SERBIAN ACADEMY OF NONLINEAR SCIENCES
http://www.sann.kg.ac.rs/en/sans/

3rd CONFERENCE ON NONLINEARITY
4 – 8.09.2023, Belgrade, Serbia

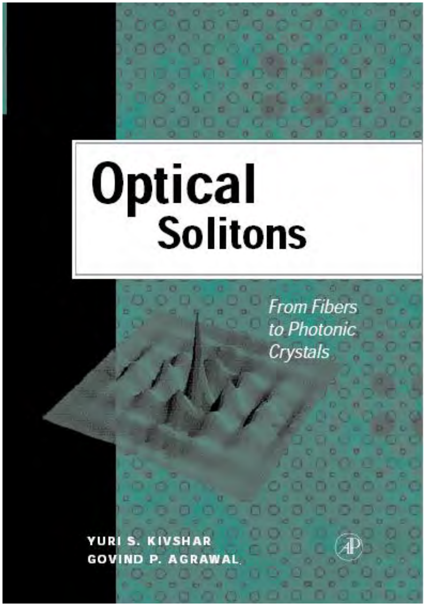
Nonlinear metaphotonics

Yuri Kivshar

Australian
National
University

From solitons to metamaterials

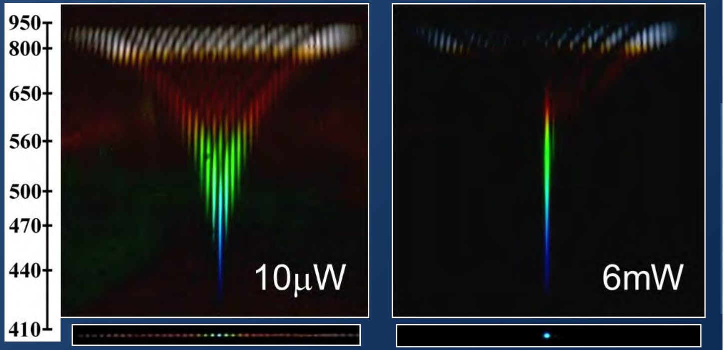
1993-2000

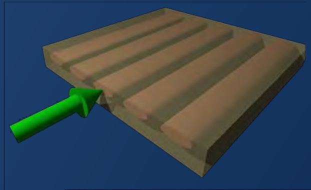


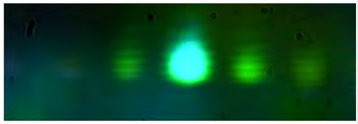
Optical
Solitons

From Fibers to Photonic Crystals

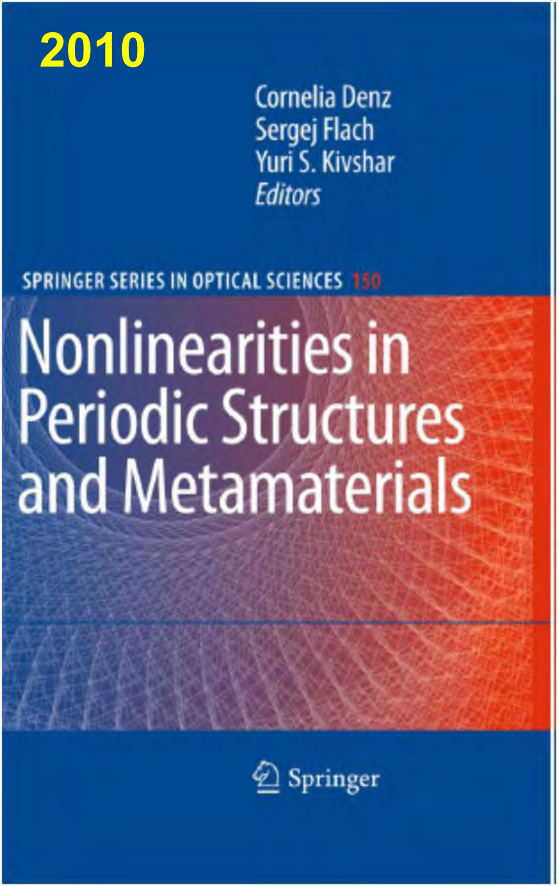
YURI S. KIVSHAR
GOVIND P. AGRAWAL







2010

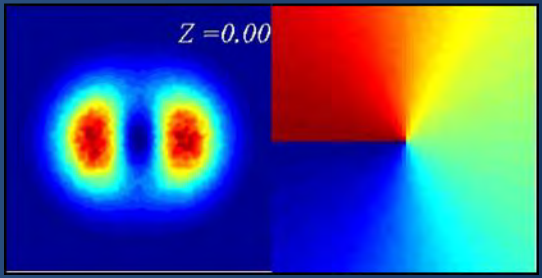


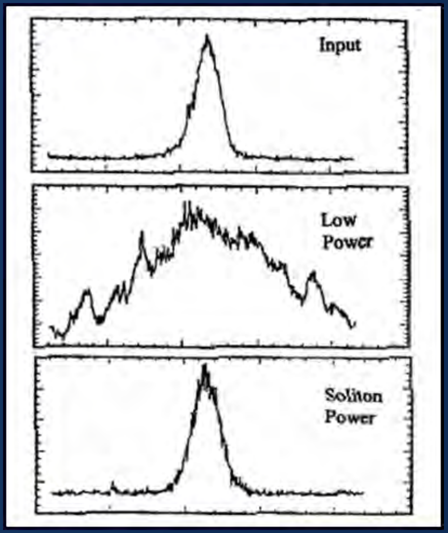
Cornelia Denz
Sergej Flach
Yuri S. Kivshar
Editors

SPRINGER SERIES IN OPTICAL SCIENCES 150

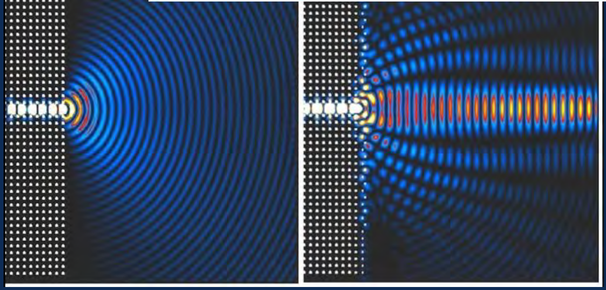
Nonlinearities in Periodic Structures and Metamaterials

Springer





2005



10.1117/1.AP.3.1.010502

10.1117/1.AP.3.1.010502

INTERVIEW

Journey from solitons to nanophotonics: an interview with Professor Yuri Kivshar

Guoqing Chang*
Institute of Physics, Chinese Academy of Sciences, China

Professor Yuri Kivshar, Australian National University, Australia

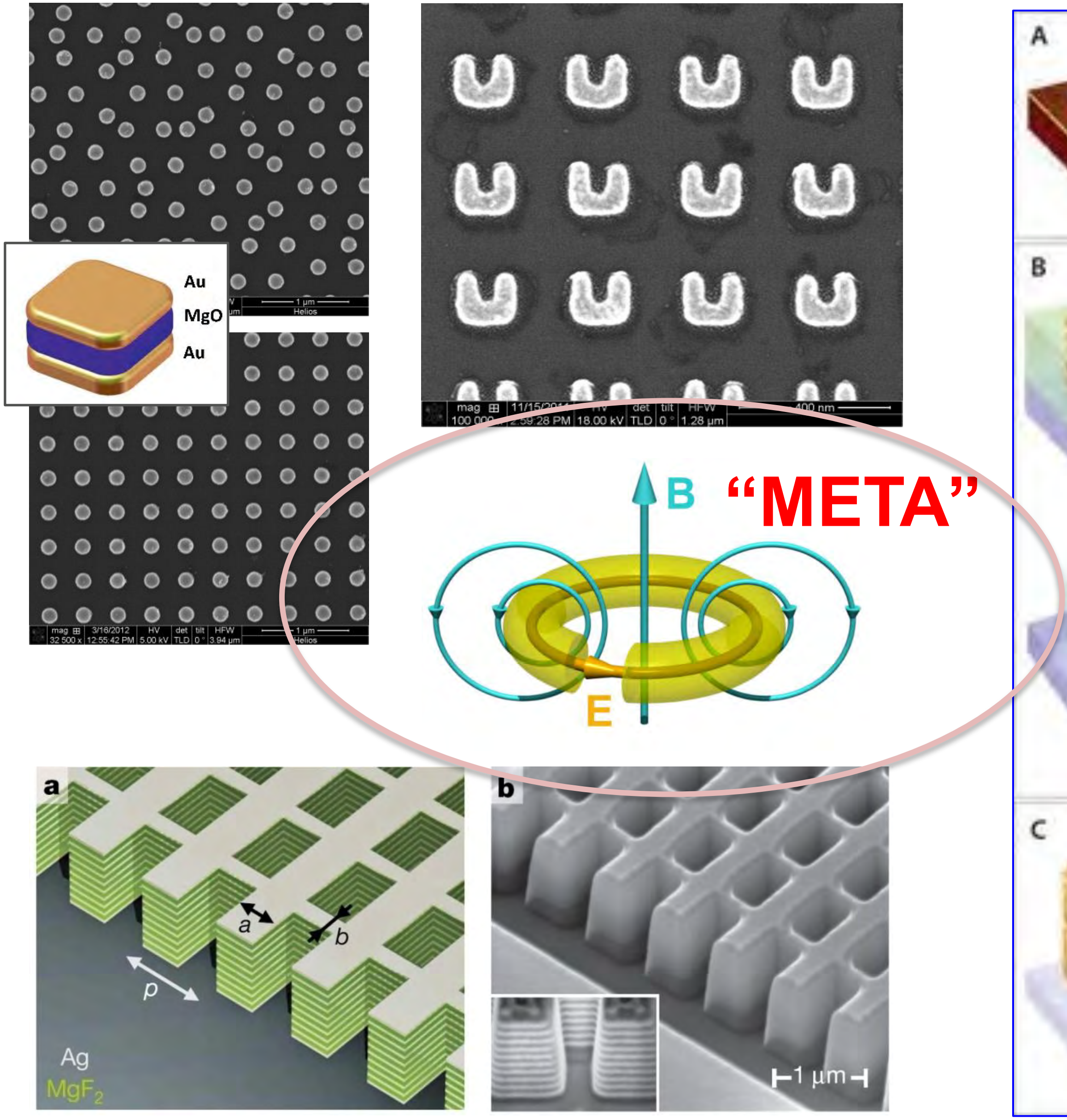
Guoqing Chang: When did you first hear about nonlinear optics?
Yuri Kivshar: My course had about 100 students who were associated with different departments, including Department of Theoretical Physics and Department of Optics. I was in the Department of Theoretical Physics, and I did not know nonlinear optics at all when I started my research on solitons with Professor Kosevich. It had nothing to do with optics, and we never discussed optics.

Once I went for lunch with some of my classmates from the Department of Optics. One of them told me his research in optics was boring. I asked him why he went there in the first place. He told me that he initially expected to work on nonlinear optics. That was my first time to hear of nonlinear optics. I asked him what nonlinear optics is and he said, "It's about nonlinear effects such as frequency generation, all this nice stuff." And I thought, "Wow, it's probably what may be related to solitons."

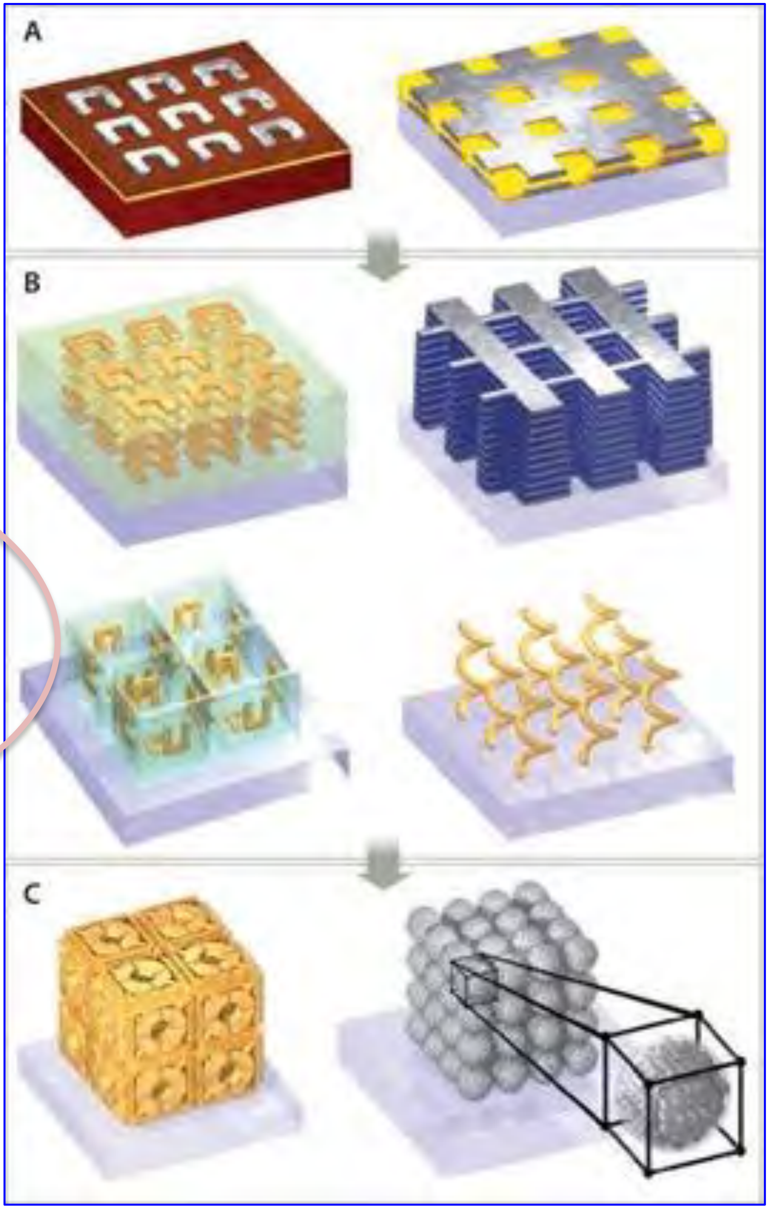
Guoqing Chang: How did you move into the soliton research in the context of nonlinear optics?
Yuri Kivshar: Solid state physics is a difficult field because it is not

Advanced Photonics **3**, 010502 (2021); DOI: 10.1117/1.AP.3.1.010502

From microwaves to optics



“META”

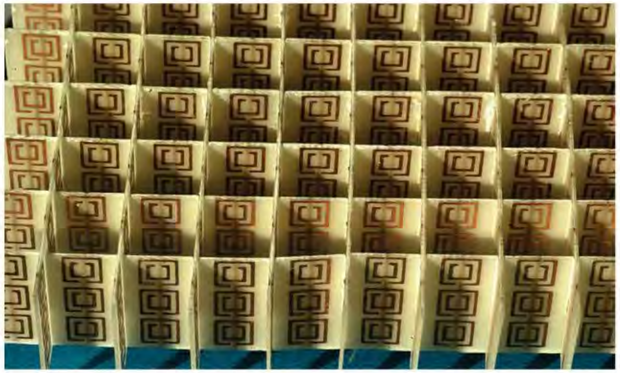


Milestones of electromagnetic metamaterials

Beyond Materials

OPN, May 2021

An obscure paper theorizing negative-index materials was resurrected 30 years later as researchers began to engineer materials to manipulate electromagnetic waves.

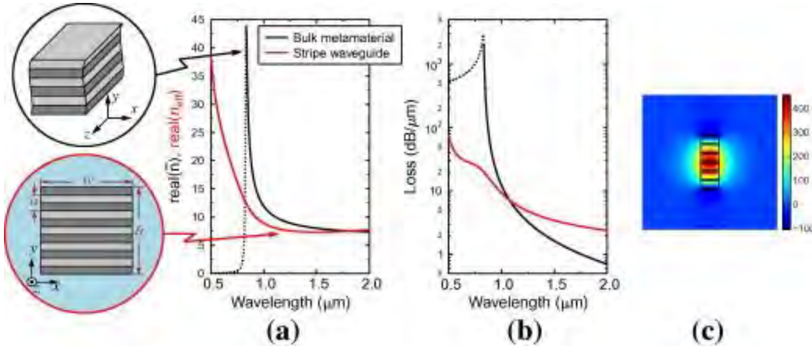


A split-ring structure negative-index material, as theorized by Veselago.

Courtesy of D.R. Smith

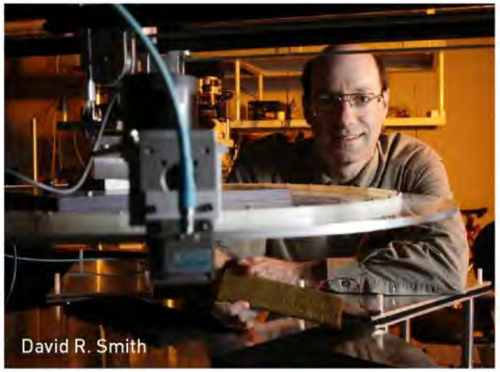
1967: Going negative

All known, natural materials have a positive index of refraction, which indicates how much light bends when it enters a substance. But what if, asked Russian physi-



Sir John Pendry

P. Henning/NTNU, CC-BY-2.0



David R. Smith

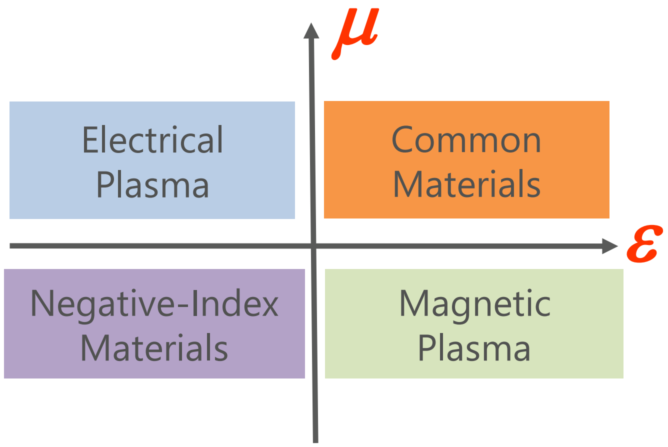
CMIP, Duke University

1999: Demonstrating metamaterials

Metamaterials are engineered to have properties that are not found in nature; the key to these properties is within the material's microstructure—which must be finer than the electromagnetic wavelengths concerned—rather than their chemistry. British physicist Sir John Pendry designed such materials with negative electrical permittivity and negative magnetic permeability using loops of wire and split-ring resonators in the 1990s. This demonstration of artificial magnetism, the key ingredient of the negative-index response, launched the field.

2006: A microwave "invisibility cloak"

In 2000, U.S. physicist David R. Smith demonstrated a negative-index material at microwave frequencies, later unearthing Veselago's 1967 paper. He then teamed up with Pendry and developed the theory of transformation optics (also pioneered by Ulf Leonhardt), which described how metamaterials could manipulate light. In 2006, the team demonstrated an invisibility cloak of sorts—bending microwaves around an object. The proof of concept spurred a flurry of research into how to scale microwave metamaterial designs to optical frequencies.



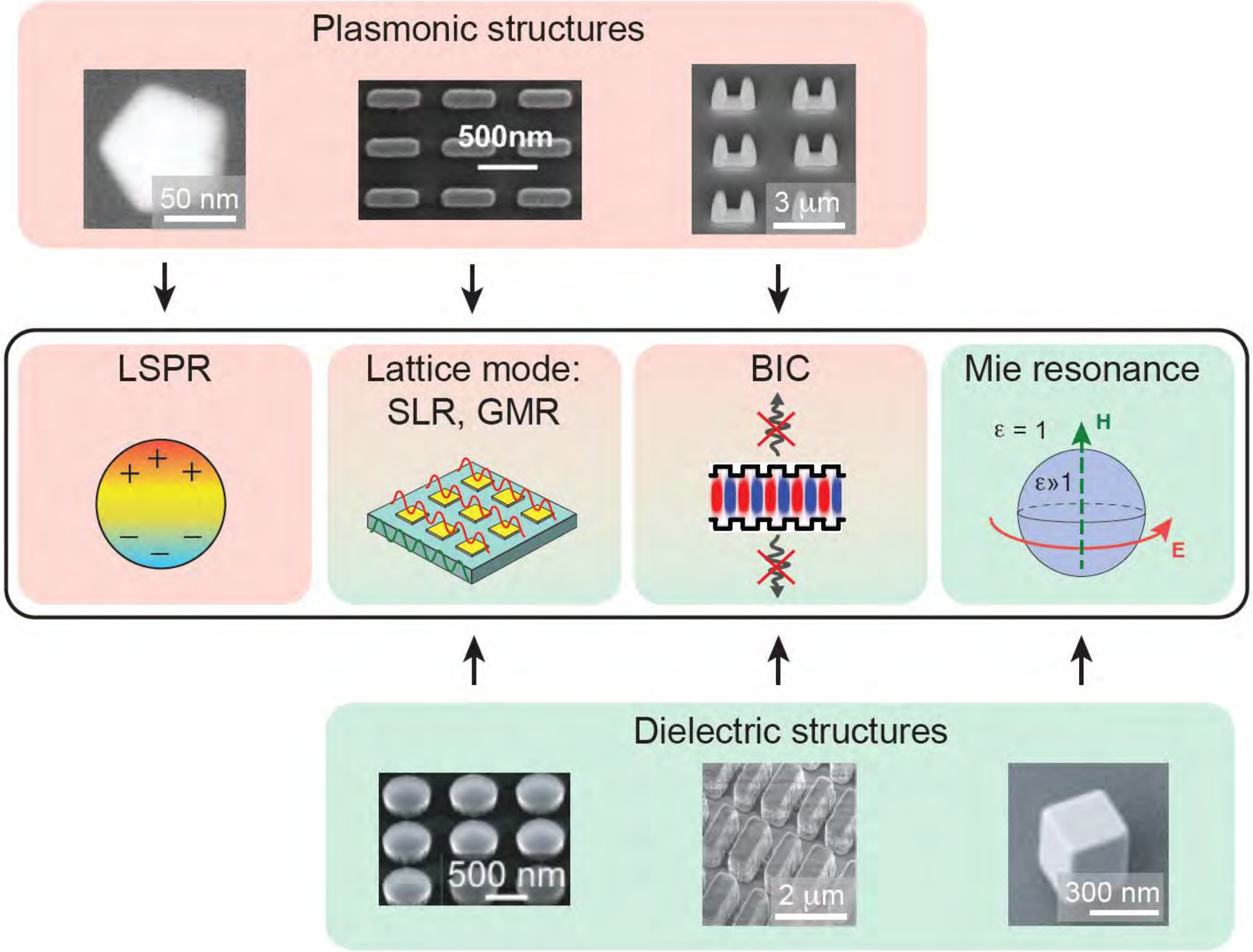
Electrical Plasma

Common Materials

Negative-Index Materials

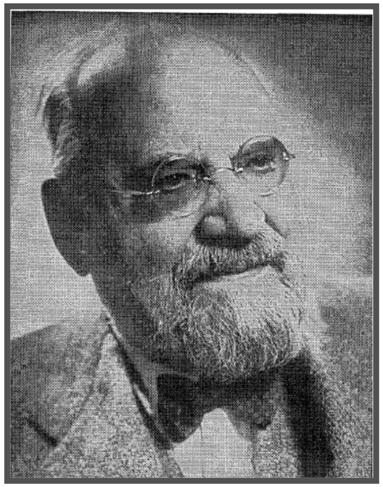
Magnetic Plasma

Resonances in metaphotonics



From: Koshelev, Tonkaev, Kivshar, "Nonlinear chiral metaphotonics", under review

1908: Mie theory



Gustav Mie

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

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

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

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

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

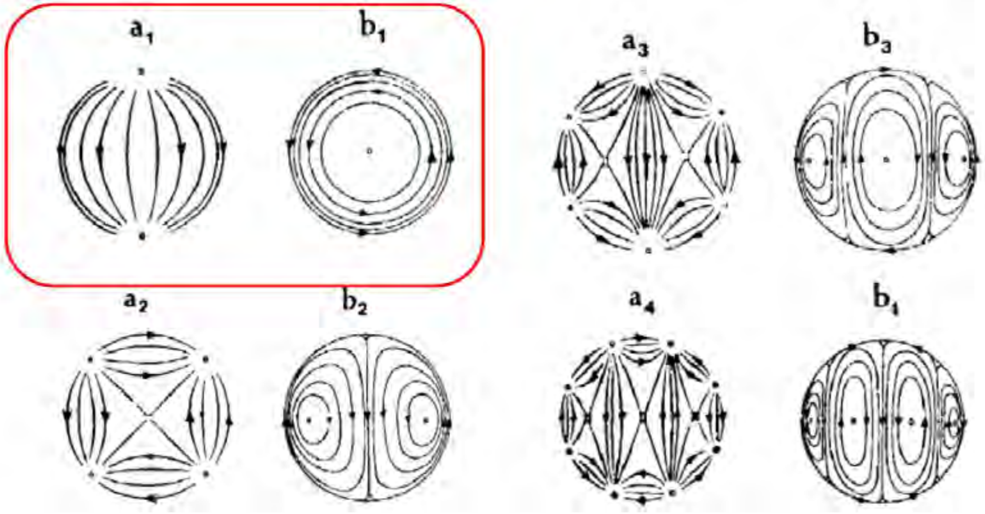
- $x \ll 1$: Rayleigh scattering
- $x \sim 1$: Mie scattering
- $x \gg 1$: Geometric scattering

1908. № 3.

ANNALEN DER PHYSIK.

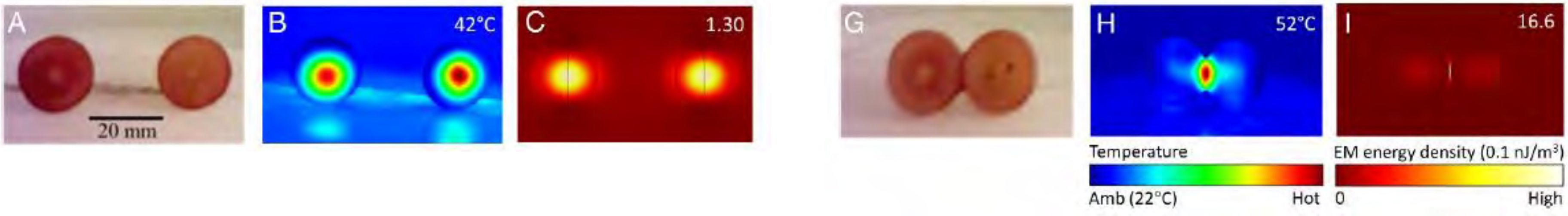
VIERTE FOLGE. BAND 25.

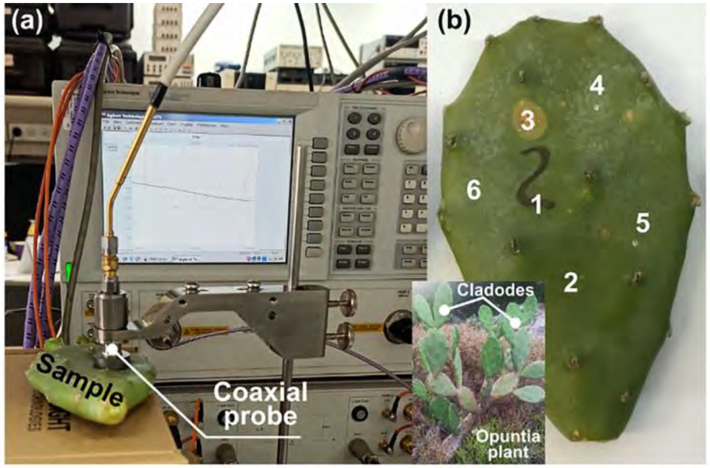
1. *Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösungen;*
von Gustav Mie.



Mie resonances at home

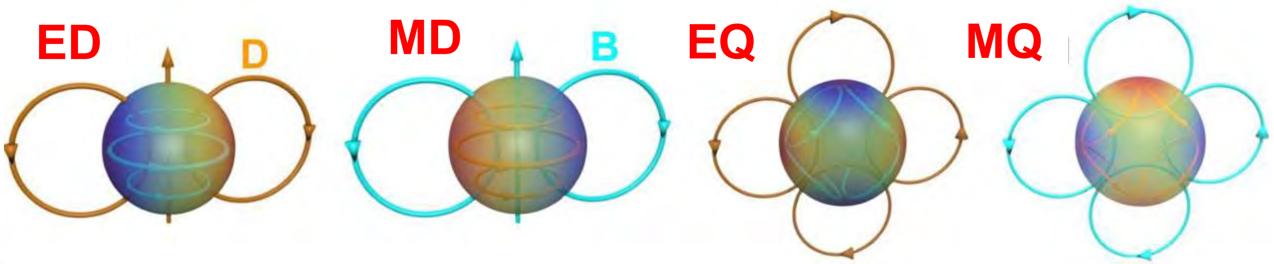
H. Khattak et al, PNAS **116,** 4000 (2019)

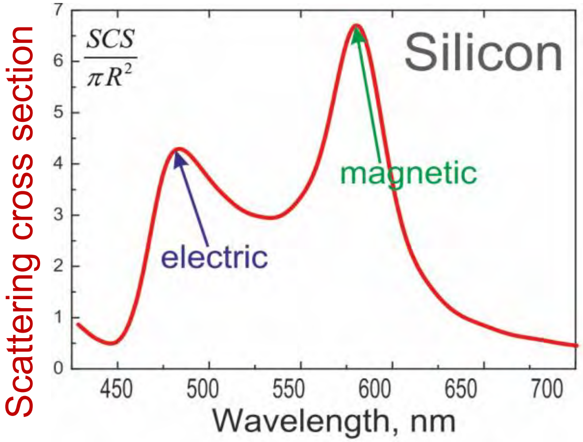


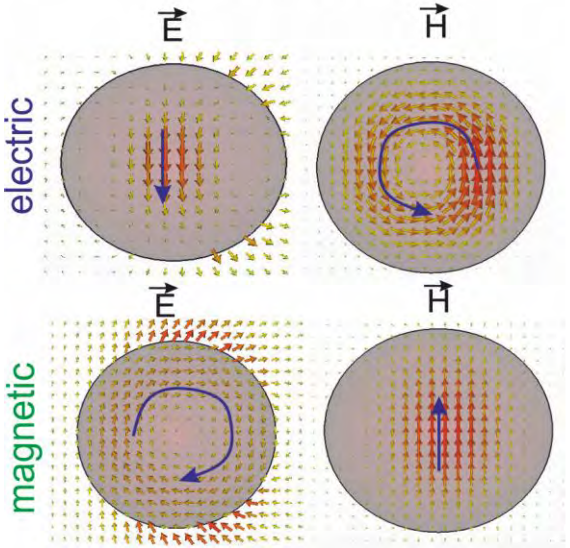


Pavel Ginzburg' group:
Appl. Phys. Lett. **120**, 053301 (2022)

Multipolar response







- **Enhancement of nonlinear effects near Mie resonances**

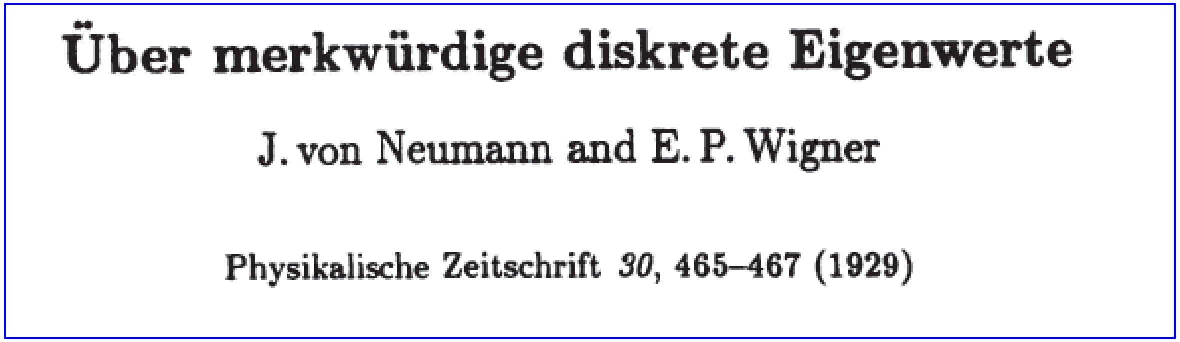
- **Multipolar interferences and Kerker effects**

- **High-Q resonances: bound states in the continuum**

Bound state in the continuum (BIC)

J. von Neumann

E.P. Wigner

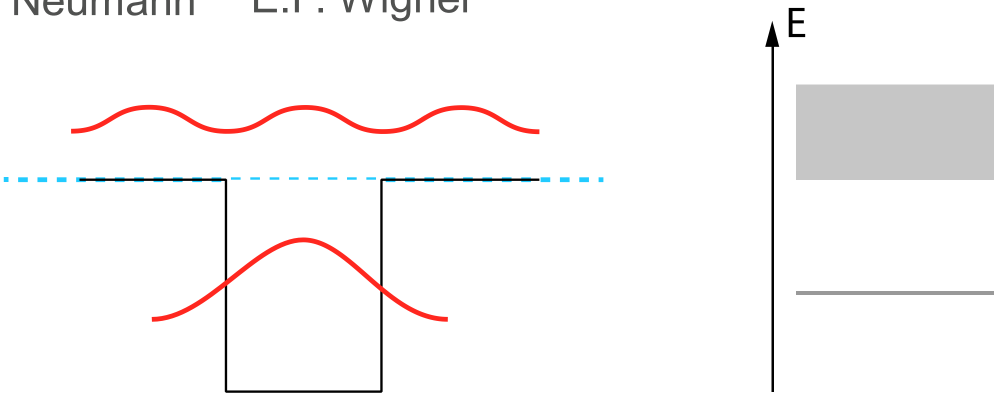


Über merkwürdige diskrete Eigenwerte

J. von Neumann and E. P. Wigner

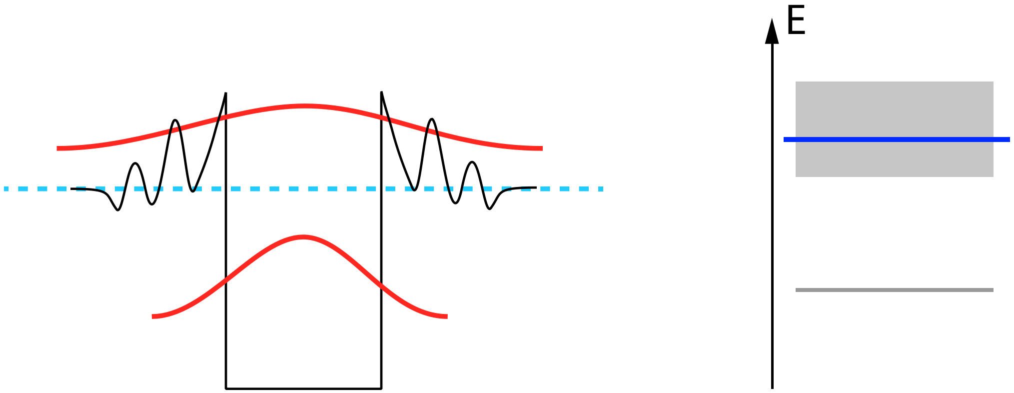
Physikalische Zeitschrift *30*, 465–467 (1929)

1929



Continuum

Discrete level



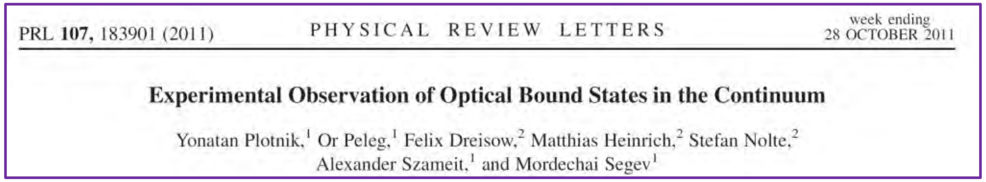
Bound state in the continuum

Discrete level

Bound states in the continuum in optics

2011 Arrays of coupled waveguides

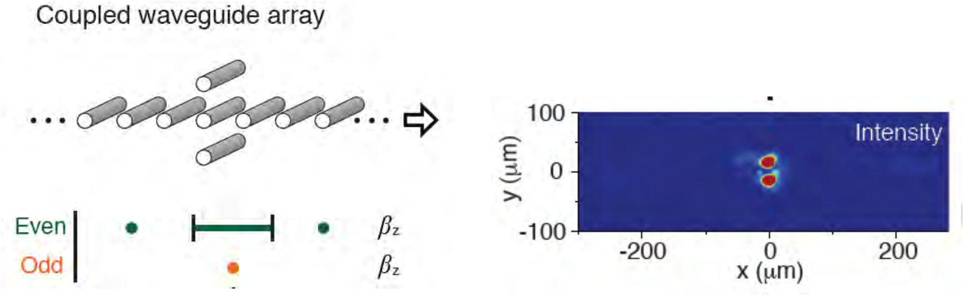
2013 Photonic crystal slabs

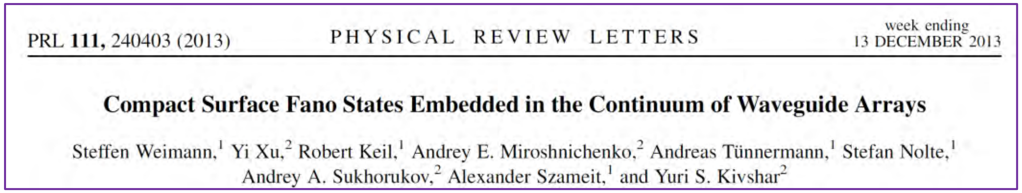


PRL **107,** 183901 (2011) PHYSICAL REVIEW LETTERS week ending 28 OCTOBER 2011

Experimental Observation of Optical Bound States in the Continuum

Yonatan Plotnik,[1] Or Peleg,[1] Felix Dreisow,[2] Matthias Heinrich,[2] Stefan Nolte,[2]
Alexander Szameit,[1] and Mordechai Segev[1]

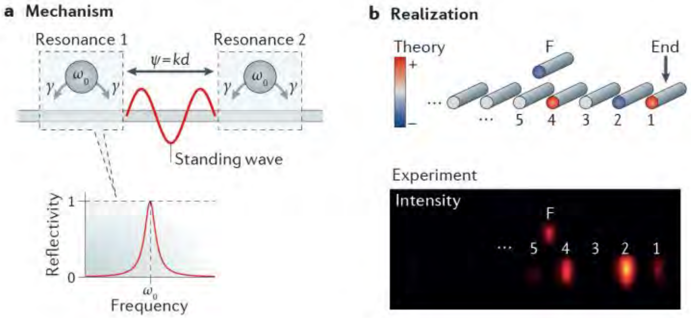


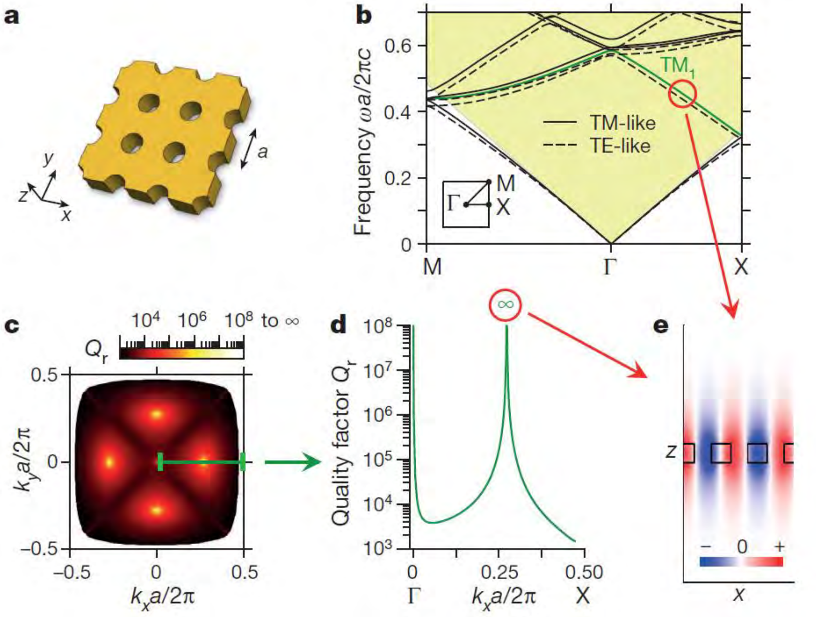


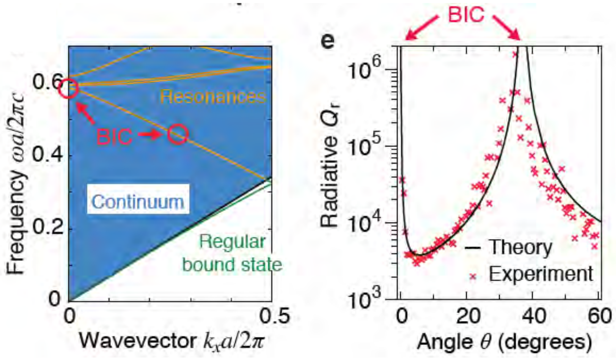
PRL **111,** 240403 (2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

Compact Surface Fano States Embedded in the Continuum of Waveguide Arrays

Steffen Weimann,[1] Yi Xu,[2] Robert Keil,[1] Andrey E. Miroshnichenko,[2] Andreas Tünnermann,[1] Stefan Nolte,[1]
Andrey A. Sukhorukov,[2] Alexander Szameit,[1] and Yuri S. Kivshar[2]



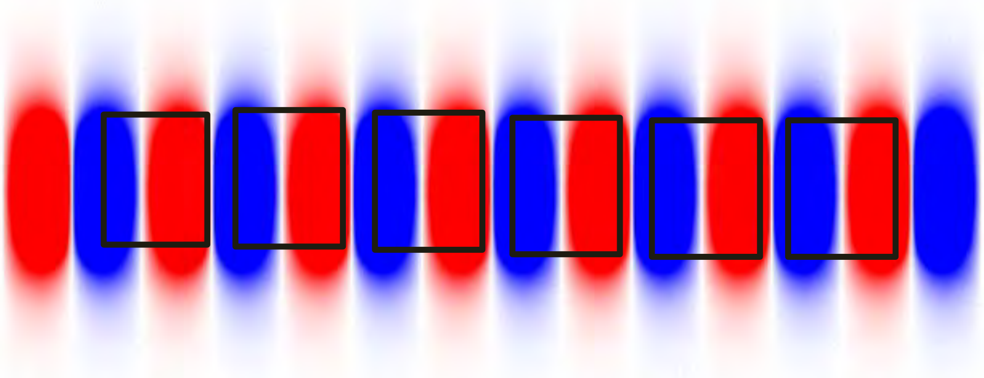




Hsu et al, Nature 2013

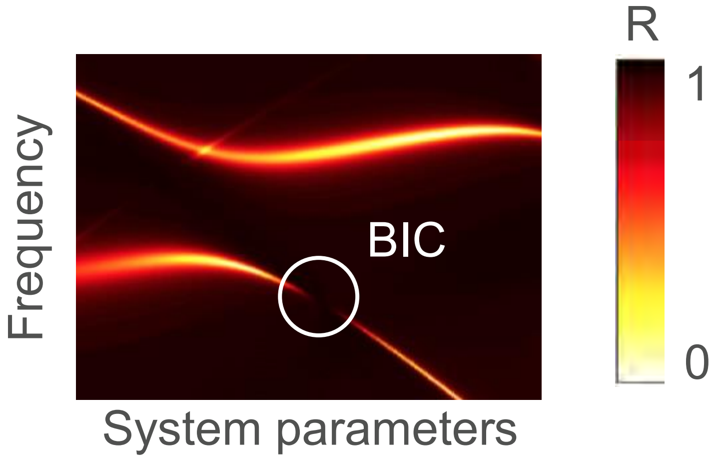
Classification of BICs

Symmetry-protected (conventional)

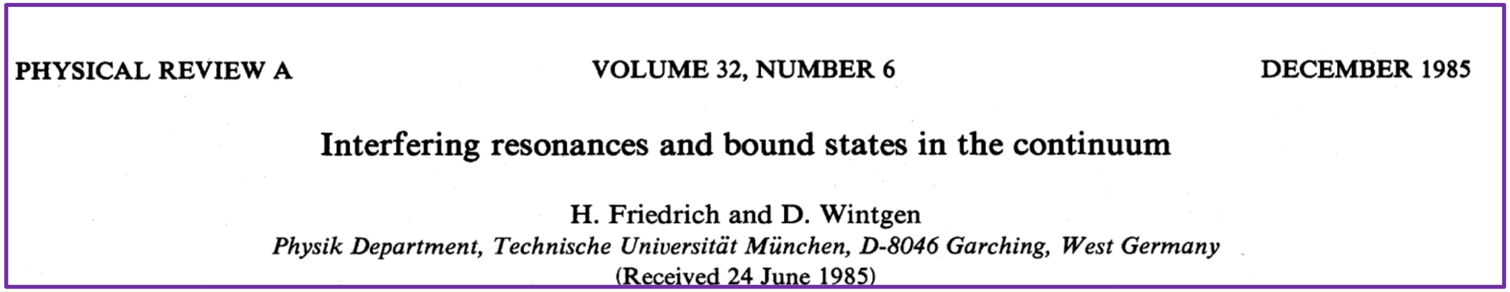


in-plane inversion symmetry
time reversal symmetry

Accidental (Friedrich-Wintgen)



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



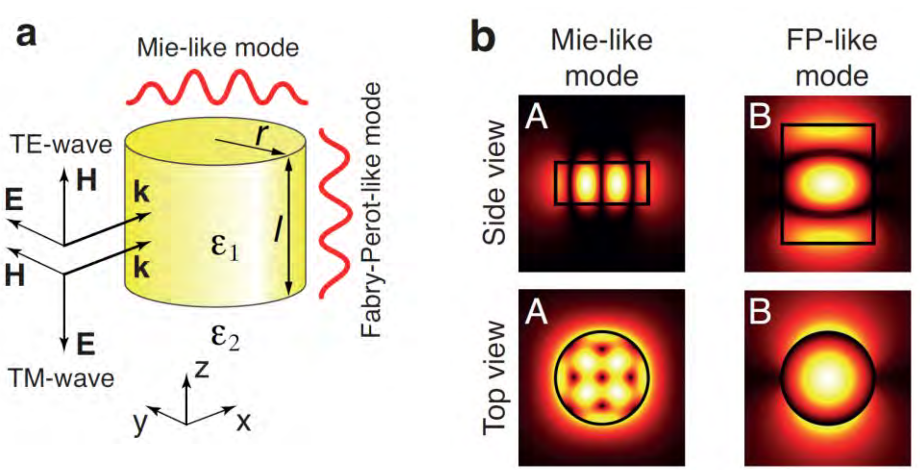
PHYSICAL REVIEW A VOLUME 32, NUMBER 6 DECEMBER 1985

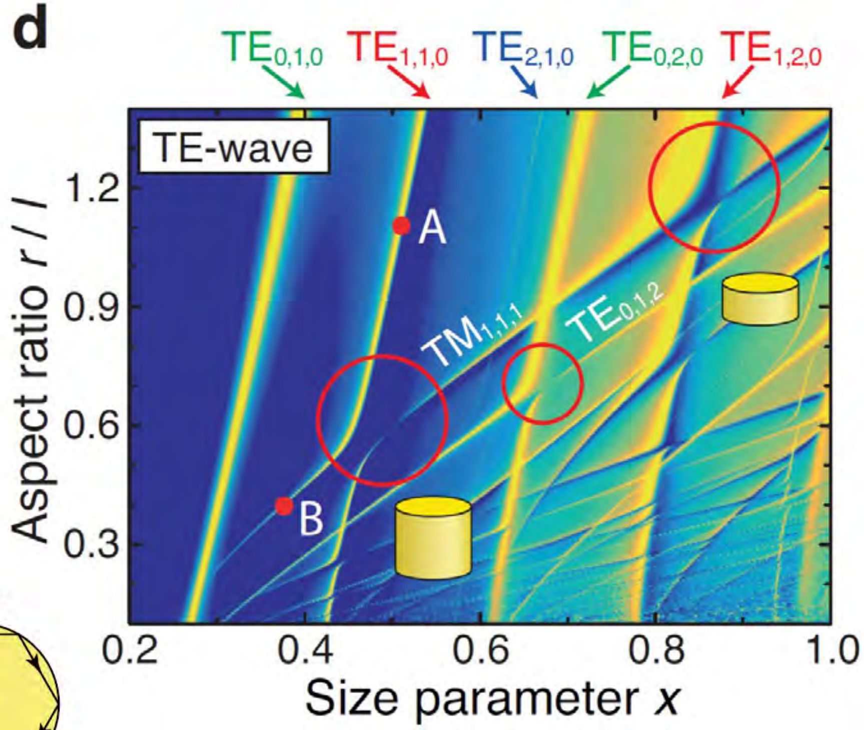
Interfering resonances and bound states in the continuum

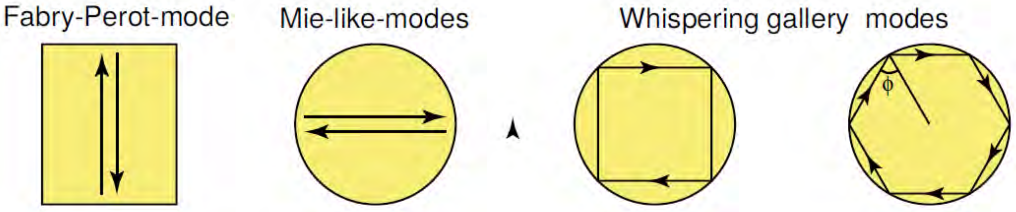
H. Friedrich and D. Wintgen
Physik Department, Technische Universität München, D-8046 Garching, West Germany

(Received 24 June 1985)

BIC in a subwavelength resonator







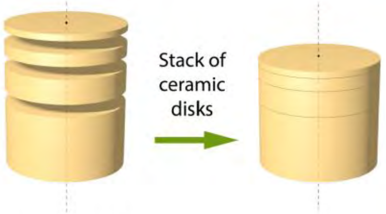
PRL **119,** 243901 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2017

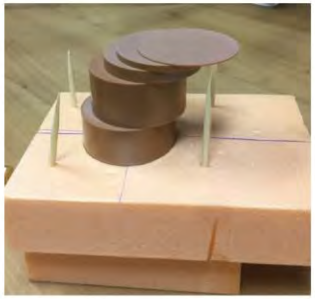
High-*Q* Supercavity Modes in Subwavelength Dielectric Resonators

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]

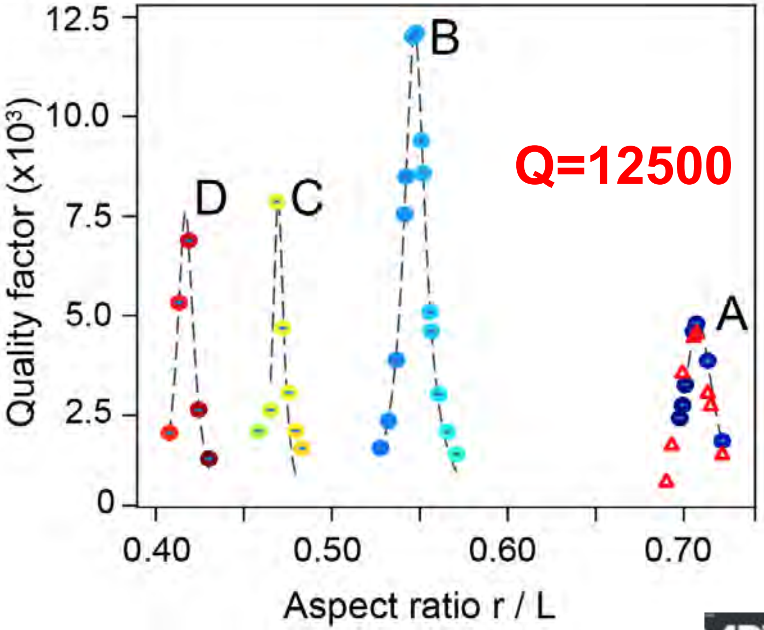
Recent experimental demonstrations

RF experiment

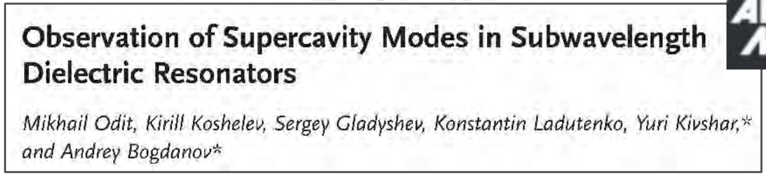




$\varepsilon = 45$
$\tan\delta = 10^{-4}$



Q=12500

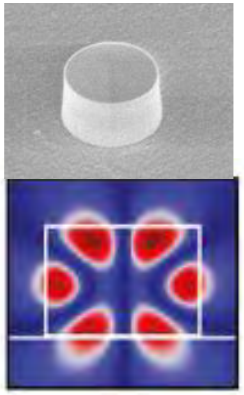


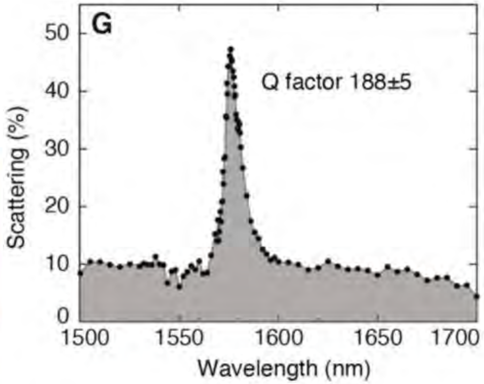
Observation of Supercavity Modes in Subwavelength Dielectric Resonators

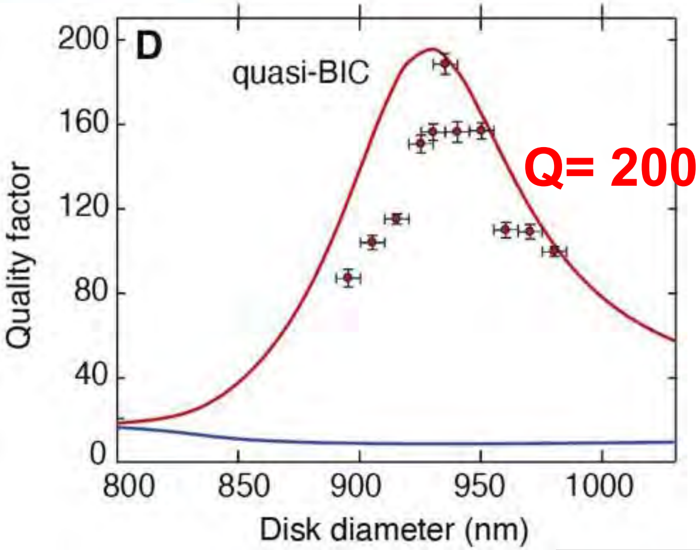
Mikhail Odit, Kirill Koshelev, Sergey Gladyshev, Konstantin Ladutenko, Yuri Kivshar, and Andrey Bogdanov**

ADVANCED MATERIALS

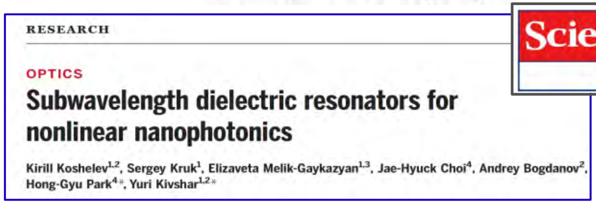
Near-IR experiment







Q= 200



RESEARCH

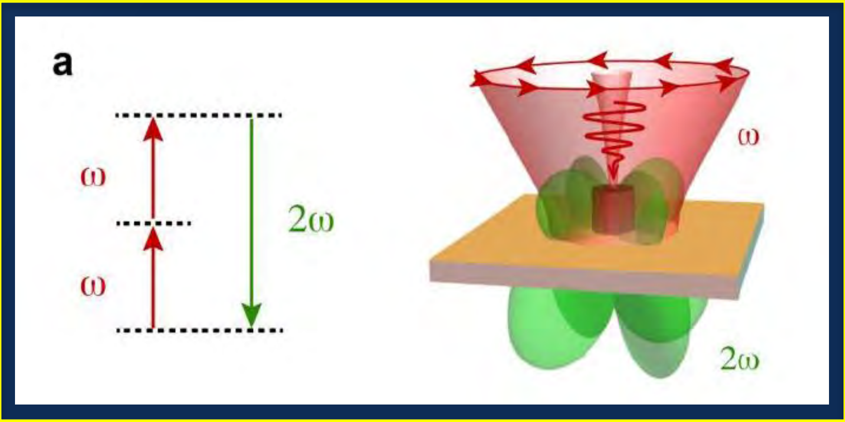
OPTICS

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]*

Science AAAS

Nonlinear nanophotonics



Nonlinear optics

1958-60: invention of the laser

1964: Townes, Basov and Prokhorov shared the **Nobel prize** for their fundamental work leading to the construction of lasers

1981: Bloembergen and Schawlow received the **Nobel prize** for their contribution to the development of laser spectroscopy. One typical application of this is *nonlinear optics* which means methods of influencing one light beam with another and permanently joining several laser beams

Nicolaas
Bloembergen

Arthur Leonard
Schawlow

A.M. Prokhorov

Alexander Mikhaylovich Prokhorov
(Russian:
Прóхоро
2002) wa
his pione
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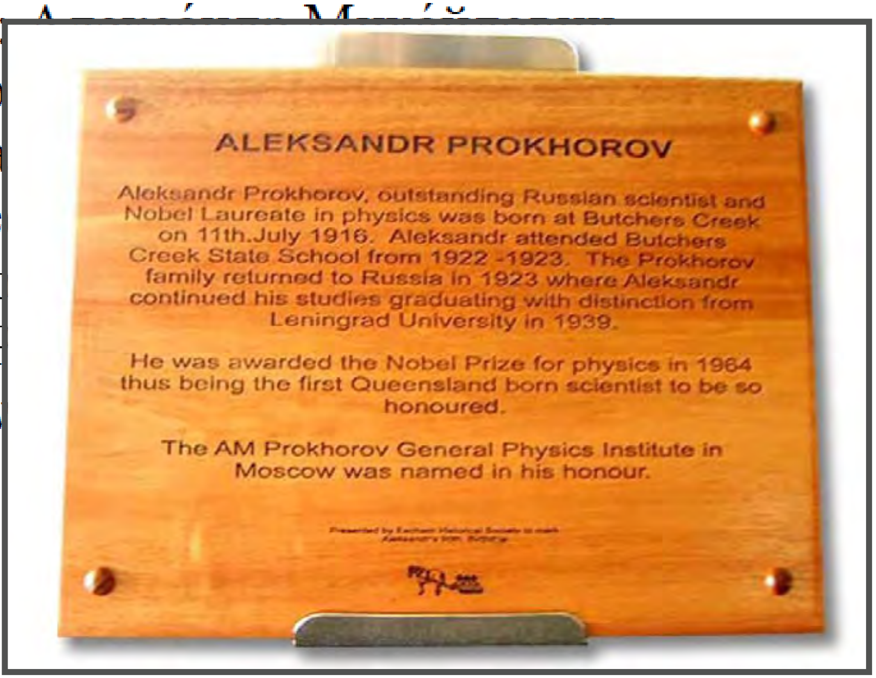


ALEKSANDR PROKHOROV

Aleksandr Prokhorov, outstanding Russian scientist and Nobel Laureate in physics was born at Butchers Creek on 11th.July 1916. Aleksandr attended Butchers Creek State School from 1922 -1923. The Prokhorov family returned to Russia in 1923 where Aleksandr continued his studies graduating with distinction from Leningrad University in 1939.

He was awarded the Nobel Prize for physics in 1964 thus being the first Queensland born scientist to be so honoured.

The AM Prokhorov General Physics Institute in Moscow was named in his honour.

LASERS & SOURCES

Meet Alexander Prokhorov: the Australian-born co-inventor of the laser and Nobel Prize winner

While he is a celebrated scientific hero in Russia, his formative years were actually spent in far north Queensland.

Aug. 4, 2016

Optical polarisation

$$\mathbf{P} = \varepsilon_0 \left(\underbrace{\chi^{(1)} \cdot \mathbf{E}}_{1} + \underbrace{\chi^{(2)} : \mathbf{EE}}_{2} + \underbrace{\chi^{(3)} \vdots\, \mathbf{EEE}}_{3} + \cdots \right)$$

- χ(j) (j=1,2,...) is j-th order susceptibility;
- χ(j) is a tensor of rank j+1;
- for this series to converge χ(1)E >>χ(2)E2 >>χ(3)E3

- **χ(1)** is the linear susceptibility (dominant contribution). Its effects are included through the refractive index (real part) and the absorption α (imaginary part).
- **χ(2)** is the nonlinear **quadratic** susceptibility (SHG)
- **χ(3)** is the nonlinear **cubic** susceptibility (solitons, modulational instability)

Towards efficient nonlinear nanoantennas

Materials

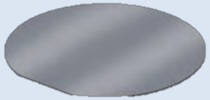
Metals

+ High $\chi^{(2)}$ and $\chi^{(3)}$
High light confinement

− Absorption
Small mode volume

SHG/THG Efficiency 10^{-9}, 10^{-10}
10^{-7} (Dangyuan Lei, CityU)

Si, Ge



High $\chi^{(3)}$

THG Efficiency 10^{-6}

III-V semiconductors

High $\chi^{(2)}$

SHG Efficiency >10^{-4}

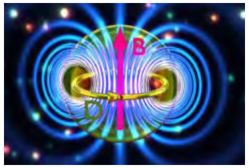
Resonant modes

SHG $\sim\kappa Q_{\omega}^{2} Q_{2\omega}$

THG $\sim\kappa Q_{\omega}^{3} Q_{3\omega}$

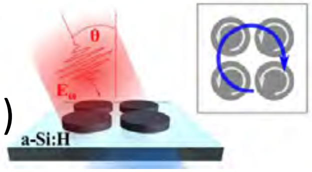
MD resonance

Shcherbakov at al
Nano Lett. (2014)



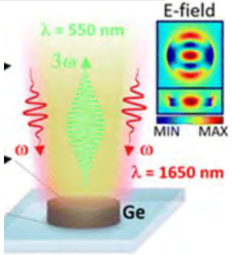
Fano effect

Shorokhov at al
Nano Lett. (2016)



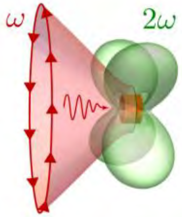
Anapole state

Grinblat et al
Nano Lett. (2016)



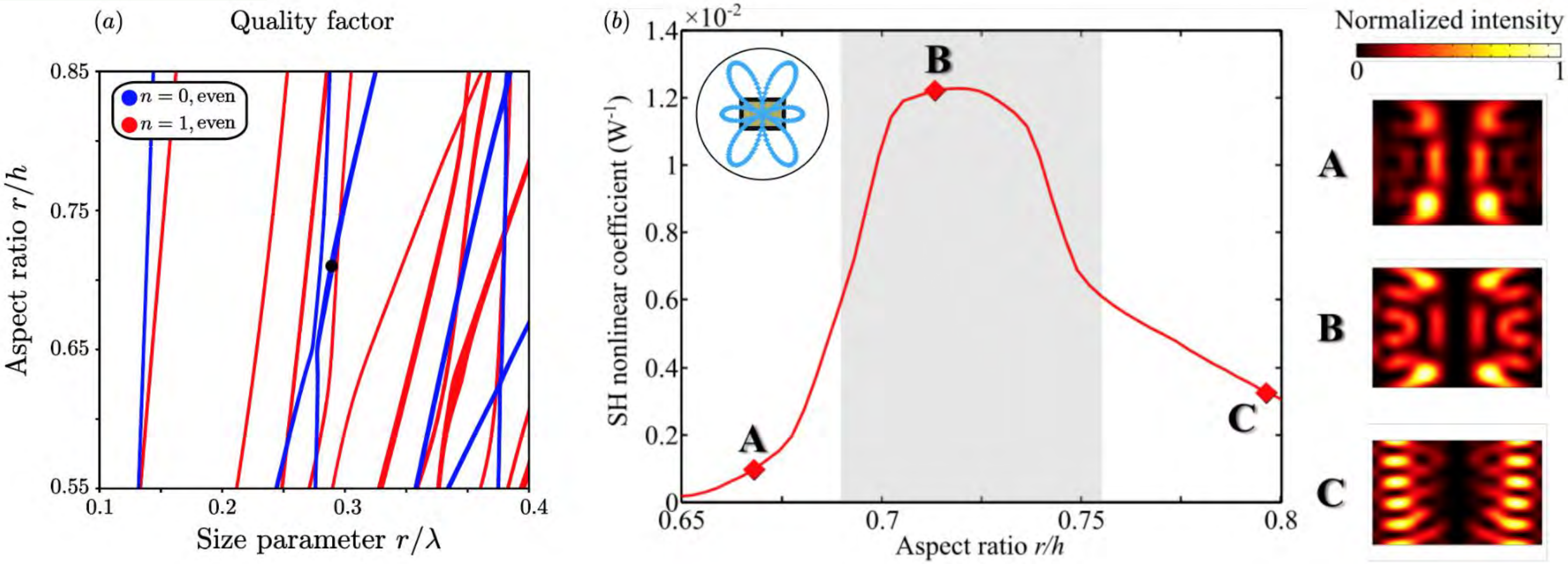
BIC

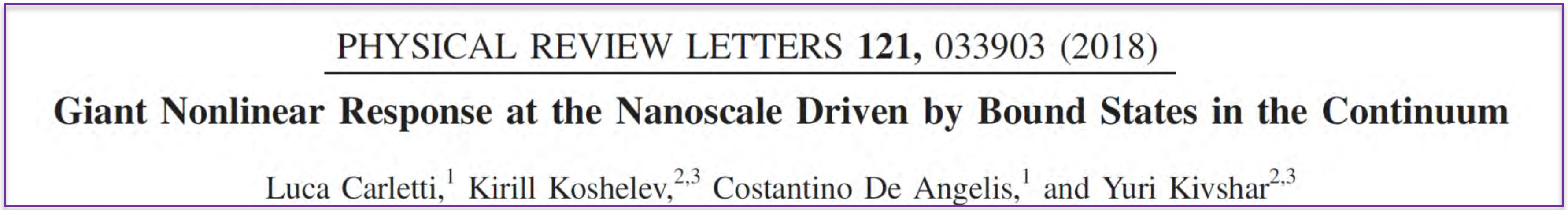
Carletti et al,
Phys Rev Lett (2018)



Nonlinear response of quasi-BIC states

Mode	Polarization	$\rho_{SH} \times 10^4$ (W^{-1})	η	λ_{FF} (μm)	Q
BIC	Azimuthal	210	0.77	1.55	114
BIC	Linear	270	0.06	1.55	114
MD	Linear	1.8	0.84	2.98	10



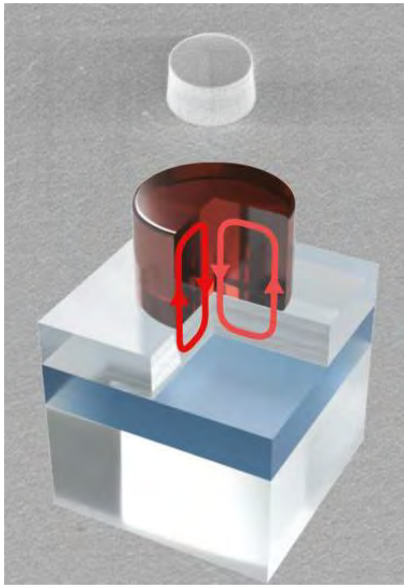


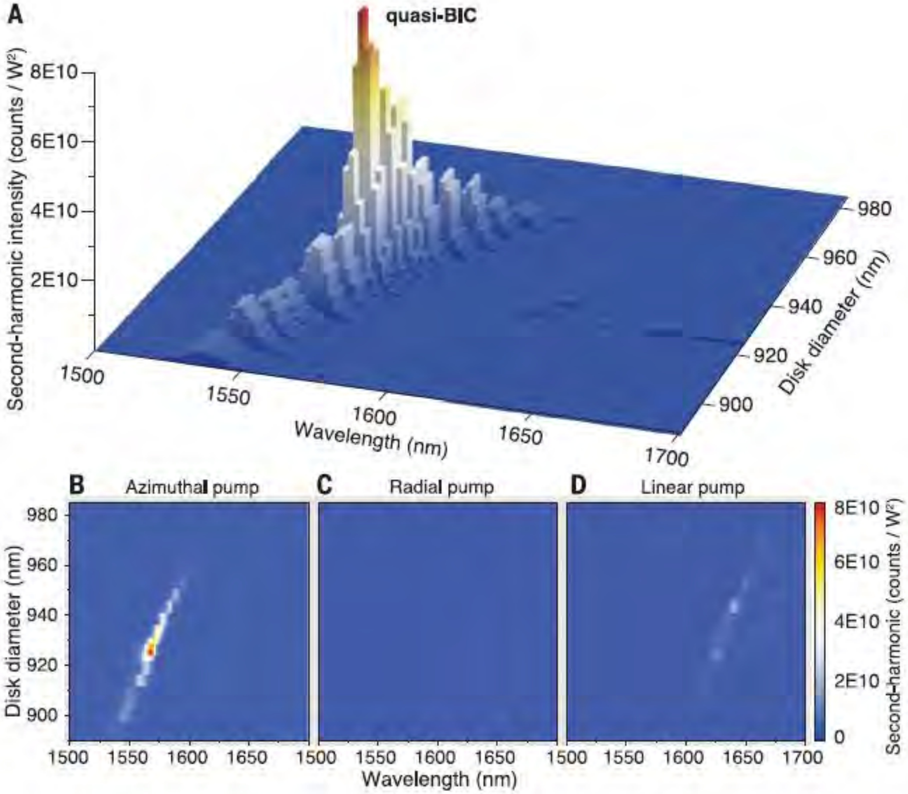
PHYSICAL REVIEW LETTERS **121,** 033903 (2018)

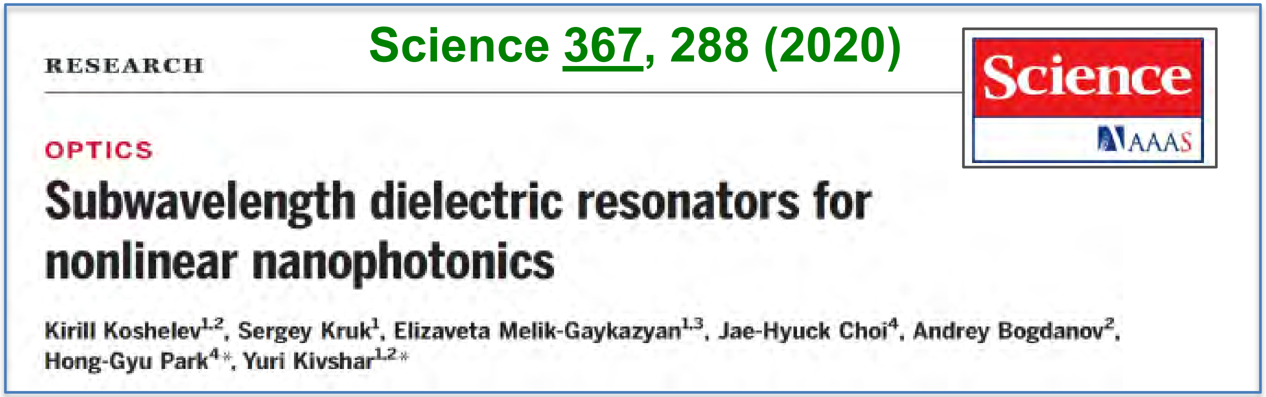
Giant Nonlinear Response at the Nanoscale Driven by Bound States in the Continuum

Luca Carletti,[1] Kirill Koshelev,[2,3] Costantino De Angelis,[1] and Yuri Kivshar[2,3]

SHG from quasi-BIC states







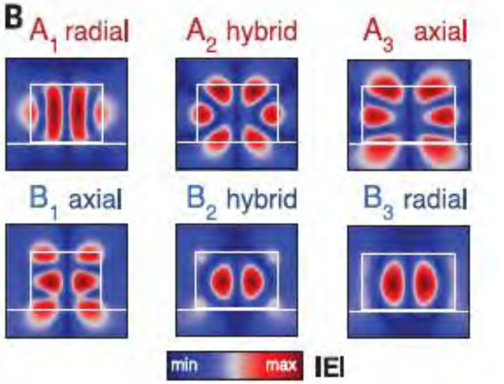
Science 367, 288 (2020)

RESEARCH

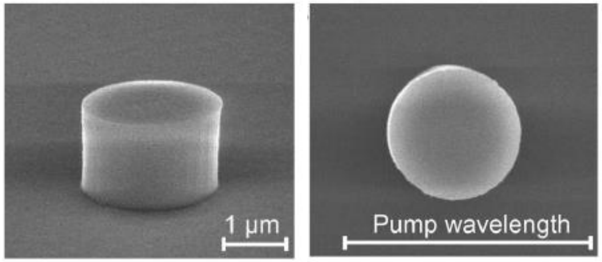
OPTICS

Subwavelength dielectric resonators for nonlinear nanophotonics

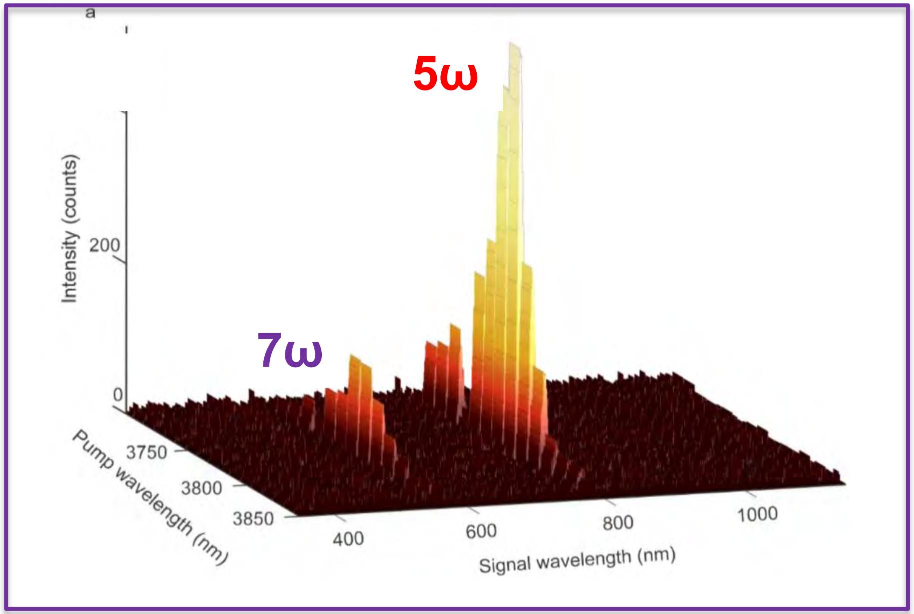
Kirill Koshelev[1,2], Sergey Kruk[1], Elizaveta Melik-Gaykazyan[1,3], Jae-Hyuck Choi[4], Andrey Bogdanov[2], Hong-Gyu Park[4]*, Yuri Kivshar[1,2]*

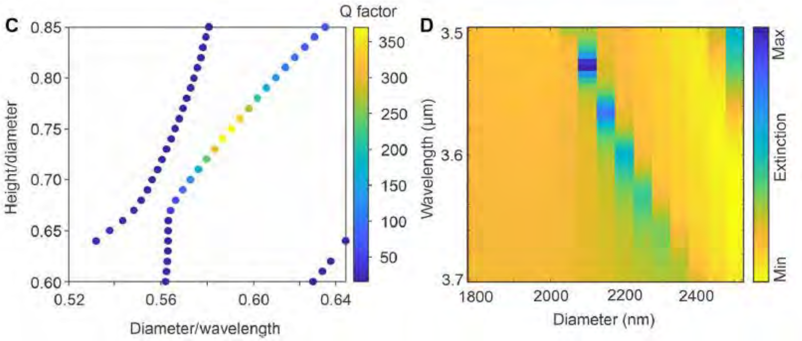


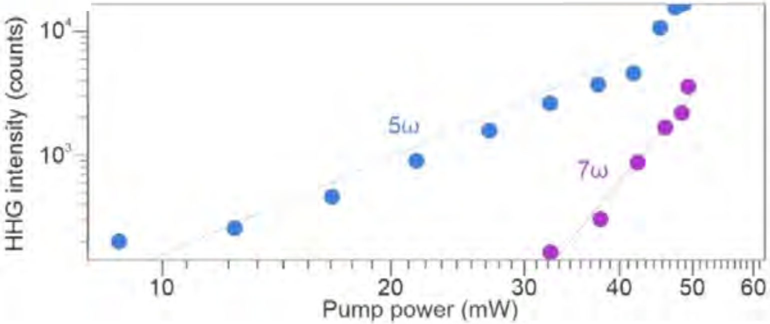
High-harmonic generation

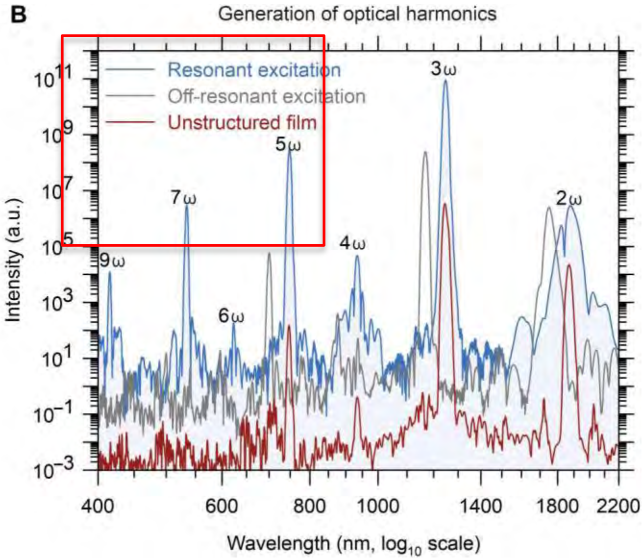


AlGaAs









SCIENCE ADVANCES | RESEARCH ARTICLE 2023

APPLIED PHYSICS

High-harmonic generation from a subwavelength dielectric resonator

Anastasiia Zalogina[1,2]*, Luca Carletti[3], Anton Rudenko[4], Jerome V. Moloney[4], Aditya Tripathi[1], Hoo-Cheol Lee[5], Ilya Shadrivov[1], Hong-Gyu Park[5], Yuri Kivshar[1]*, Sergey S. Kruk[1]*

Metasurfaces

光子学研究 ISSN 2327-9125 CN 31-2126/O4

2013 — 2023

PHOTONICS Research

Volume 10—11 | 2022—2023

Special Issue on

Optical Metasurfaces:
Fundamentals and Applications

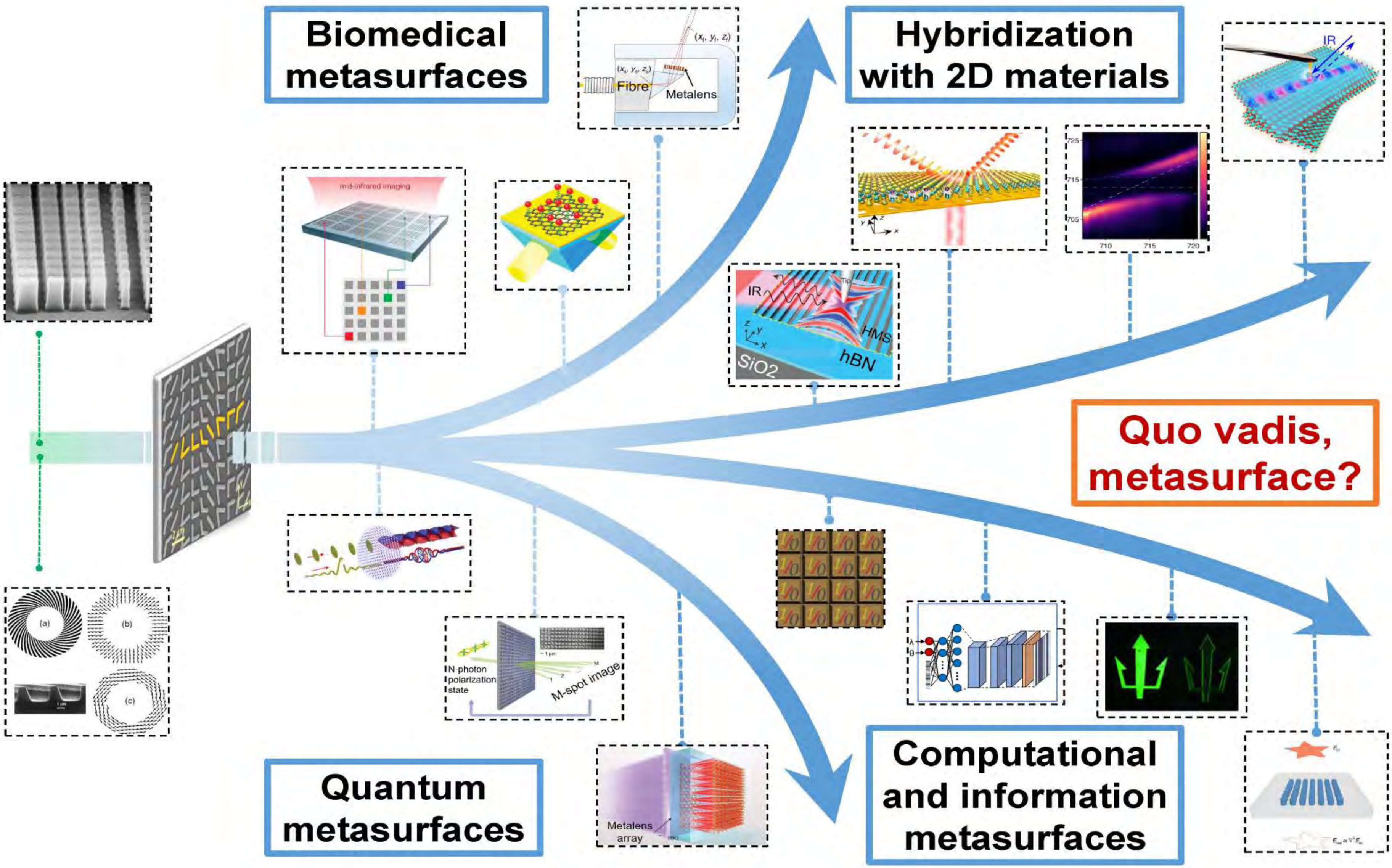
Optical
Spin
Manipulation
PAGE 10

CHINESE LASER PRESS

OPTICA PUBLISHING GROUP

Formerly OSA

Expanding world of metasurfaces



Biomedical metasurfaces

Hybridization with 2D materials

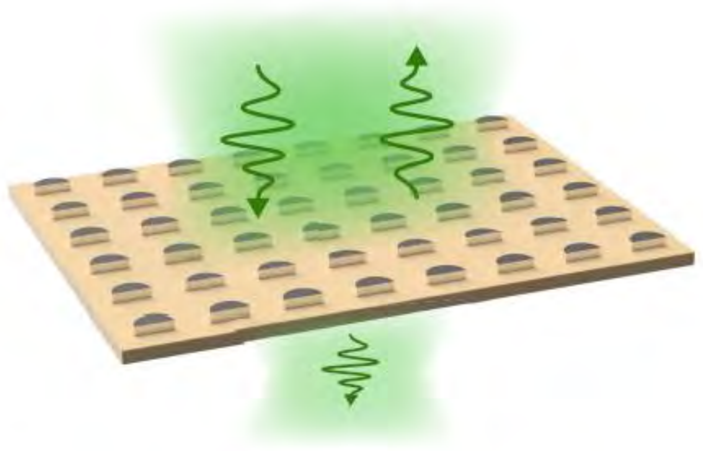
Quo vadis, metasurface?

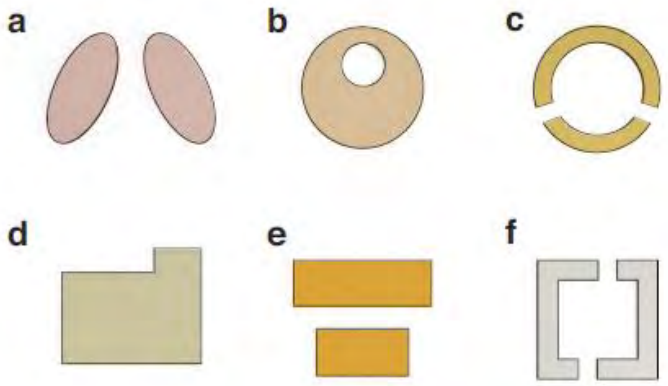
Quantum metasurfaces

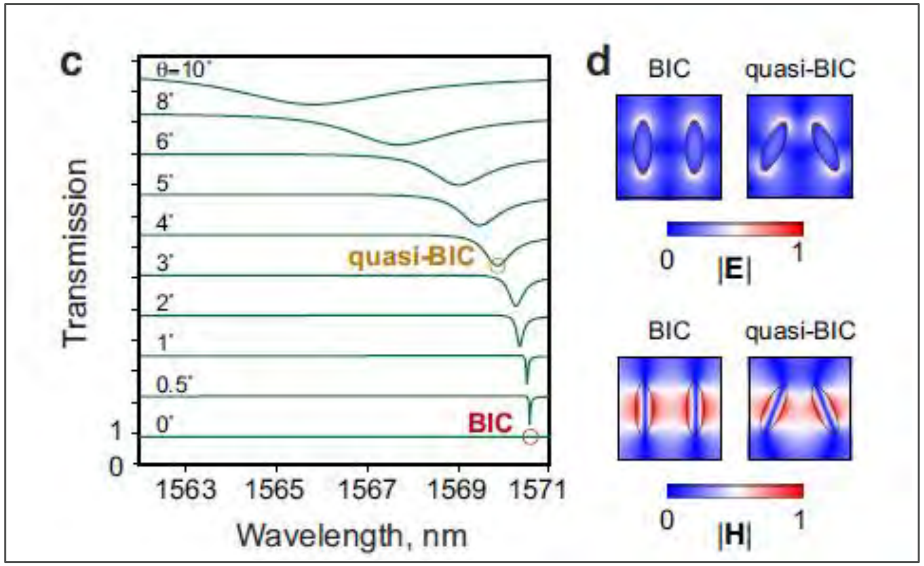
Computational and information metasurfaces

C.W. Qiu, T. Zhang, G. Hu, Y. Kivshar, Nano Letters (2021)

High-Q quasi-BIC metasurfaces



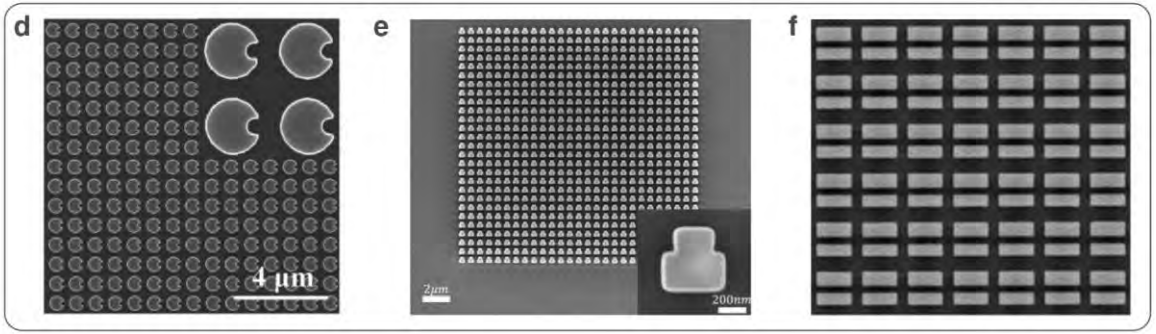




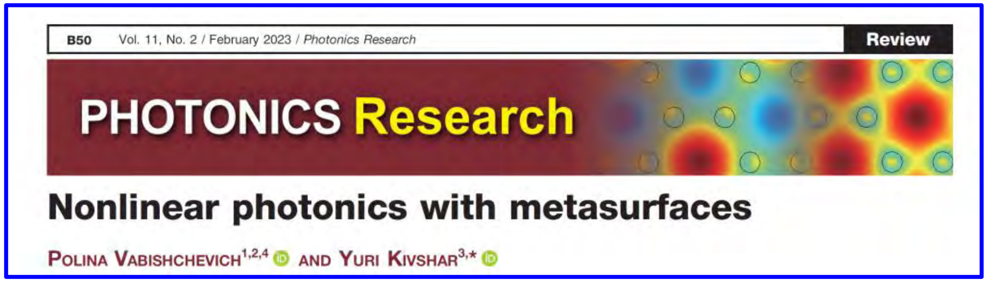
PHYSICAL REVIEW LETTERS **121,** 193903 (2018)

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]



Extreme nonlinear optics



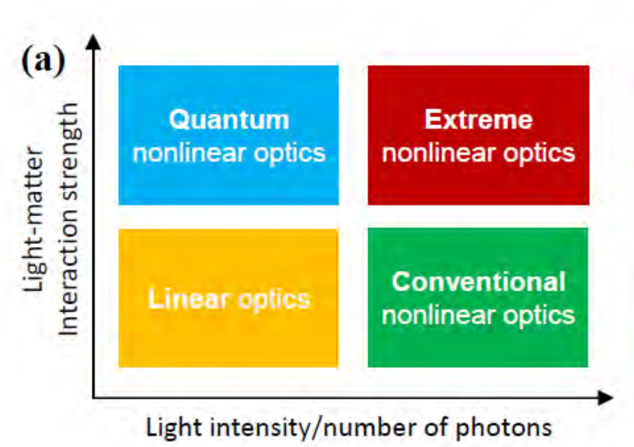
B50 Vol. 11, No. 2 / February 2023 / *Photonics Research*

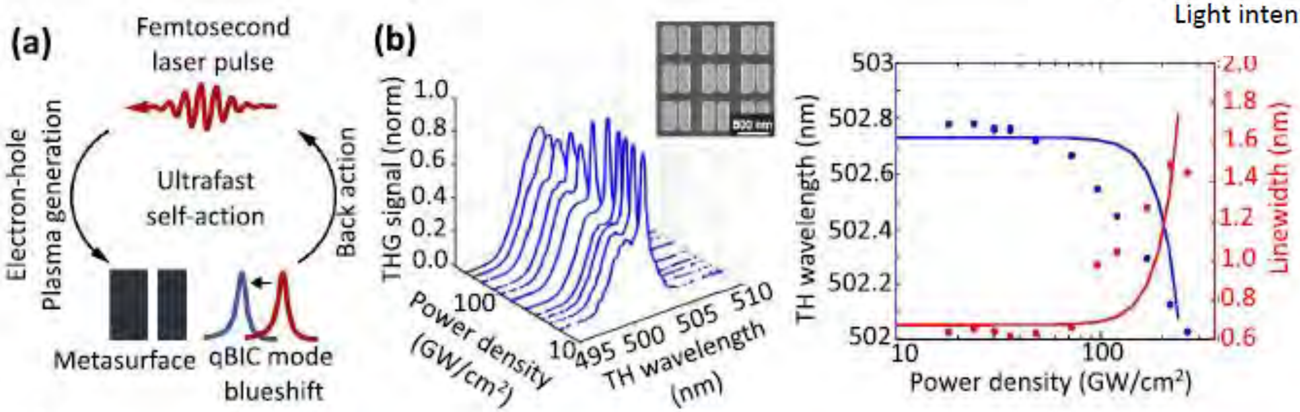
Review

PHOTONICS Research

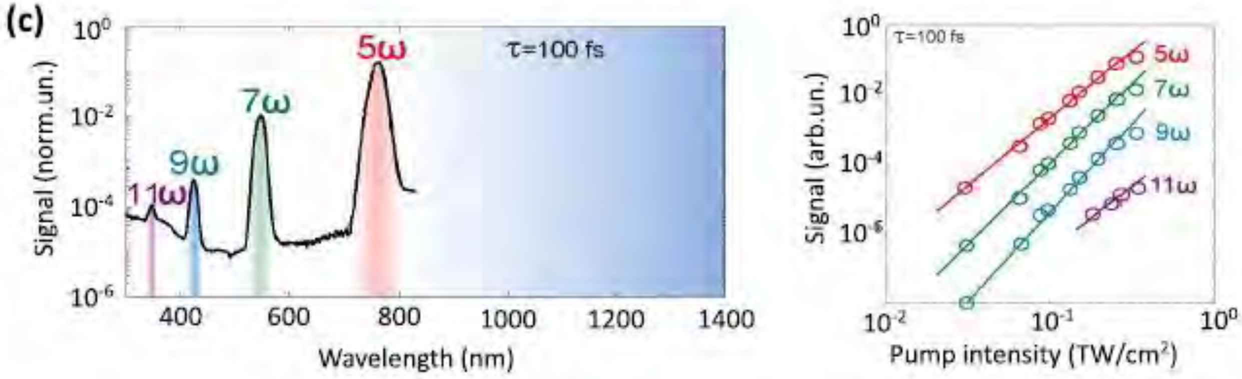
Nonlinear photonics with metasurfaces

POLINA VABISHCHEVICH[1,2,4] AND YURI KIVSHAR[3,*]





Nano Letters
21, 8848 (2021)

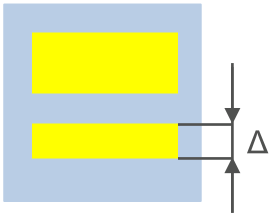


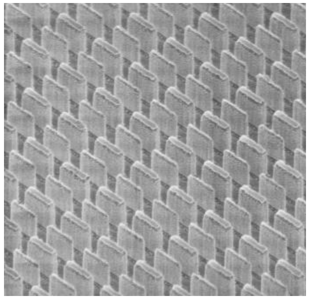
ACS Photonics
9, 567 (2022)

Expected enhanced THG

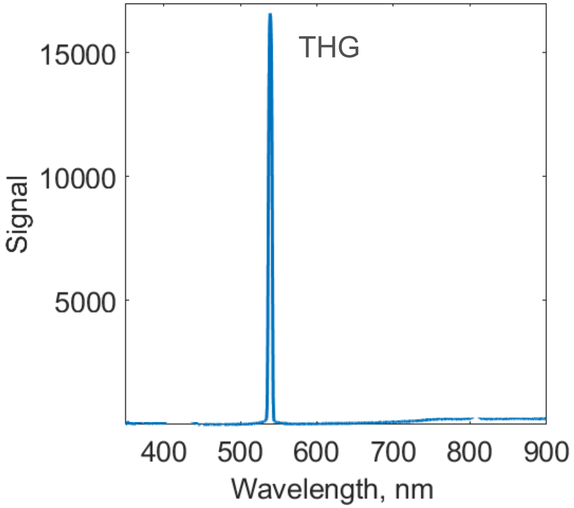
$$\mathbf{P}(t) = \varepsilon_0 \left(\chi^{(1)}\mathbf{E}(t) + \chi^{(2)}\mathbf{E}^2(t) + \chi^{(3)}\mathbf{E}^3(t) + \ldots\right),$$

a-Si metasurface



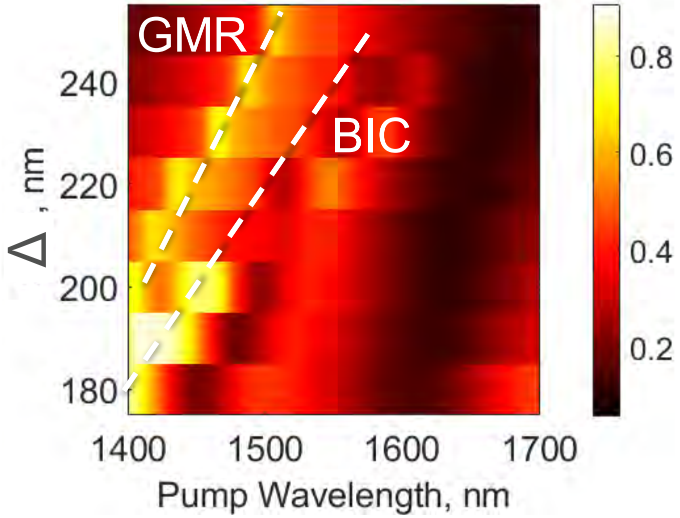


BIC resonance at 1630 nm

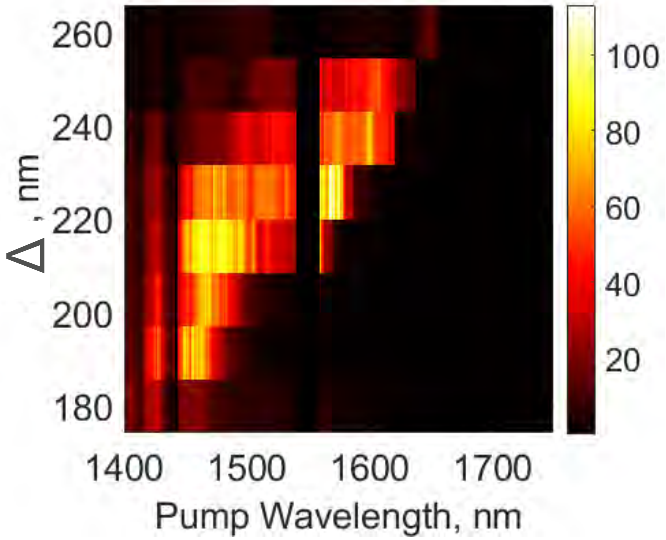


Collaboration with Qinghai Song

Linear reflection



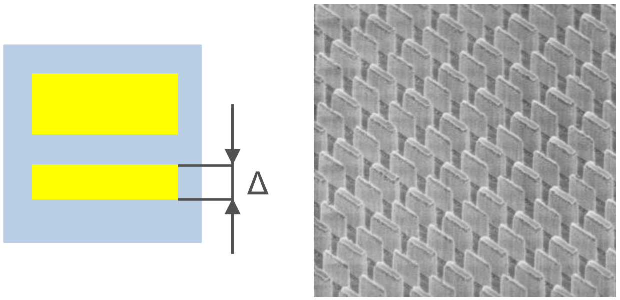
THG enhancement

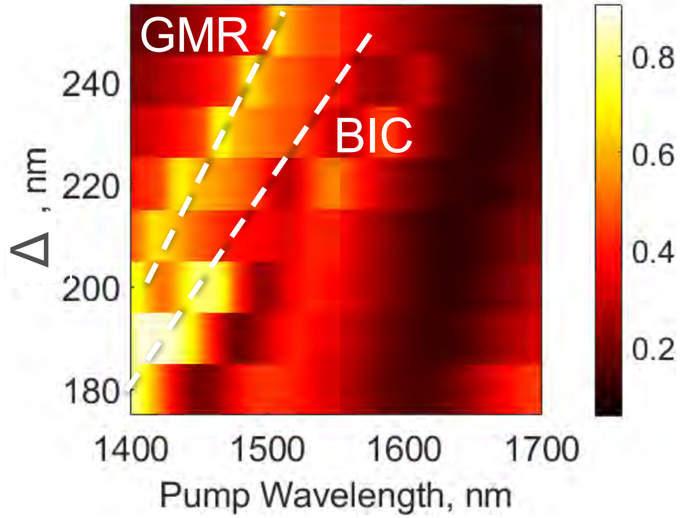


Unexpectedly large SHG

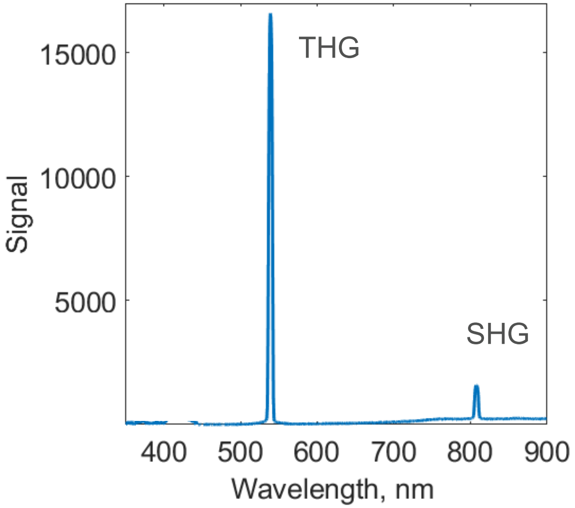
$$\mathbf{P}(t) = \varepsilon_0 \left(\chi^{(1)} \mathbf{E}(t) + \chi^{(2)} \mathbf{E}^2(t) + \chi^{(3)} \mathbf{E}^3(t) + \ldots \right),$$

a-Si metasurface

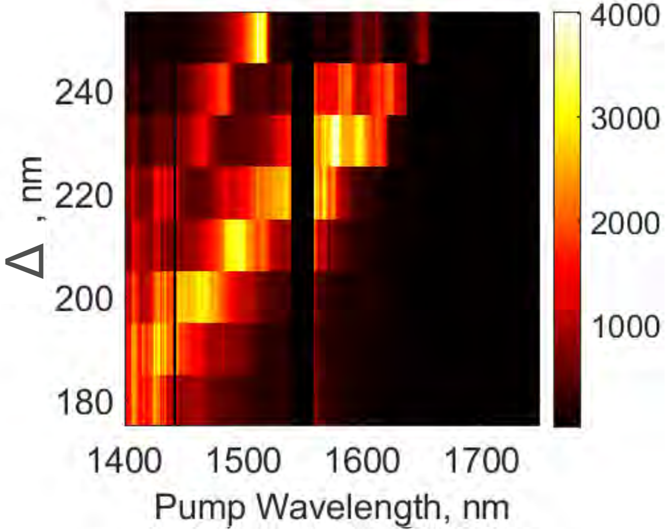


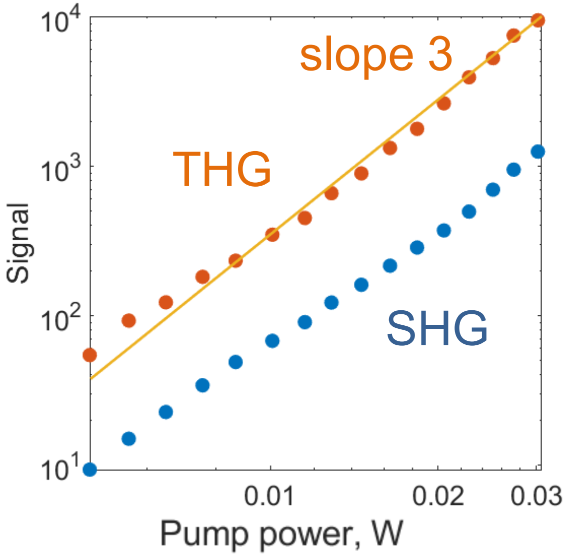


BIC resonance at 1630 nm



SHG enhancement

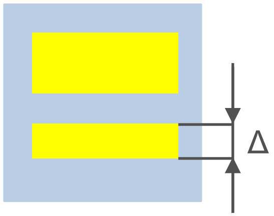


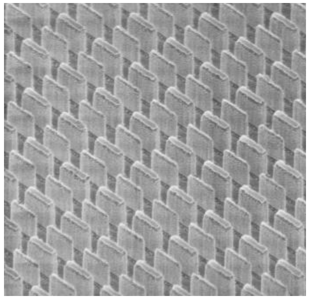


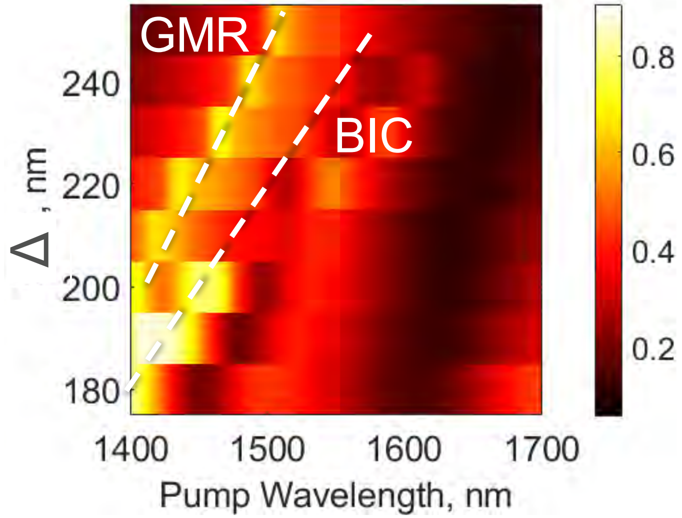
And even fourth harmonics !

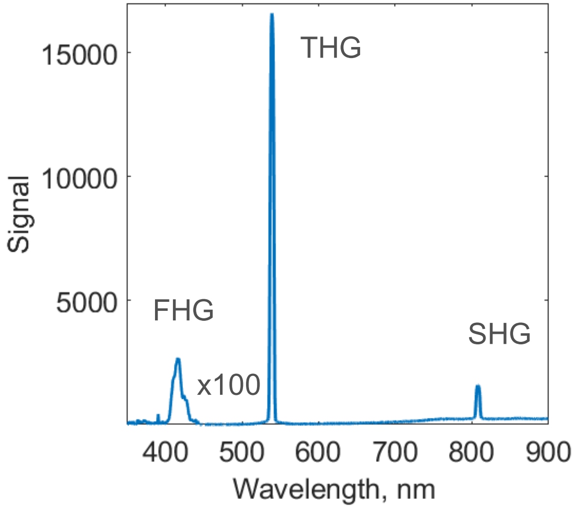
$$\mathbf{P}(t) = \varepsilon_0 \left(\chi^{(1)}\mathbf{E}(t) + \chi^{(2)}\mathbf{E}^2(t) + \chi^{(3)}\mathbf{E}^3(t) + \ldots\right),$$

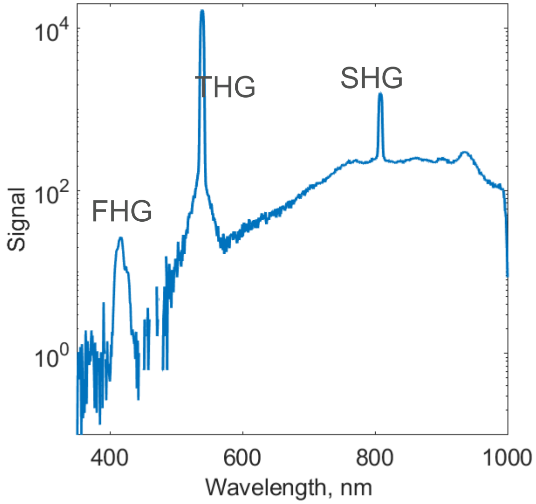
a-Si metasurface

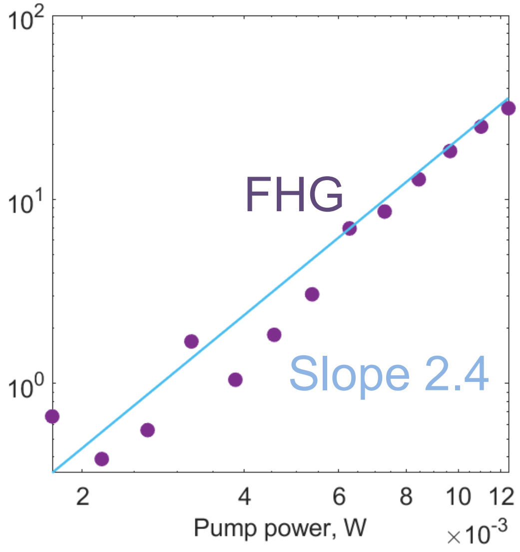












P. Tonkaev et al, in preparation

Take-home messages

- ☐ The study of metamaterials is an active field that now often appears under new brand names of meta-optics or metaphotonics
- ☐ Recent advances in meta-optics and metaphotonics are associated with the physics of resonances (including but not limited by) Mie resonances and quasi bound states in the continuum
- ☐ Metasurfaces and subwavelength dielectric particles may exhibit strong nonlinear effects including exotic and high-harmonic generation