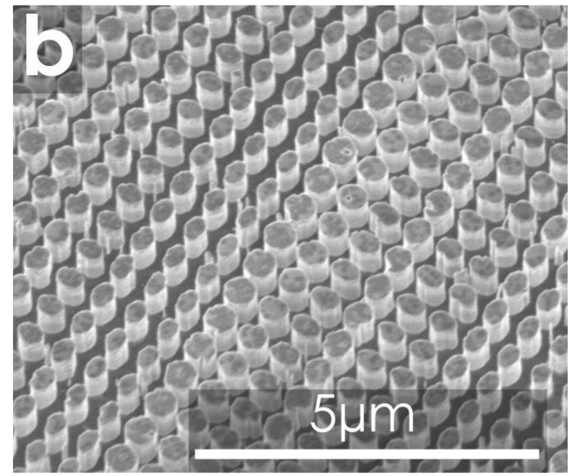
1650 nm pump → 550 nm TH



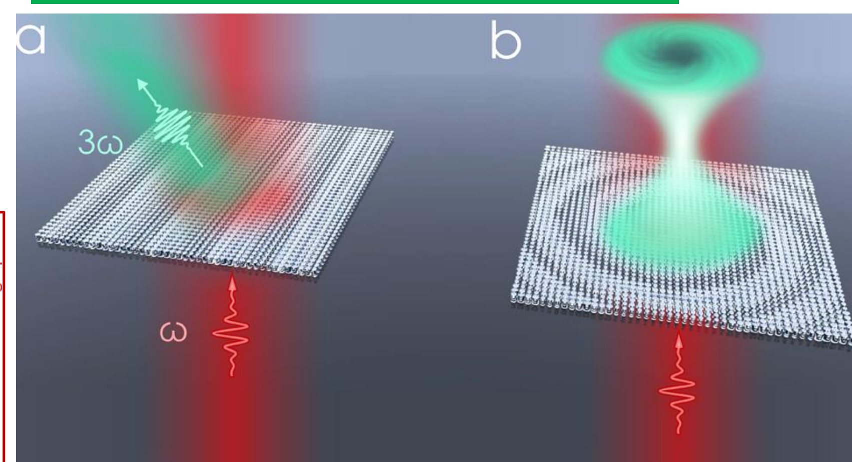


1.4×10^{-4} W^{-2} Conversion Efficiency





92% Difraction Efficiency



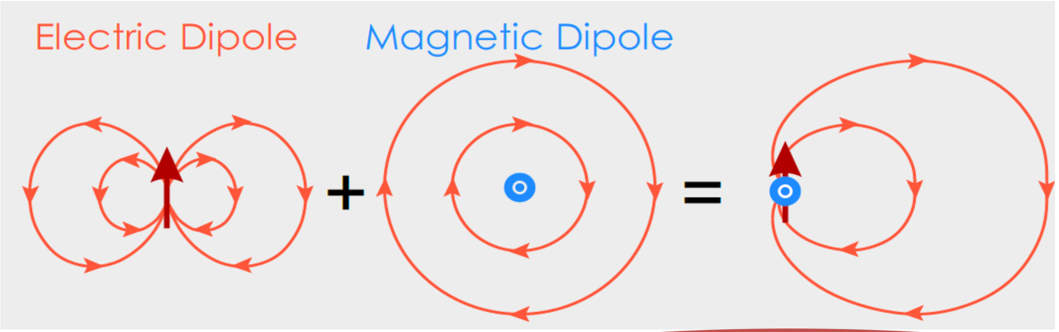
NANO LETTERS Cite This: Nano Lett. XXXX, XXX, XXX−XXX pubs.acs.o

Nonlinear Wavefront Control with All-Dielectric Metasurfaces

Lei Wang,[†] Sergey Kruk,[*,†] Kirill Koshelev,[†,§] Ivan Kravchenko,[∥] Barry Luther-Davies,[‡] and Yuri Kivshar[†,§]

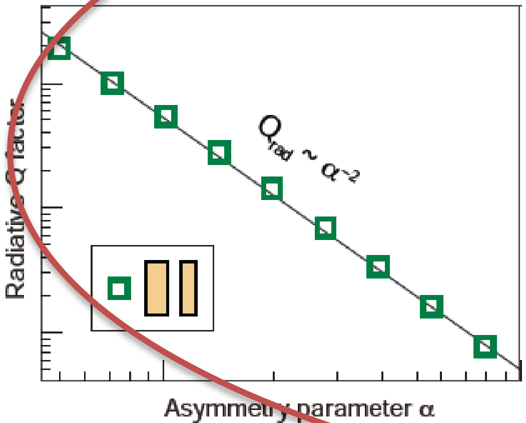
Two strategies for metasurface engineering

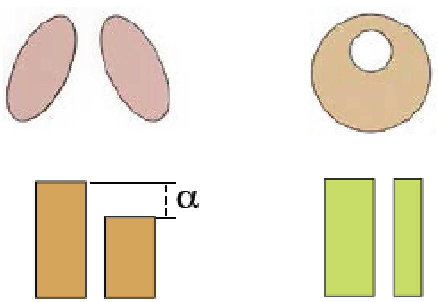
Multipoles for highly efficient transmission



Milton Kerker

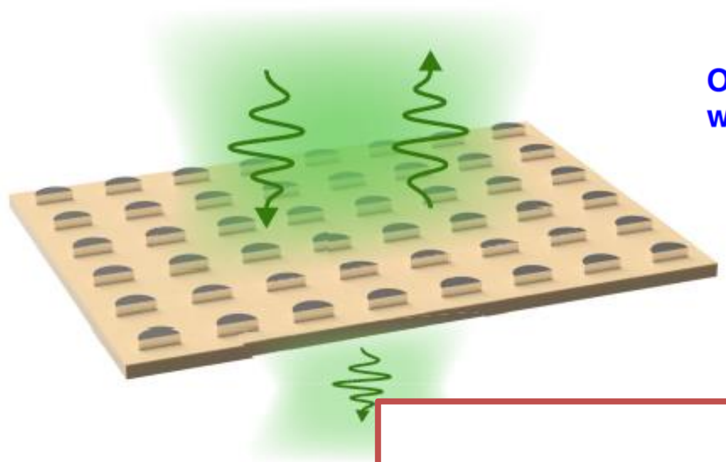
Resonances with bound states in the continuum





J. von Neumann E. Wigner

Metasurfaces with a broken symmetry



APPLIED PHYSICS LETTERS **99**, 201107 (2011)

Observing metamaterial induced transparency in individual Fano resonators with broken symmetry

Ranjan Singh,[1,2,a)] Ibraheem A. I. Al-Naib,[3] Yuping Yang,[2] Dibakar Roy Chowdhury,[1] Wei Cao,[2] Carsten Rockstuhl,[4] Tsuneyuki Ozaki,[3] Roberto Morandotti,[3] and Weili Zhang[2,b)]

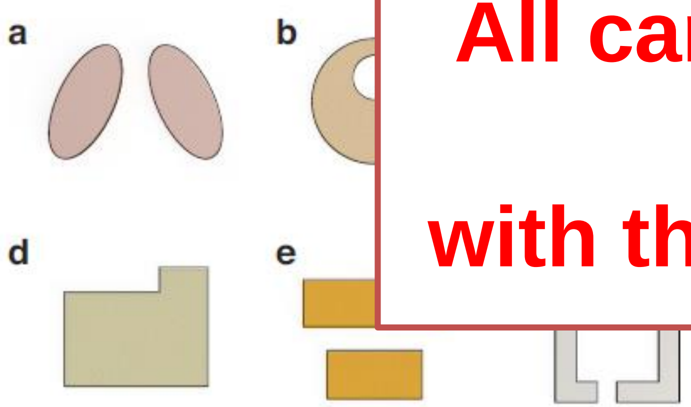
Research Article Vol. 26, No. 3 | 5 Feb 2018 | OPTICS EXPRESS 2905

Optics EXPRESS

High-quality trapped modes in all-dielectric

CHESLAV V. KHARDIKOV,[1,3,4]
ATERYNA L. DOMINA,[4] SU XU,[2]
SUN[2]

All can be explained with the BIC concept!



ar barcoding
c metasurfaces

Yesilkoy[1], Duk-Yong Choi[3],

www.MaterialsViews.com

ADVANCED OPTICAL MATERIALS
www.advopticalmat.de

Electric and Magnetic Response in Dielectric Dark States for Low Loss Subwavelength Optical Meta Atoms

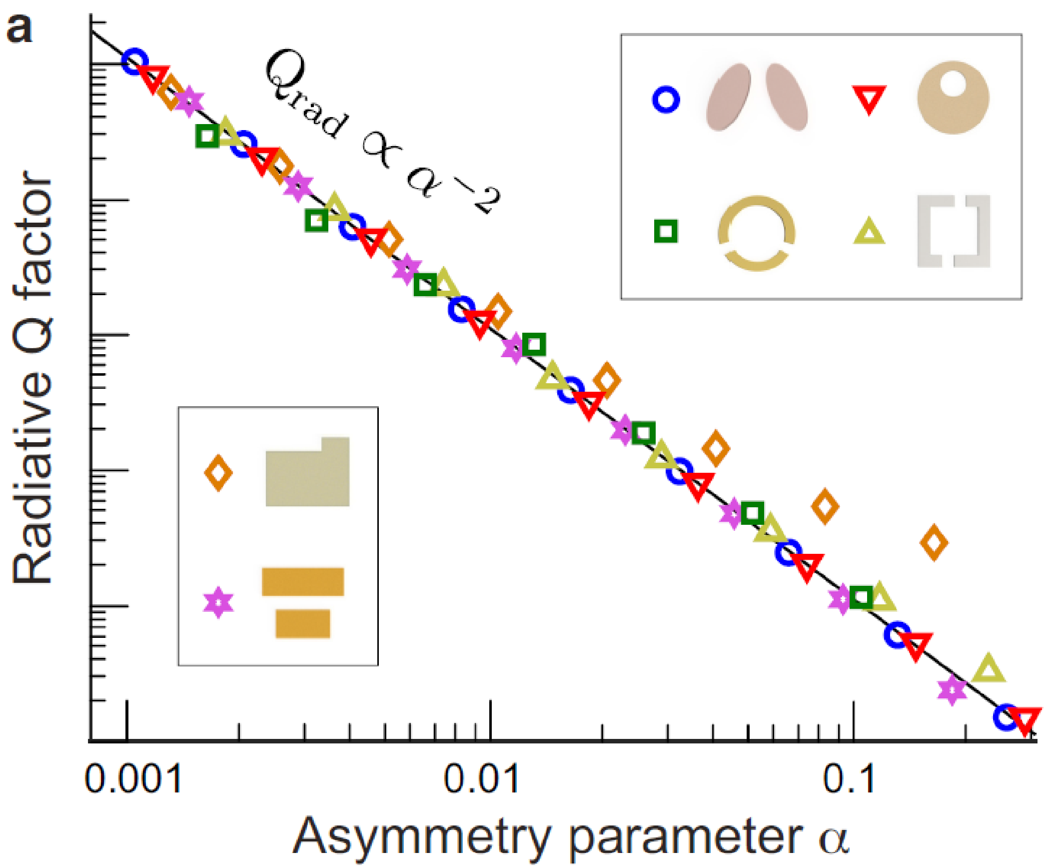
Aditya Jain, Parikshit Moitra, Thomas Koschny, Jason Valentine, and Costas M. Soukoulis*

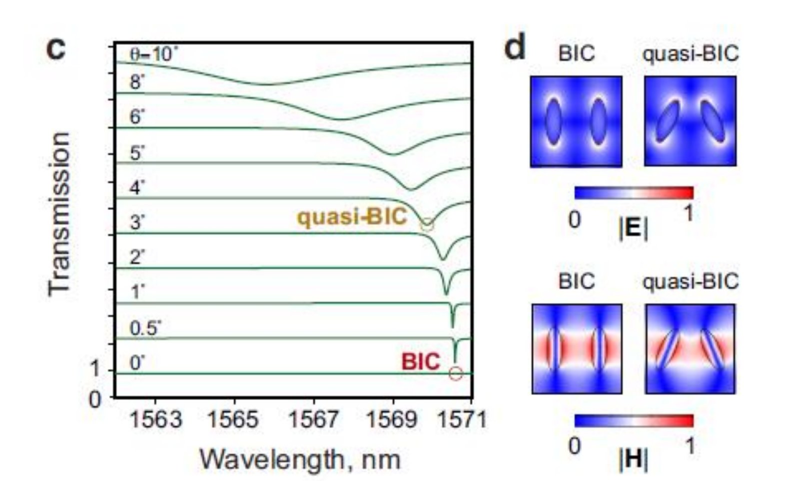
PRL **99**, 147401 (2007) PHYSICAL REVIEW LETTERS week ending 5 OCTOBER 2007

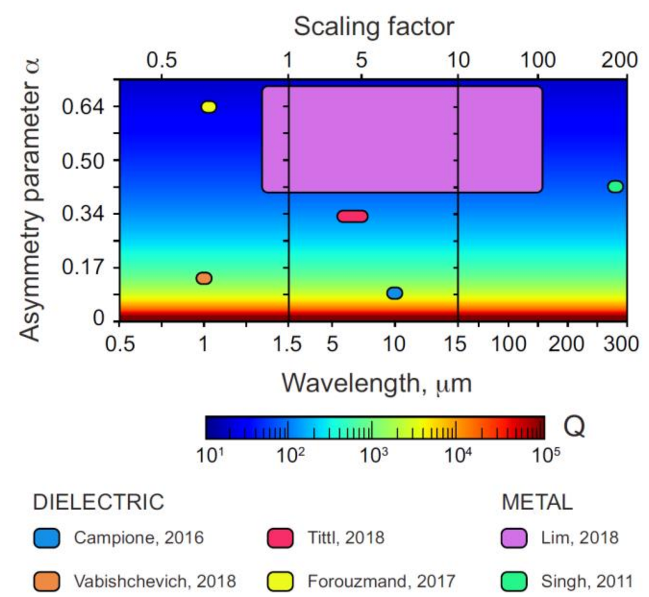
Sharp Trapped-Mode Resonances in Planar Metamaterials with a Broken Structural Symmetry

V. A. Fedotov,[1,*] M. Rose,[1] S. L. Prosvirnin,[2] N. Papasimakis,[1] and N. I. Zheludev[1,†]

High-Q quasi-BIC metasurfaces





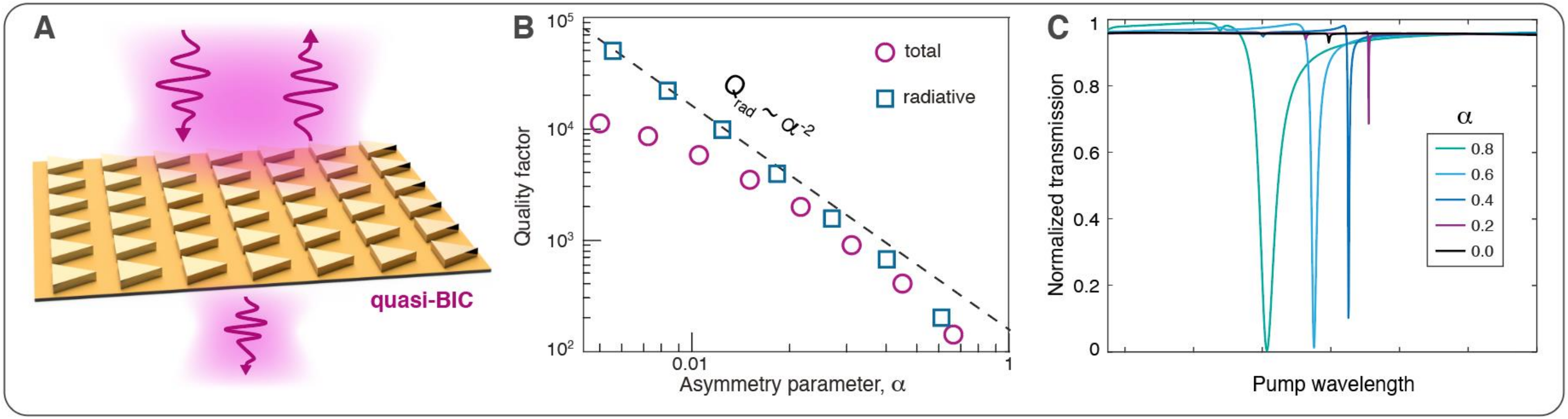


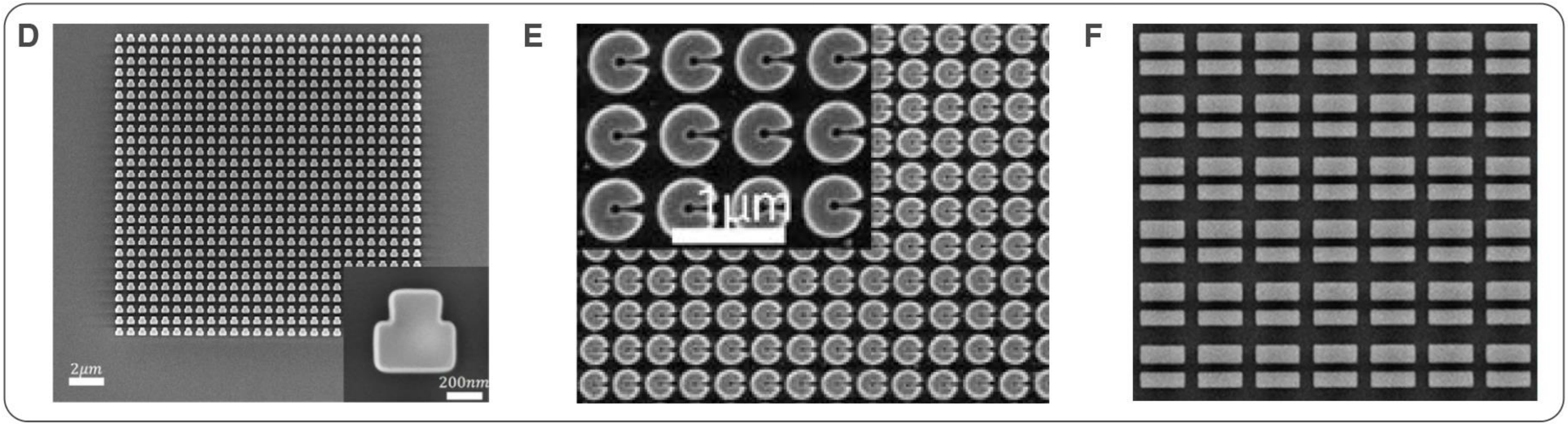
PHYSICAL REVIEW LETTERS **121,** 193903 (2018)

Asymmetric Metasurfaces with High-*Q* Resonances Governed by Bound States in the Continuum

Kirill Koshelev,[1,2] Sergey Lepeshov,[2] Mingkai Liu,[1] Andrey Bogdanov,[2] and Yuri Kivshar[1,2]

Metasurfaces and BIC resonances

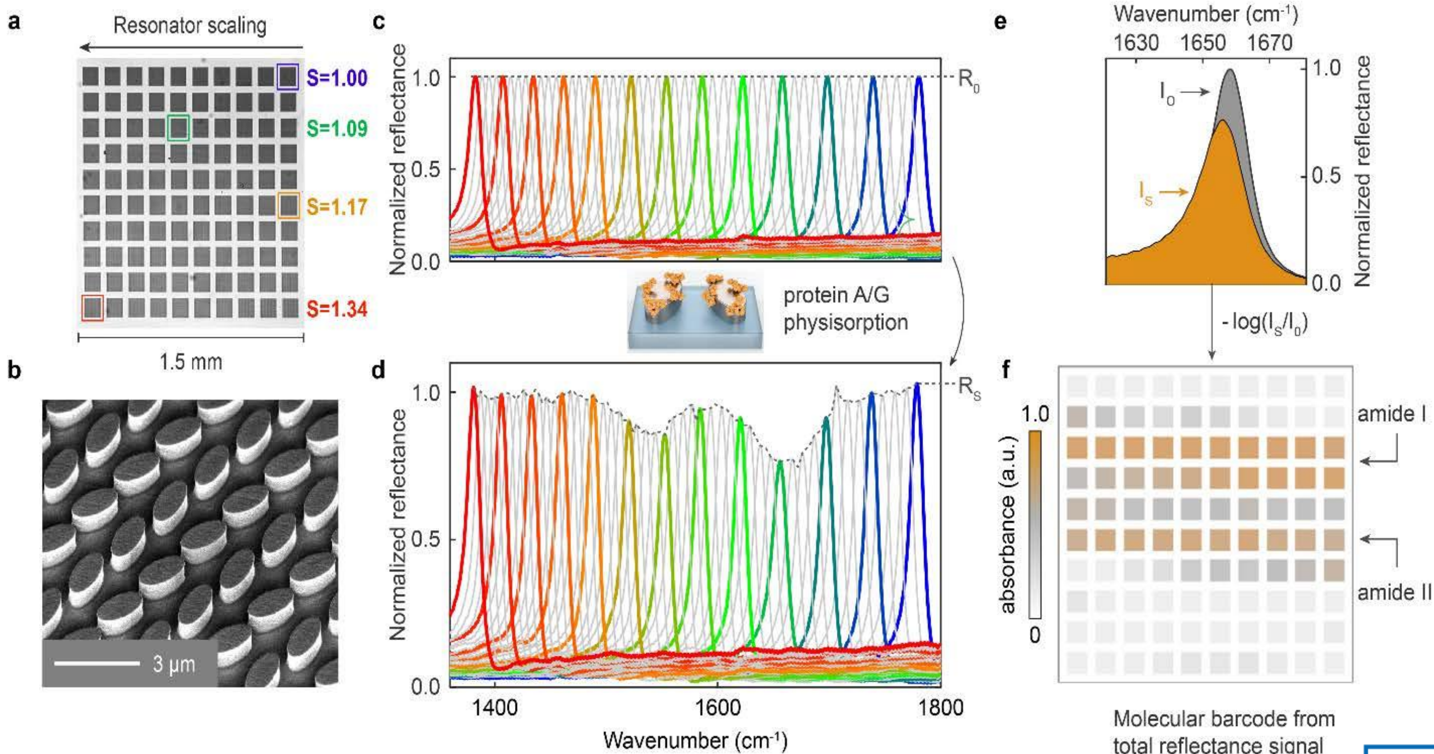


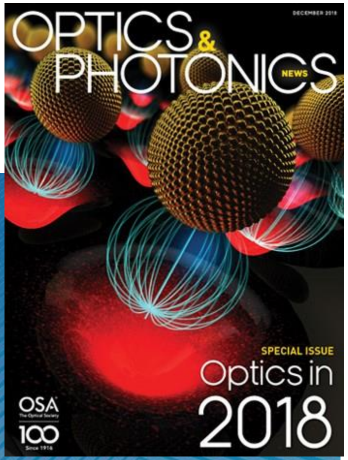


Metasurfaces for surface-enhanced spectroscopies

A. Tittle et al, Science 360, 1105 (2018)

Imaging-based molecular barcoding with pixelated dielectric metasurfaces





RESEARCHERS

Andreas Tittl, **Filiz Yesilkoy** and **Hatice Altug** (hatice.altug@epfl.ch), École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

Stefan A. Maier, Imperial College London, London, U.K., and Ludwig-Maximilians-Universität München, München, Germany

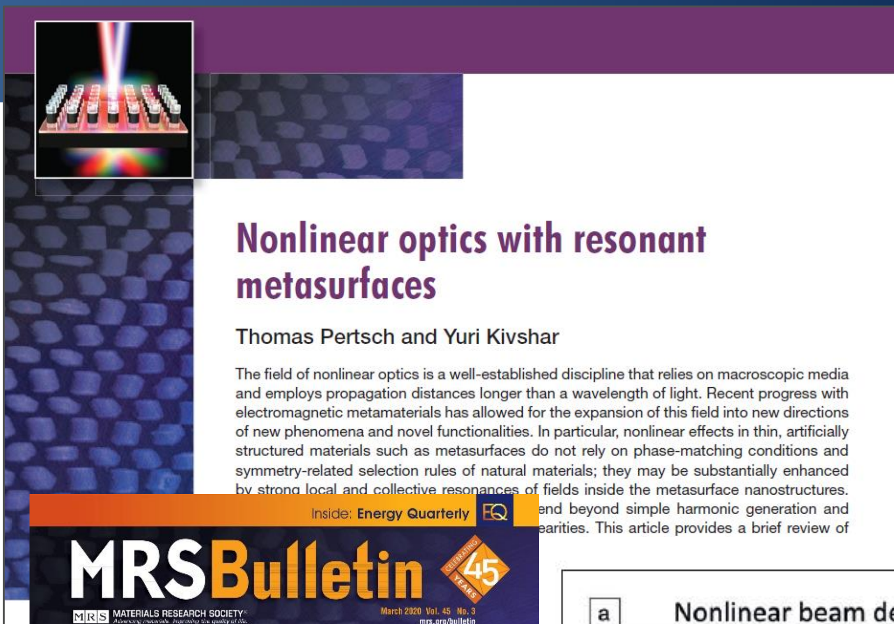
Yuri S. Kivshar, Australian National University, Canberra, Australia

Ultrasensitive hyperspectral biosensing based on high-Q dielectric metasurfaces

Filiz Yesilkoy[1], Eduardo Romero Arvelo[1,2], Yasaman Jahani[1], Mingkai Liu[3], Andreas Tittl[1], Volkan Cevher[2], Yuri Kivshar[3], and Hatice Altug[1*]

nature photonics

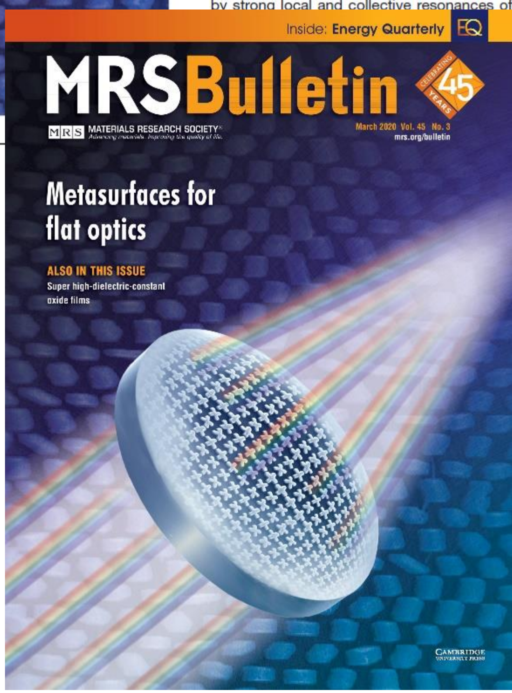
Nonlinear metasurfaces



Nonlinear optics with resonant metasurfaces

Thomas Pertsch and Yuri Kivshar

The field of nonlinear optics is a well-established discipline that relies on macroscopic media and employs propagation distances longer than a wavelength of light. Recent progress with electromagnetic metamaterials has allowed for the expansion of this field into new directions of new phenomena and novel functionalities. In particular, nonlinear effects in thin, artificially structured materials such as metasurfaces do not rely on phase-matching conditions and symmetry-related selection rules of natural materials; they may be substantially enhanced by strong local and collective resonances of fields inside the metasurface nanostructures. ... end beyond simple harmonic generation and ... earities. This article provides a brief review of

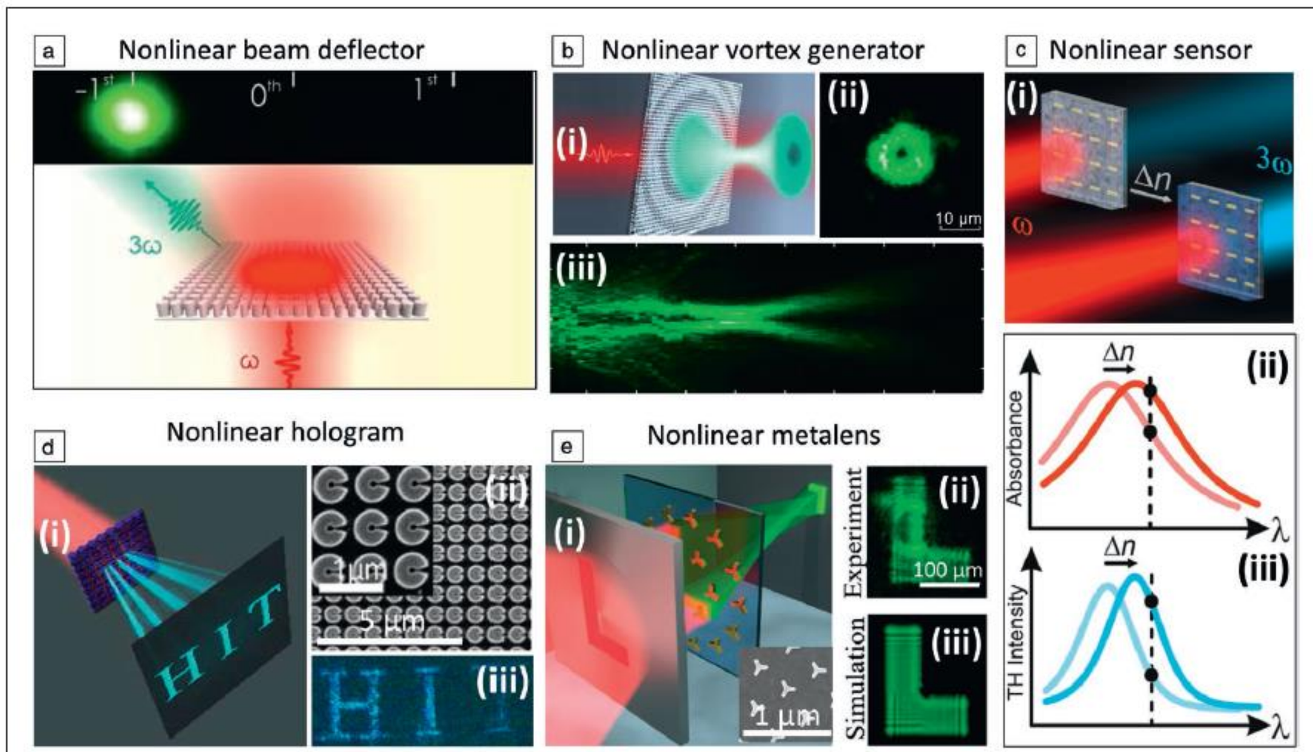


March 2020

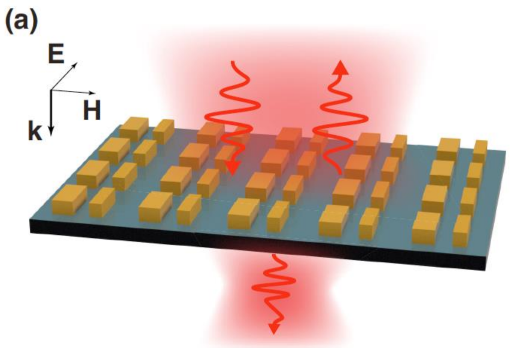
Metasurfaces: Subwavelength nanostructure arrays for ultrathin flat optics and photonics

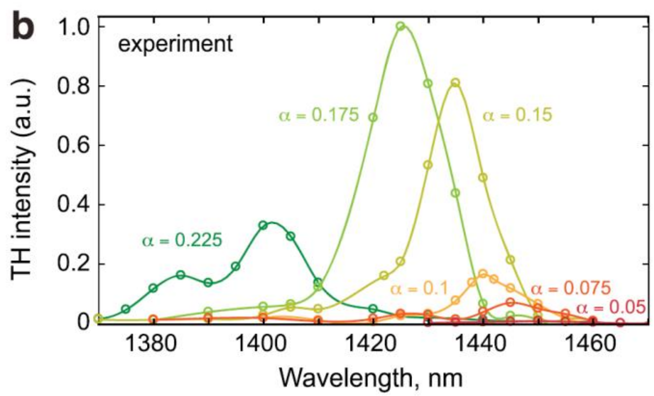
Junsuk Rho, Guest Editor

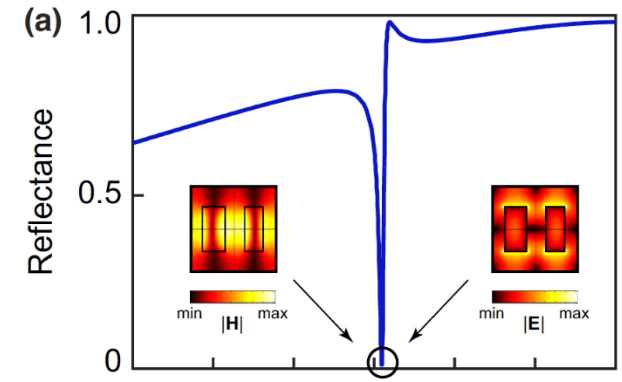
Examples of nonlinear metadevices



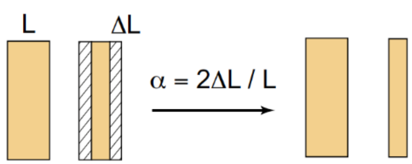
BIC-enhanced nonlinear effects

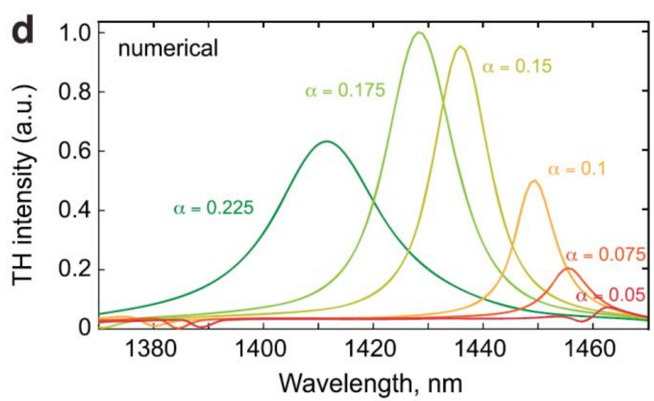


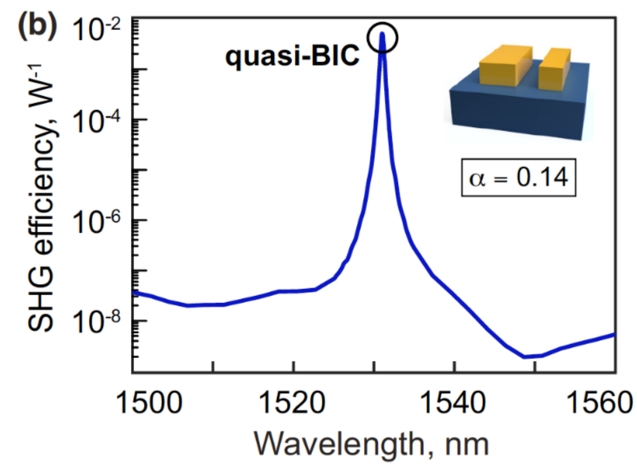


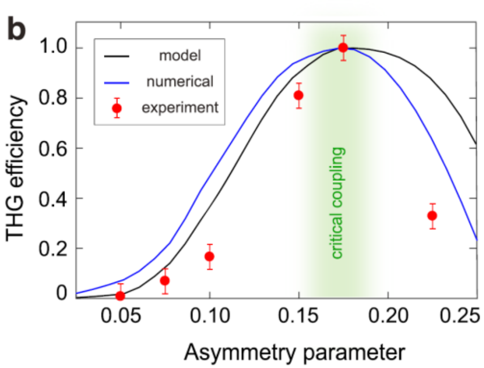


Breaking symmetry









ACS Photonics

Letter

Cite This: *ACS Photonics* 2019, 6, 1639−1644

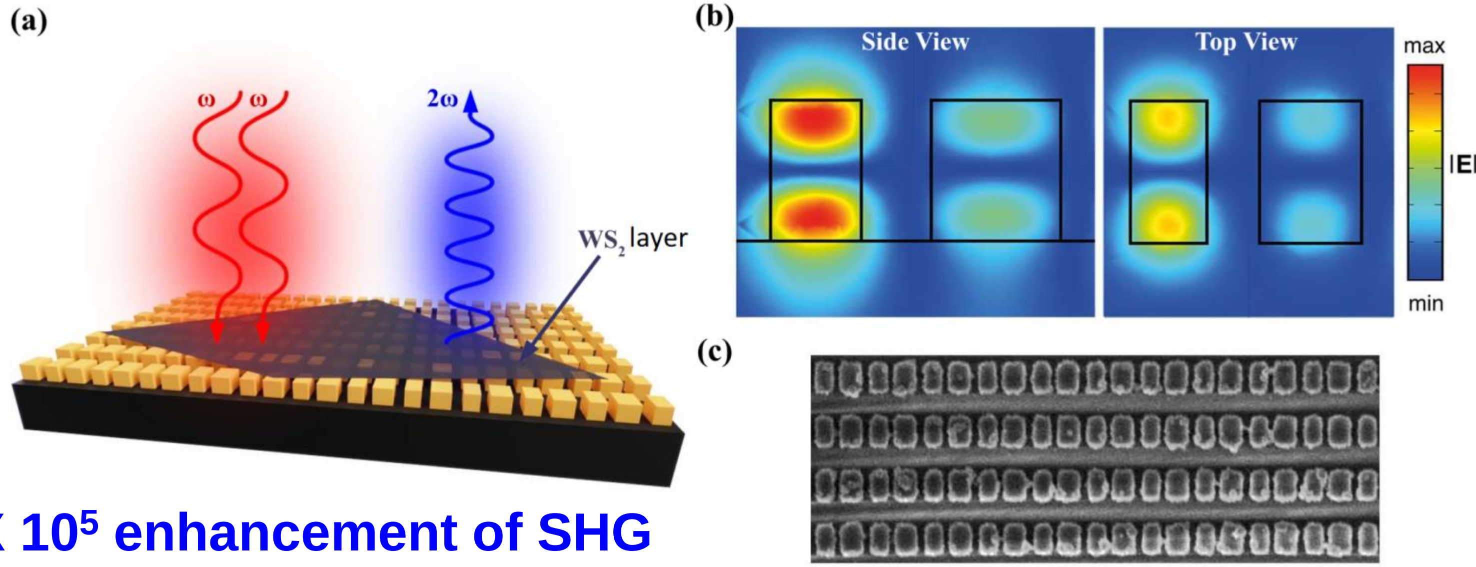
pubs.acs.org/journal/apchd5

Nonlinear Metasurfaces Governed by Bound States in the Continuum

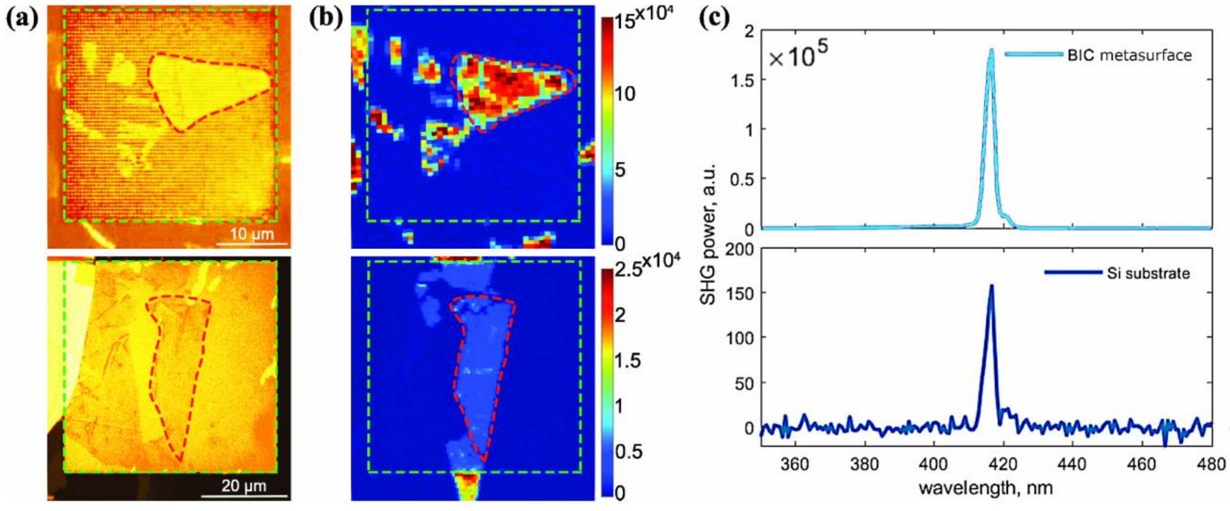
Kirill Koshelev,[*,†,‡] Yutao Tang,[§] Kingfai Li,[§] Duk-Yong Choi,[∥,⊥] Guixin Li,[§] and Yuri Kivshar[†,‡]

BIC-resonant metasurfaces and 2D materials

Collaboration with Alex Solntsev, UTS

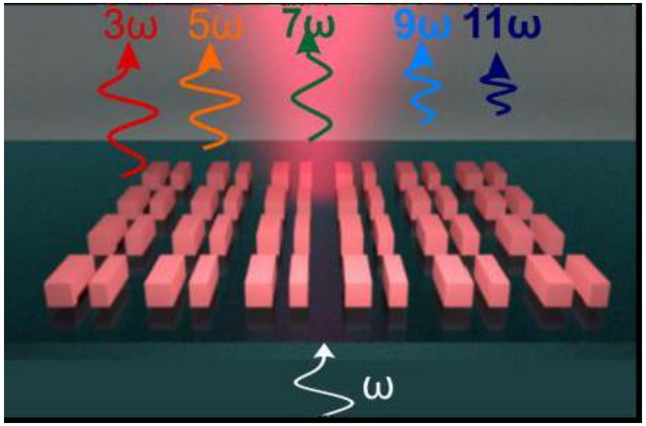


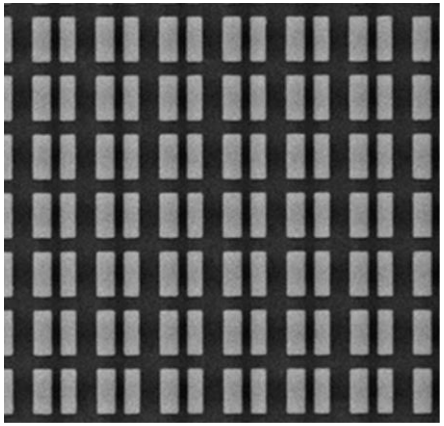
X 10^5 enhancement of SHG

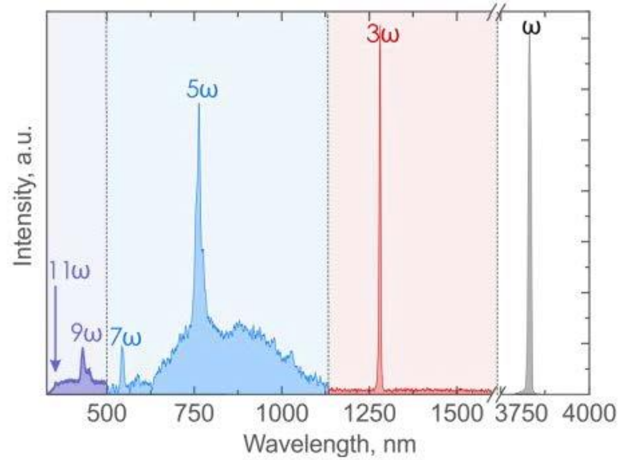


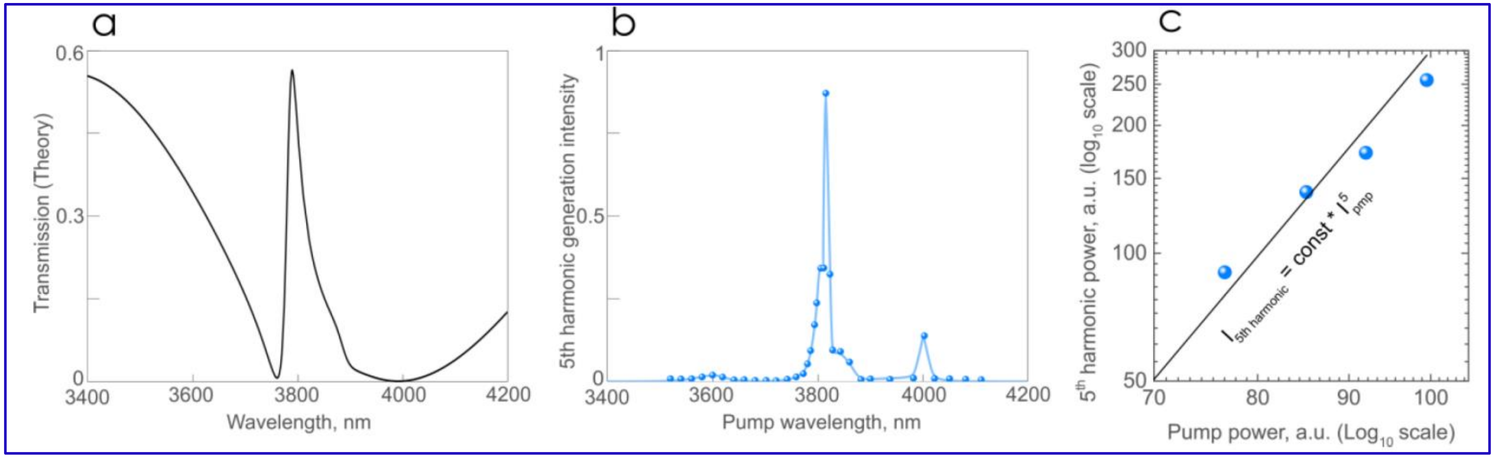
SW3N.6
CLEO May 2020

High-harmonic generation with BIC









High-Harmonic Generation in Dielectric Metasurfaces Empowered by Bound States in the Continuum

George Zograf[1,2], Anastasia Zalogina[1], Kirill Koshelev[1,2], Duk-Yong Choi[3], Viacheslav Korolev[4], Richard Hollinger[4], Daniil Kartashov[4], Michael Zürch[5], Christian Spielmann[4], Sergey Makarov[2], Barry Luther-Davies[3], Sergey Kruk[1,*] and Yuri Kivshar[1,2]

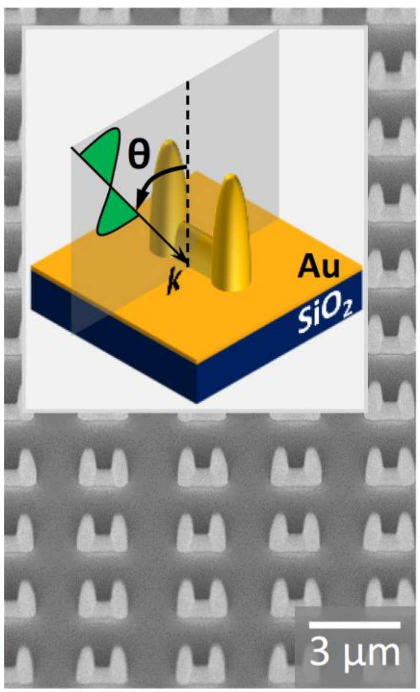
FTh1C.5
CLEO May 2020

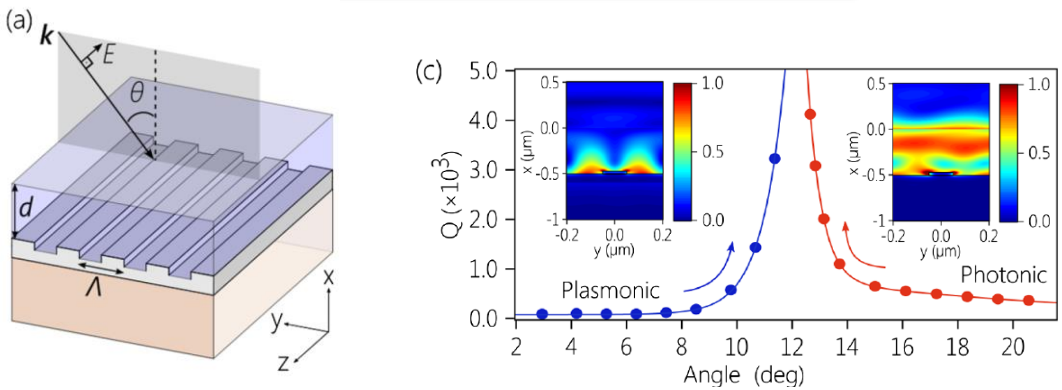
BICs in plasmonic metasurfaces

PHYSICAL REVIEW LETTERS **121**, 253901 (2018)

Formation of Bound States in the Continuum in Hybrid Plasmonic-Photonic Systems

Shaimaa I. Azzam,[*] Vladimir M. Shalaev,[†] Alexandra Boltasseva,[‡] and Alexander V. Kildishev[§]
School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA





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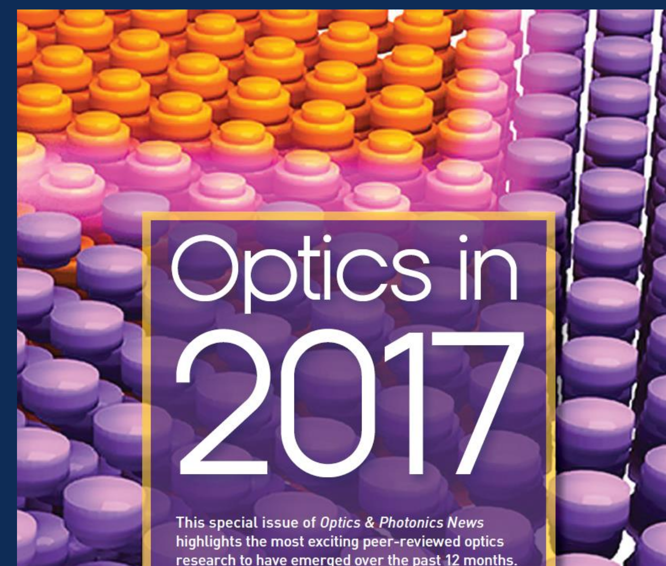
Letter

1 **Bound States in the Continuum in Anisotropic Plasmonic**
2 **Metasurfaces**

3 Yao Liang,[▽] Kirill Koshelev,[▽] Fengchun Zhang,[▽] Han Lin, Shirong Lin, Jiayang Wu, Baohua Jia,[*]
4 and Yuri Kivshar[*]

Cite This: https://dx.doi.org/10.1021/acs.nanolett.0c01752

Topological photonics

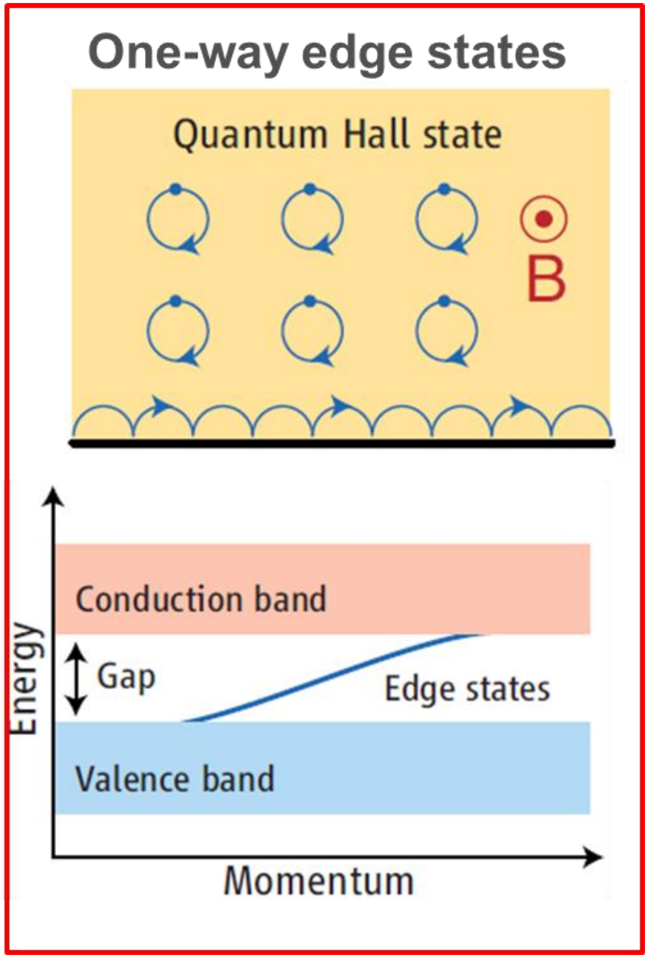


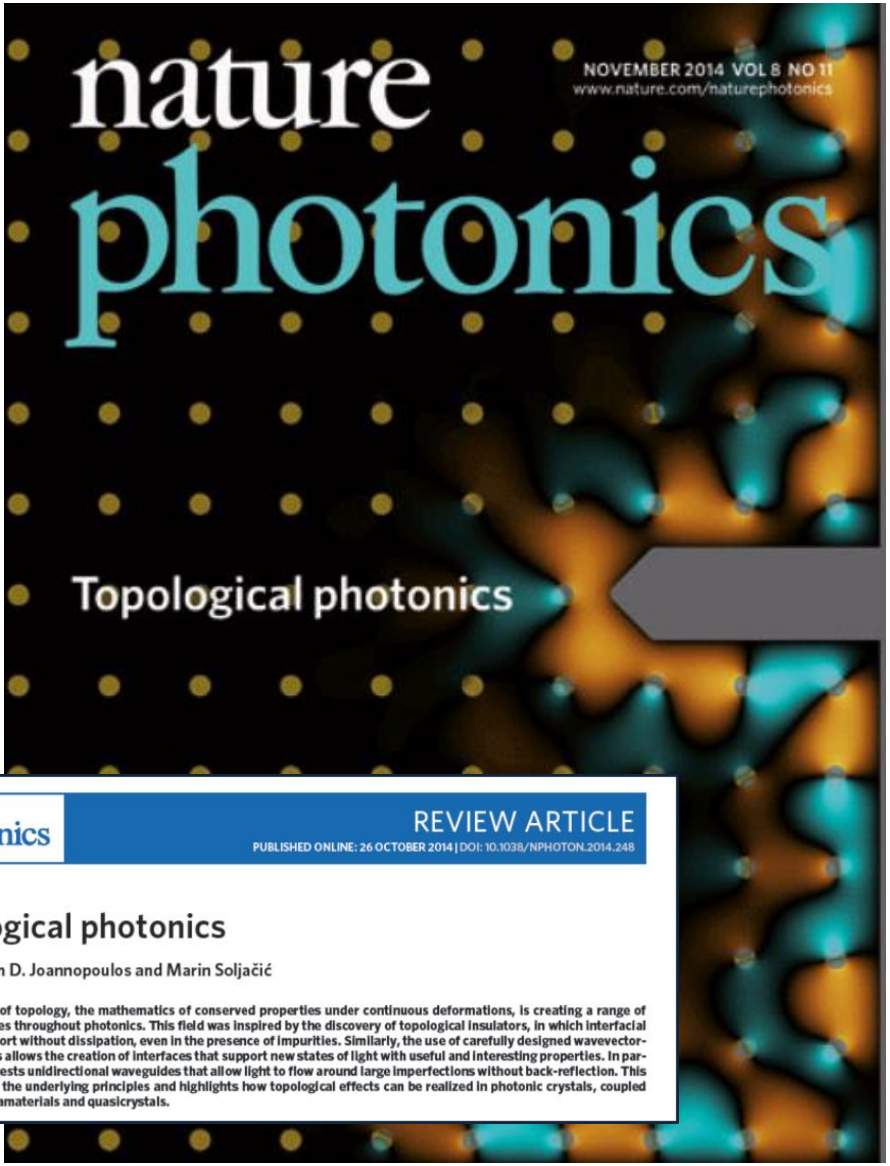
Australian National University

The Hong Kong Polytechnic University
香港理工大學

ITMO UNIVERSITY

Topological photonics





nature photonics | REVIEW ARTICLE

PUBLISHED ONLINE: 26 OCTOBER 2014 | DOI: 10.1038/NPHOTON.2014.248

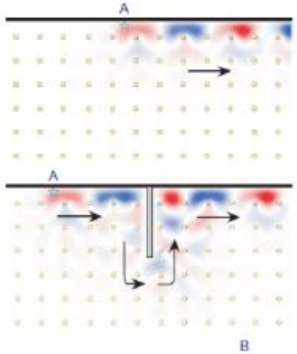
Topological photonics

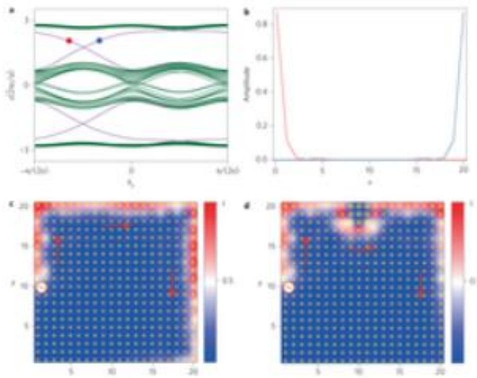
Ling Lu*, John D. Joannopoulos and Marin Soljačić

The application of topology, the mathematics of conserved properties under continuous deformations, is creating a range of new opportunities throughout photonics. This field was inspired by the discovery of topological insulators, in which interfacial electrons transport without dissipation, even in the presence of impurities. Similarly, the use of carefully designed wavevector-space topologies allows the creation of interfaces that support new states of light with useful and interesting properties. In particular, this suggests unidirectional waveguides that allow light to flow around large imperfections without back-reflection. This Review explains the underlying principles and highlights how topological effects can be realized in photonic crystals, coupled resonators, metamaterials and quasicrystals.

Depelopments of topological photonics

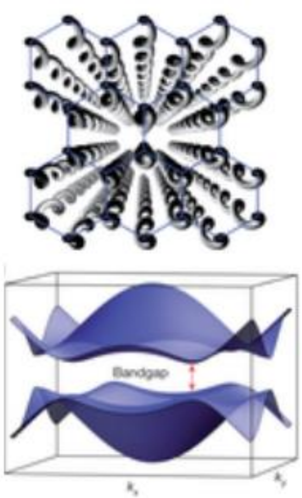
Broken TR symmetry



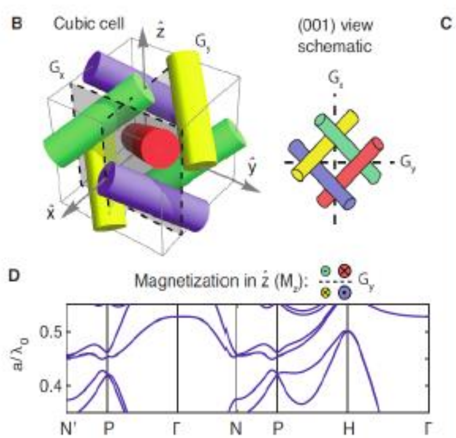


PRL **100**, 013904, (2008)
Nature 461, 772-775 (2009).

Nature Photon. 6, 782–787 (2012)

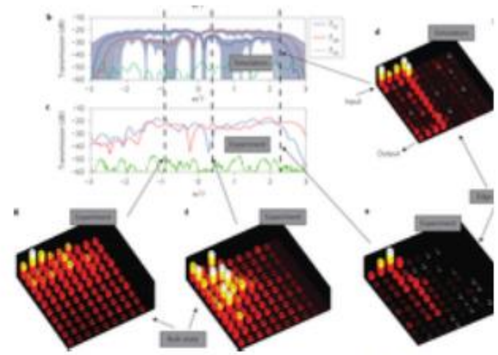


Nature 496, 196–200, (2013)

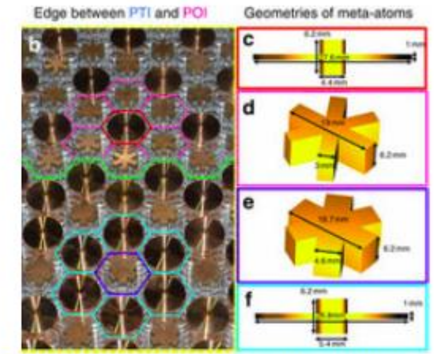


arXiv:1507.00337 (2015)
Nature Physics (2016)

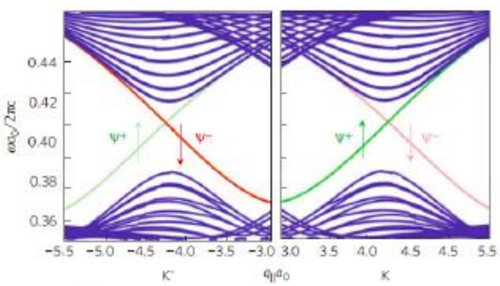
Preserved TR symmetry

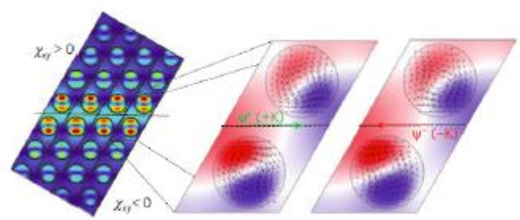


Nature Phys. **7**, 907–912 (2011).
Nature Photon. **7**, 1001–1005 (2013)

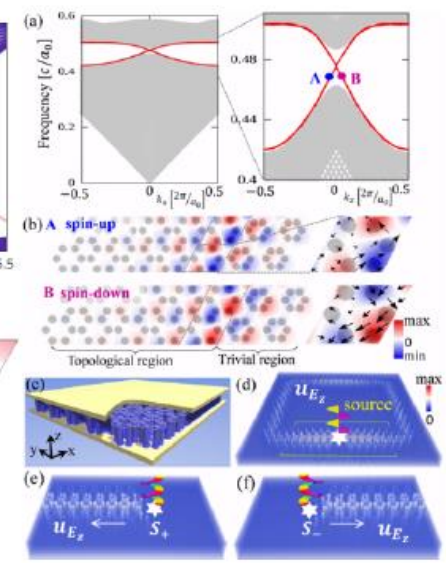


Nature Comm. 5, 5782, (2014)





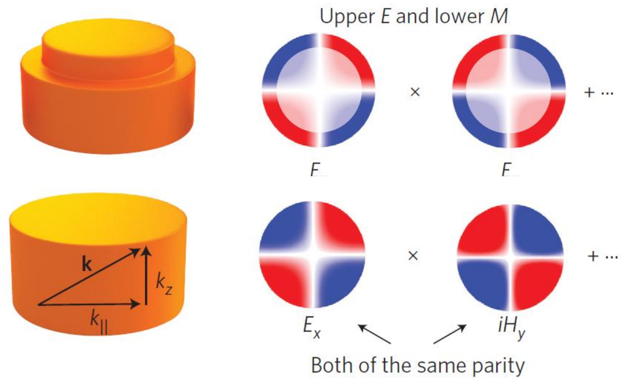
arXiv:1401.1276 (2012)
Nature Mater. **12**, 233–239 (2013)

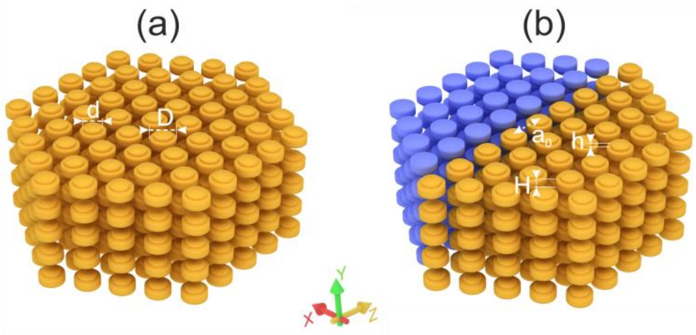


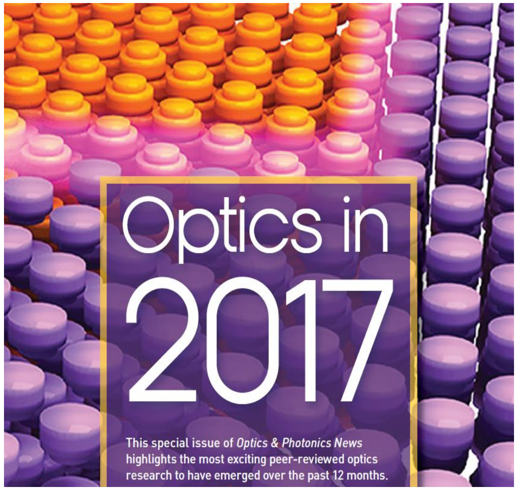
Phys. Rev. Lett. **114**, 223901 (2015)

Our research strategies in topological photonics

Resonant dielectric meta-atoms

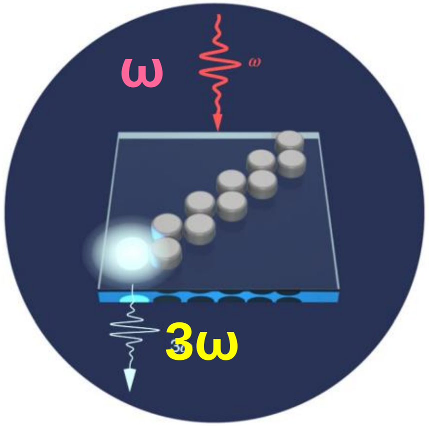


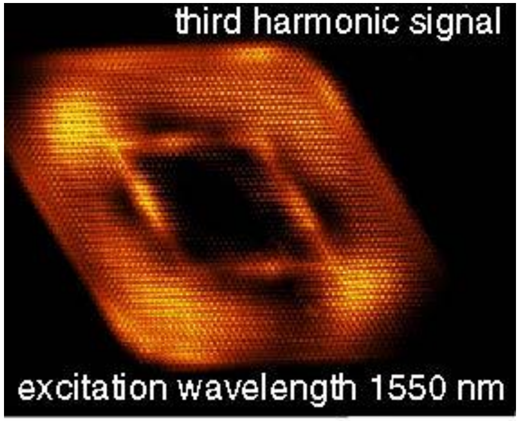


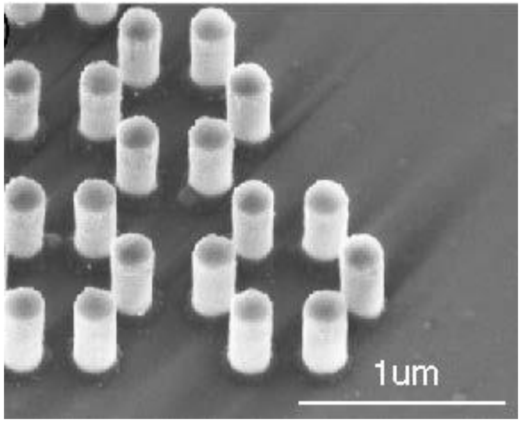


Nature Photonics **11**, 130 (2017)

Nonlinear and active topological photonics





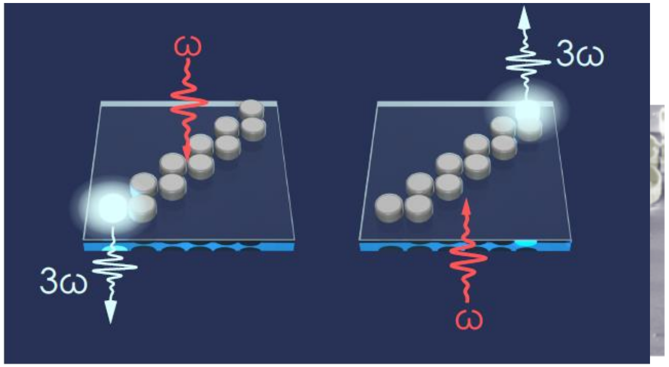


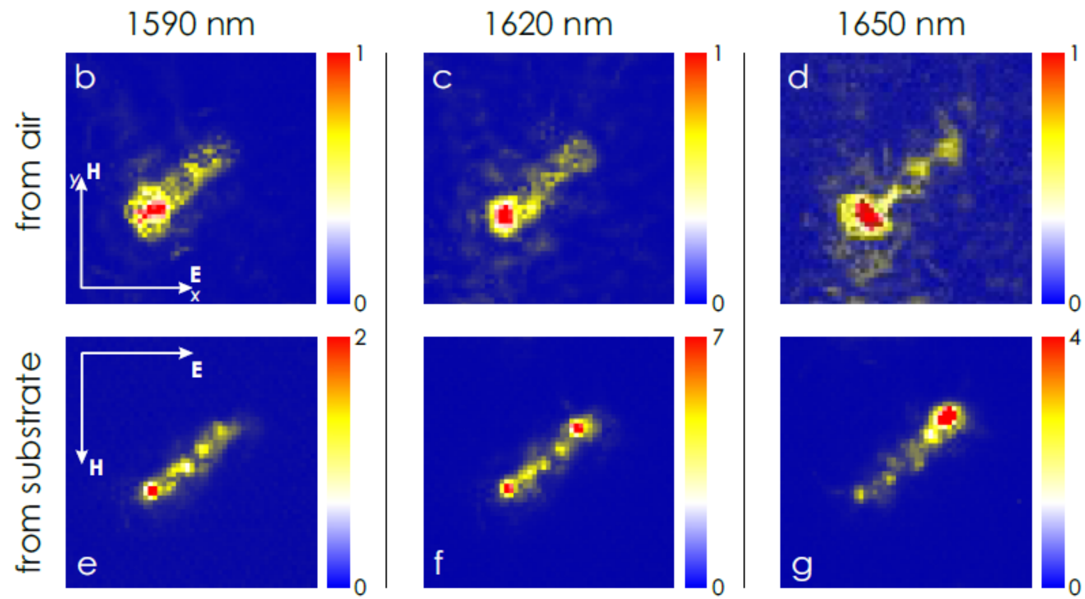
Nature Nanotechnology **14**, 126 (2019)

Phys Rev Lett **123**, 103901 (2019)

Nonlinear optics meets topology

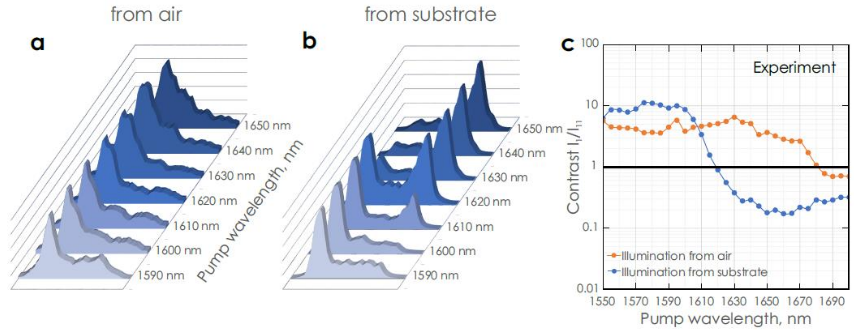
Enhancement of nonlinear interactions by the edge states

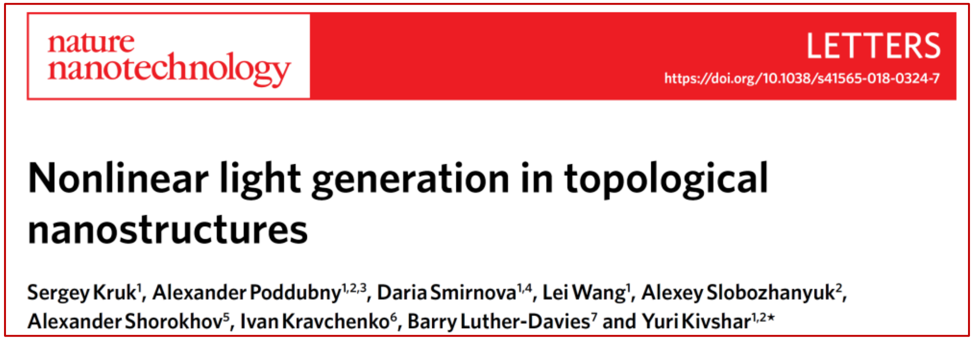




The zigzag model suggested in ACS Photonics 1, 101 (2014)

Interplay between ED and MD resonances

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Nonlinear light generation in topological nanostructures

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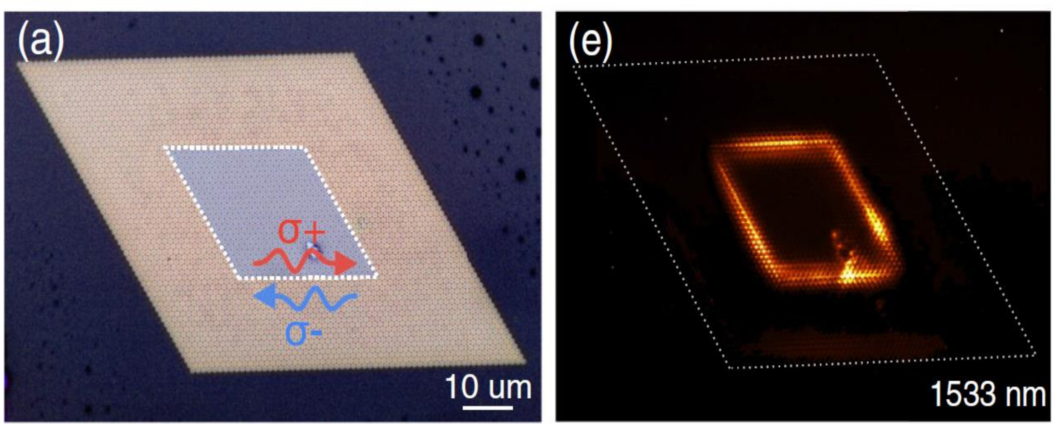

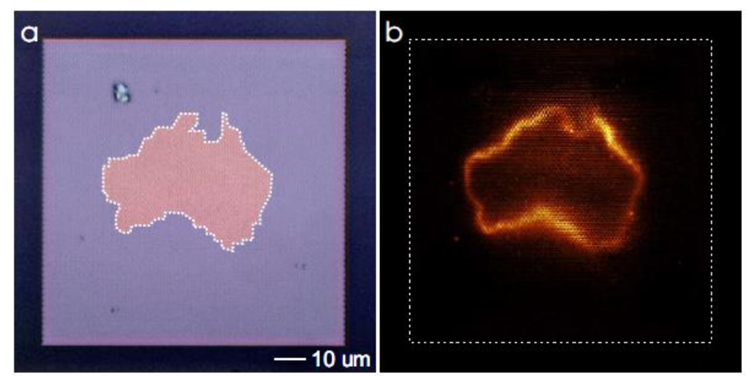

Phys Rev Lett **123**, 103901 (2019)

Concluding remarks

- Metamaterials is still an active research field (but now often appears under a new brand name of meta-optics or metaphotonics), that promises many applications in photonics and subwavelength optics;

- Dielectric nanoparticles with high refractive index can be implemented for many metaphotonics phenomena governed by Mie resonances;

- Many novel effects originate from multipolar interferences and the magnetic field enhancement, and they drive novel functionalities of all-dielectric resonant metasurfaces and metadevices

- Recent many advances in meta-optics and nanophotonics are associated with the physics of bound states in the continuum which appear due to strong coupling of guided leaky modes combined with Mie resonances

Questions, comments, and collaboration proposals:

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