The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2328-26

Preparatory School to the Winter College on Optics and the Winter College on Optics: Advances in Nano-Optics and Plasmonics

30 January - 17 February, 2012

Metamaterials current trends

N. Zheludev

University of Southampton
Southampton
U.K.

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Metamaterials

Nikolay Zheludev

Optoelectronics Research Centre
Centre for Photonic Metamaterials
University of Southampton, UK

.

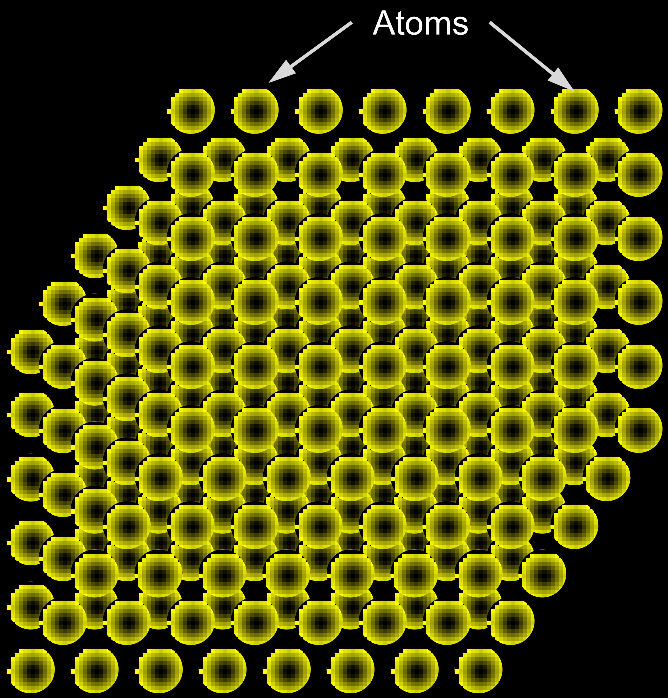
www.nanophotonics.org.uk

Winter College on Optics: Advances in Nano-Optics and Plasmonics
Triest, Italy 6-17 February, 2012

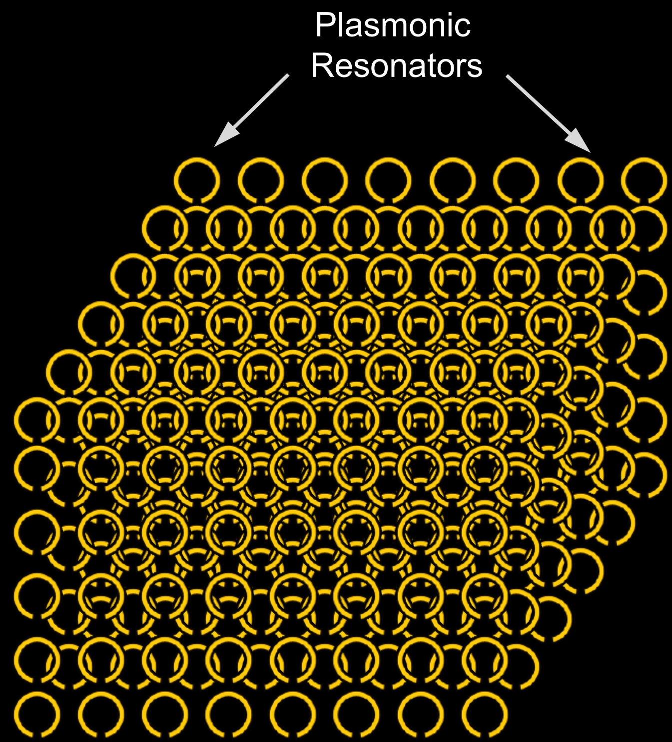
Metamaterials: mimicking Nature

Metamaterial is a manmade media with all sorts of unusual functionalities that can be achieved by **artificial structuring smaller than the length scale of the external stimulus**.

NIZ. Nature Materials **7**, 420 (2008)



Natural Solid



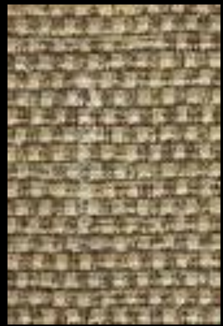
Electromagnetic Metamaterial

Materials: from mega to nano

Pyramid Brick wall: 1m

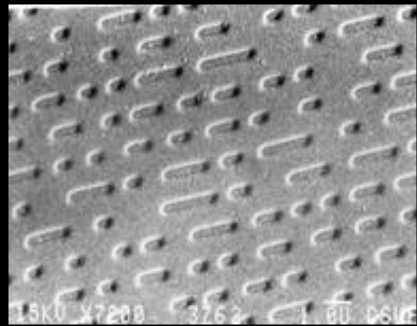
1000:1

Tweed wool: 1mm



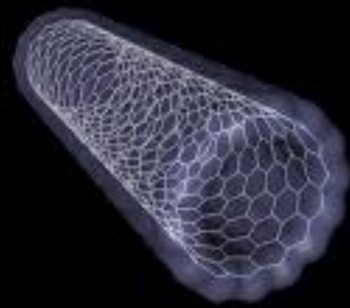
1000:1

CD tracks:1micron



1000:1

Carbon nano-tubes:1nm



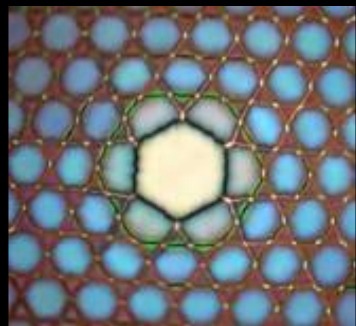
Parthenon columns: 1m

1000:1

Computer PCB: 1mm

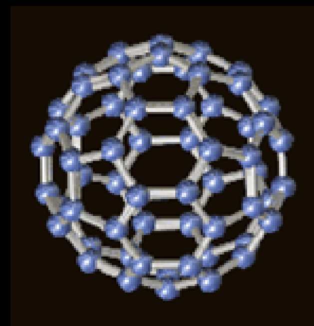
1000:1

Crystal fiber:1micron



1000:1

Carbon buckyball:1nm



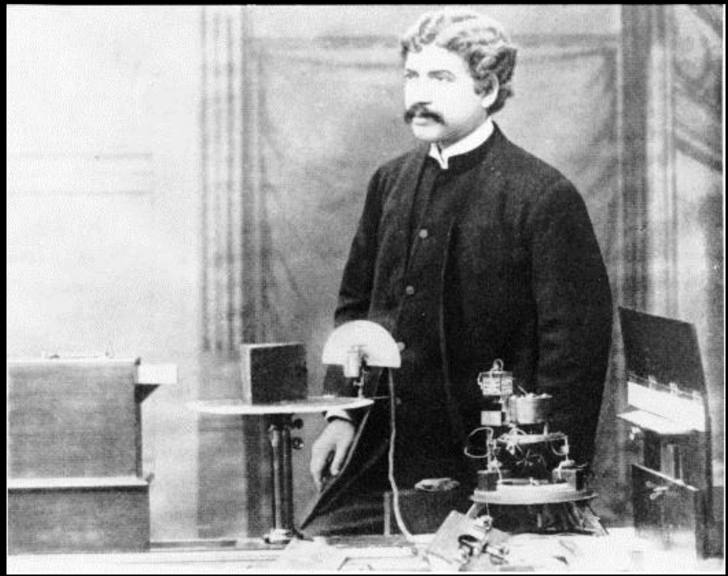
Corresponding electromagnetic scale

Microwave meta-materials

THz meta-materials

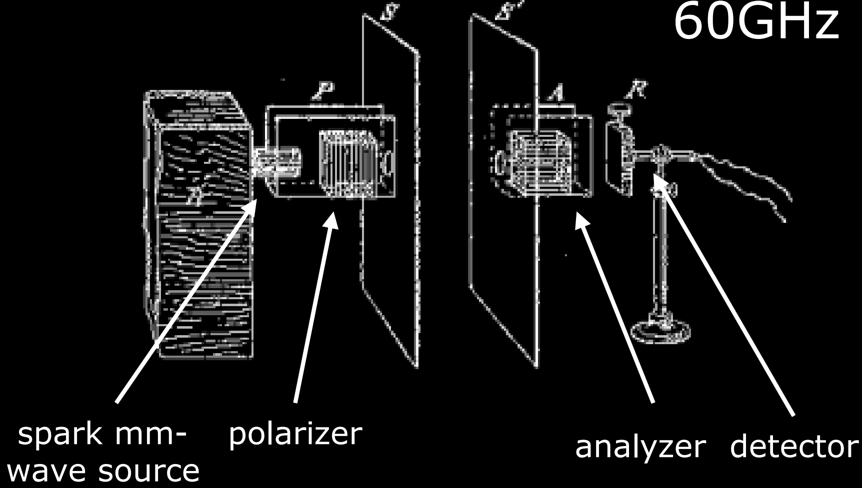
Photonic meta-materials

1st Metamaterial (J.Bose, 1898)



Sir Jagadish Chandra Bose, 1858 – 1937

Anisotropic Meta-molecule

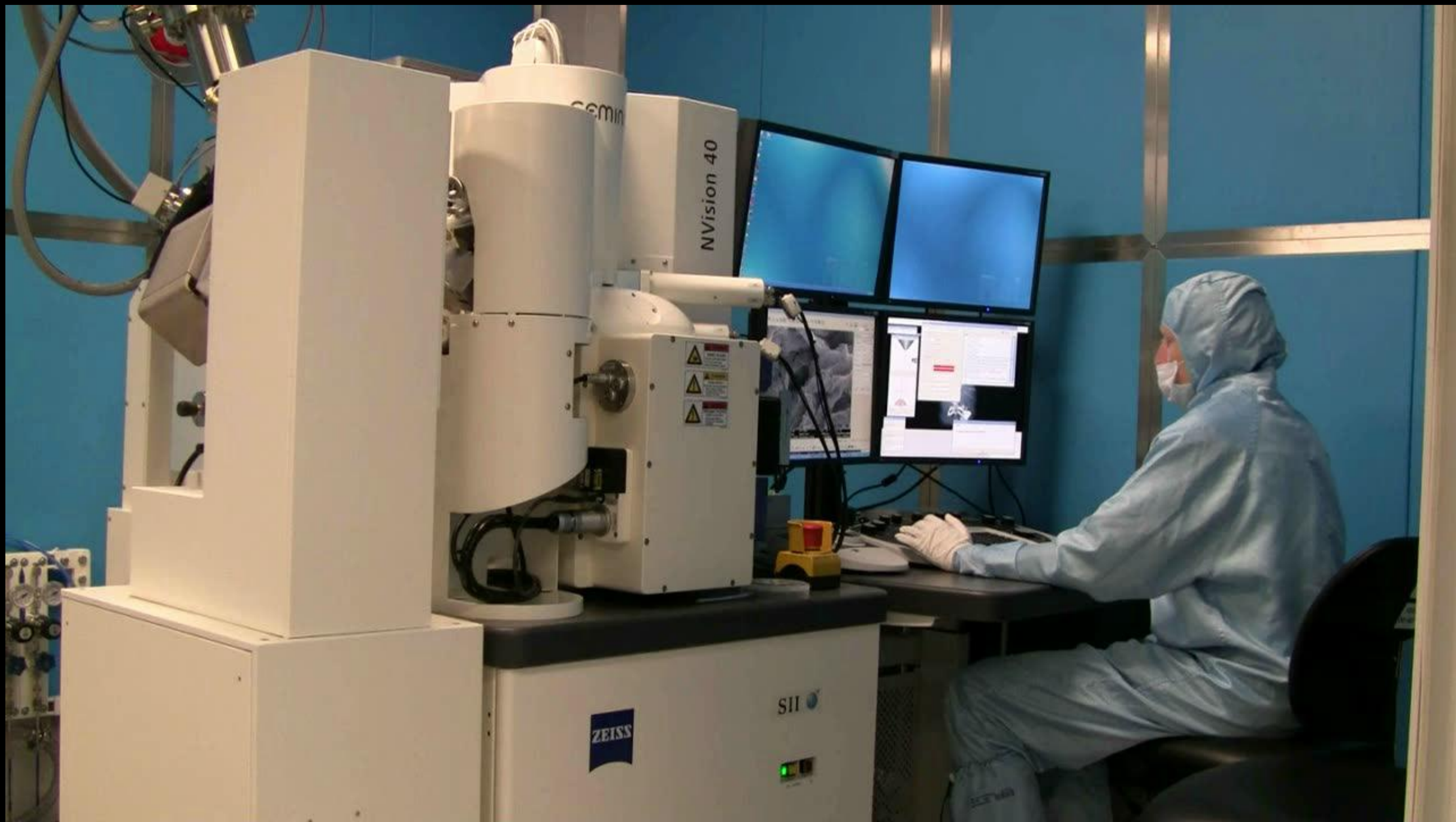


J.Bose. Proc. Royal Soc. of London, **63**, 146 (1898)

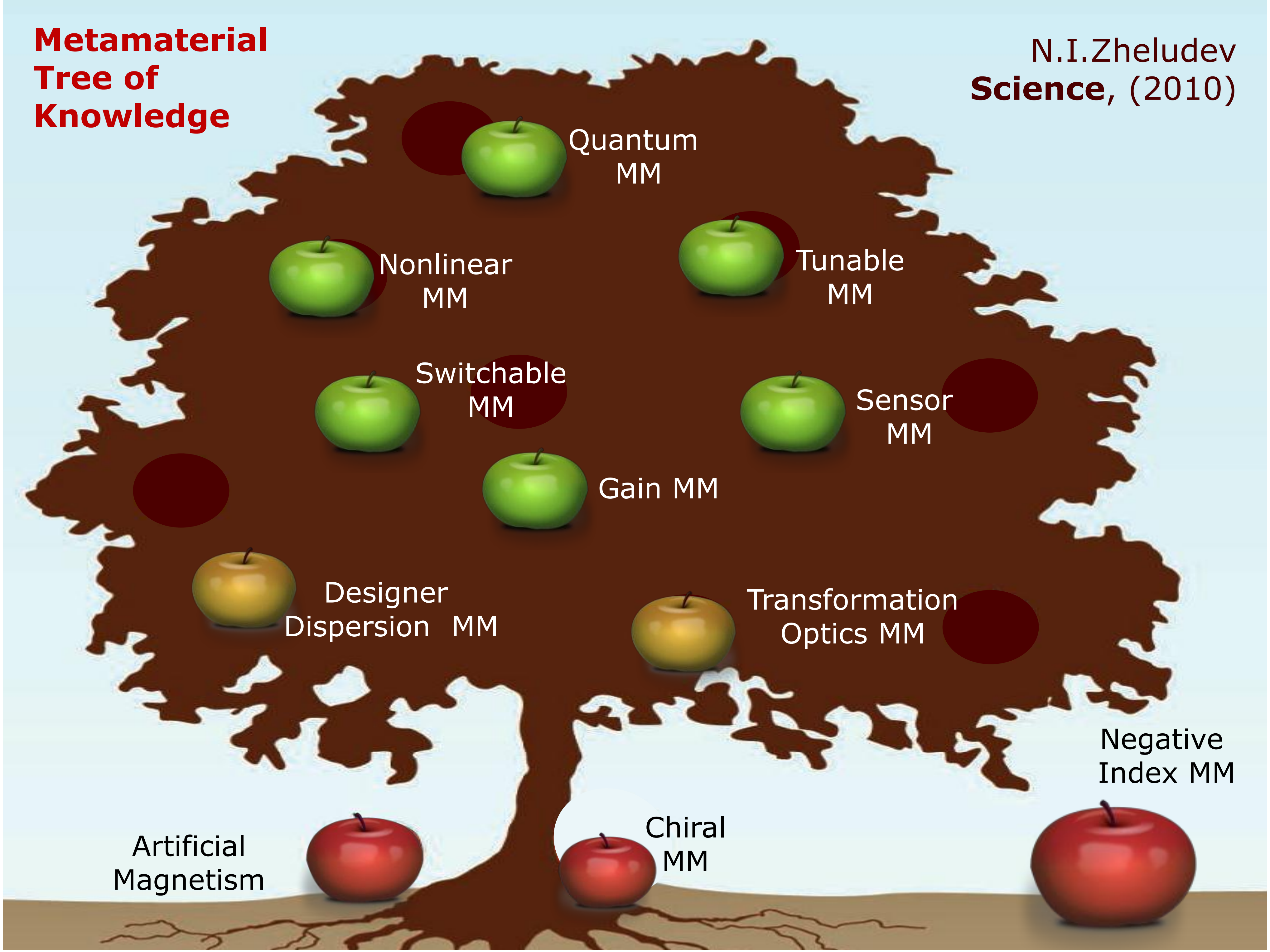
Chiral Meta-molecule

Challenging nature through nanofabrication

Optical lithography | E-beam lithography | Ion-beam milling (FIB) | Nano-imprint



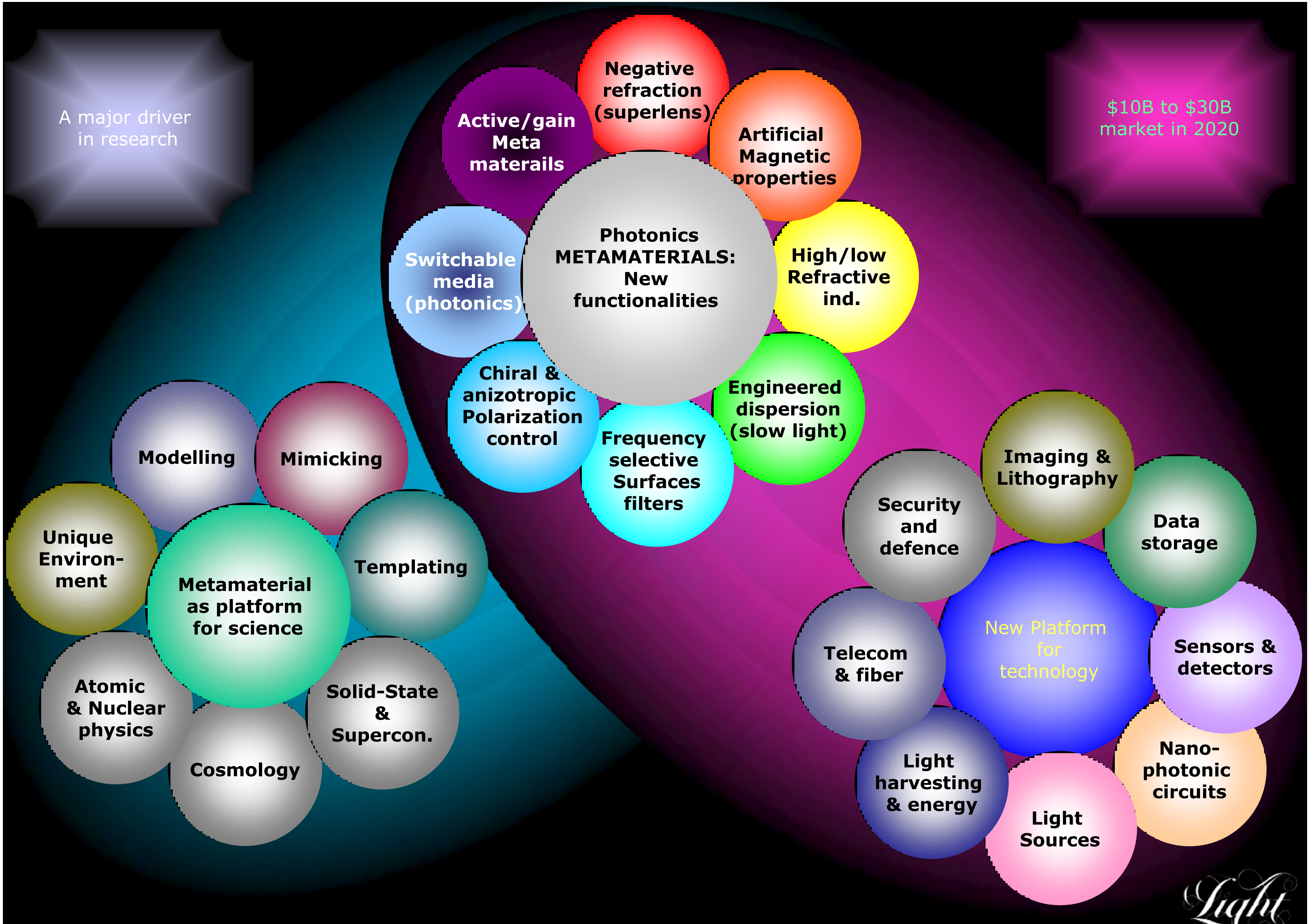
Metamaterials = Negative Index Media & Superlens
Metamaterials = Invisibility & Cloaking


Metamaterial Tree of Knowledge
N.I.Zheludev
Science, (2010)
Quantum MM
Nonlinear MM
Tunable MM
Switchable MM
Sensor MM
Gain MM
Designer Dispersion MM
Transformation Optics MM
Negative Index MM
Artificial Magnetism
Chiral MM

Metamaterials and Southampton

• 2005: "Invisible Metals"
• 2007: Optical Magnetic Mirror
• 2006-2009: Chiral & "Stereo" metamaterials
• 2006-2009 Asymmetric Transmission
• 2006 EIT in metamaterials
• 2008 Lasing Spaser
• 2009 Coherent & incoherent metamaterials
•2009-2010 Toroidal metamaterials
• 2010: Spectral collapse in metamaterials

•2010 Bas-relief metamaterials
•2010 Superconducting metamaterials
•2010 CNT in metamaterials (ultrafast switching)
•2010 Graphene in Metamaterials
•2010 Chalcogenide Glass in metamaterials (switching)
•2010 Coherent control in metamaterials
•2010 Superconducting H-Tc metamaterials



Optoelectronics Research Centre, University of Southampton

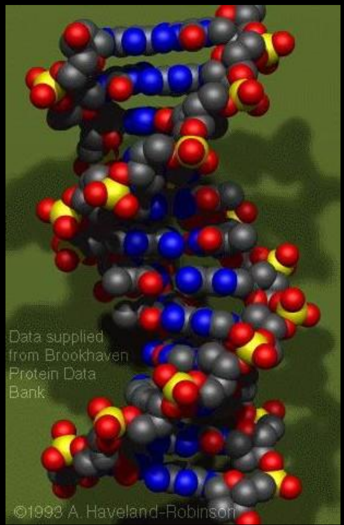
Photonic Metamaterials with engineered dispersion

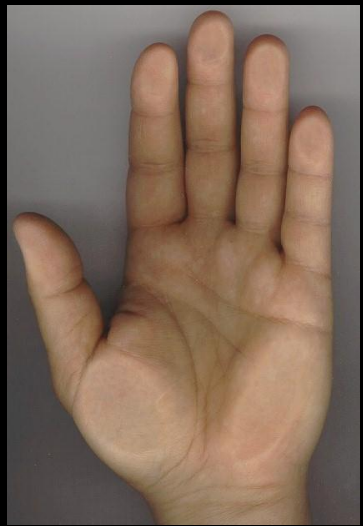
Goal:
Controlling optical properties

Applications:
Spectral filters
Delay lines
Dispersion compensation
Slow light

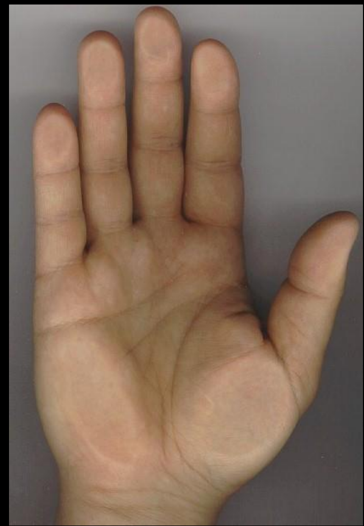
3D chirality (χιροσ)

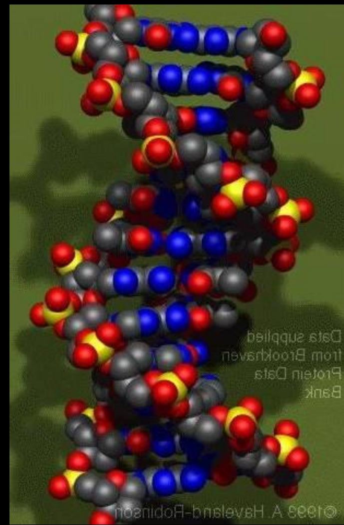
Enantiomeric forms of chiral structures

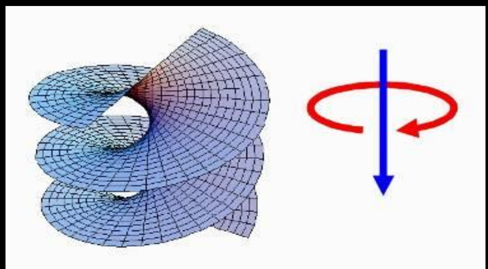


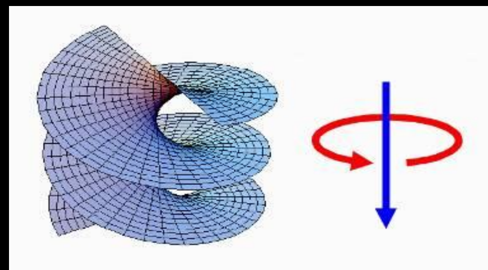


Plane of reflection





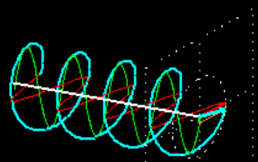




"Any man who, upon looking down at his bare feet, does not laugh, has either no sense of symmetry or no sense of humour" (Descartes)

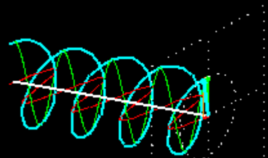
Optical Activity

In Vacuum



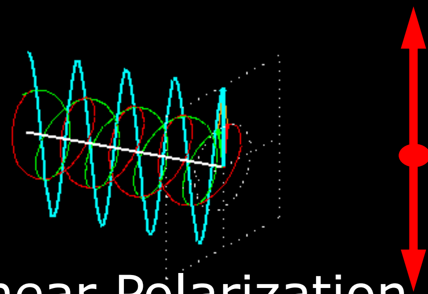
Right Helix

+

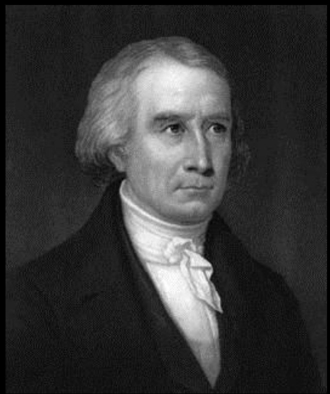


Left Helix

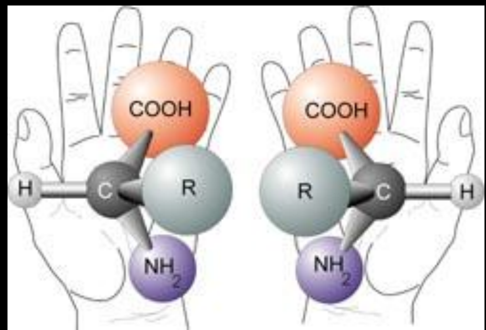
=



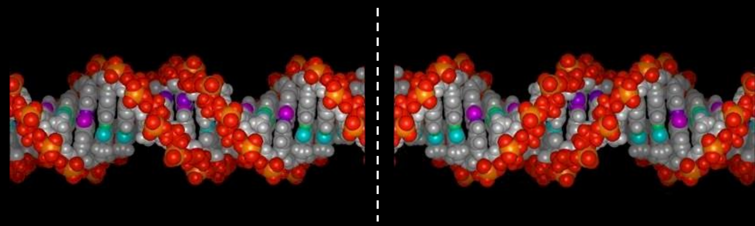
Linear Polarization



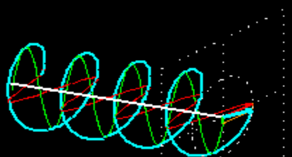
D. F. J. Arago
1786 - 1853



3D “Chiral” molecules

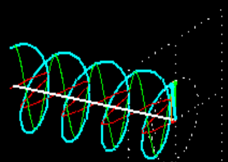


“Chiral” helix of DNA



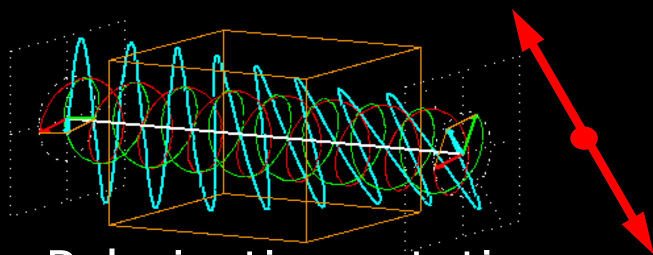
Right Helix
- fast -

+



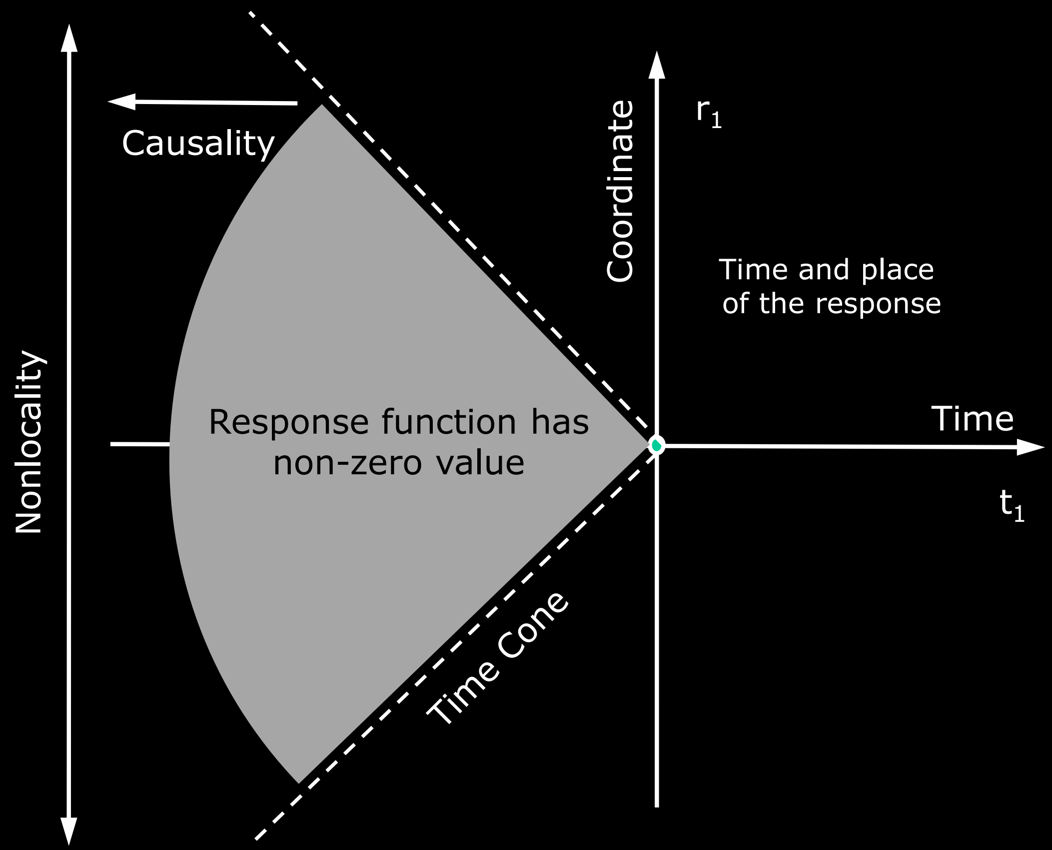
Left Helix
- slow -

=



Polarization rotation

Nonlocality & Causality of Optical Response & Constitutive Equation



Nonlocality   Causality

$$P_i(r,t)=\sum_{j=x,y,z}\int_V dr_j \int_{-\infty}^{t} dt_1 \psi_{ij}(r-r_1,t-t_1)\,E_j(r_1,t_1)$$

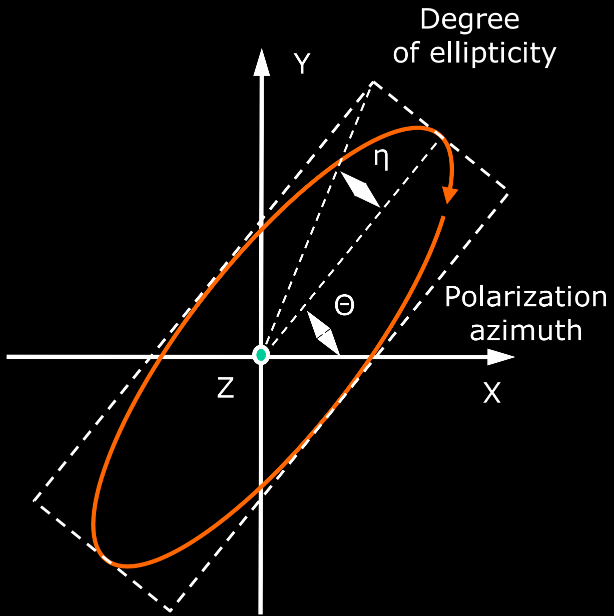
Response   Excitation

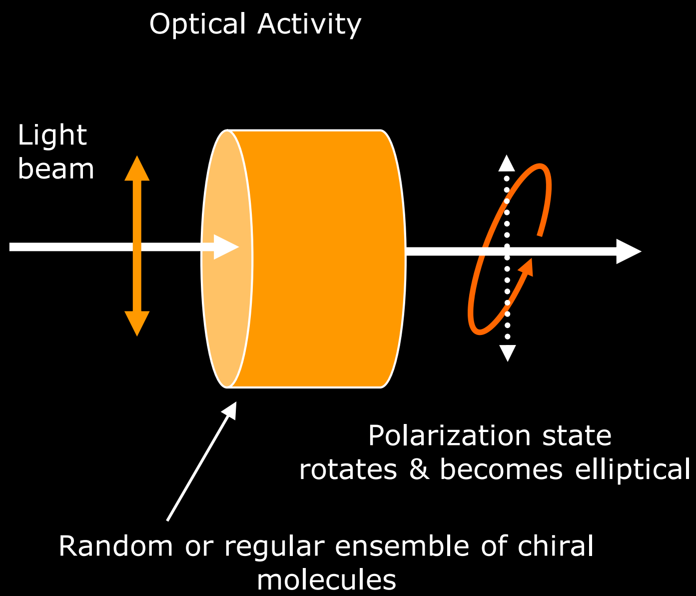
Constitutive equation

$$P_i(\omega)=\frac{1}{4\pi}\left(\varepsilon_{ij}-\delta_{ij}+i\,k_k\,\Gamma^{(1)}{}_{ijk}\right)E_j(\omega)$$

Optical Rotatory Power (optical activity) & Polarization

D. F. J. Arago and J-B. Biot at the beginning of the XIX century





Isotropic medium

$$\varepsilon_{ij} = \varepsilon\,\delta_{ij}$$

$$\Gamma^{(1)}{}_{ijk} = -\Gamma^{(1)}{}_{jik} = \Gamma\, e_{ijk}$$

Constitutive equation

$$P_i = \frac{1}{4\pi}\left(\varepsilon_{ij} - \delta_{ij} + i\,k_k\,\Gamma^{(1)}{}_{ijk}\right)E_j$$

$$\Theta = \Theta_0 + \frac{2\pi\,L}{\lambda^2}\,\mathrm{Re}\{\Gamma\}$$

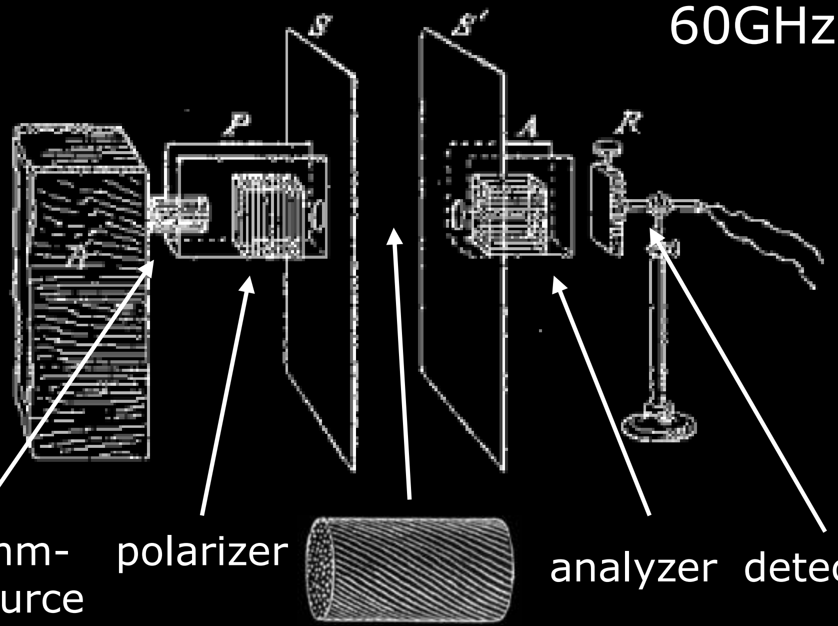
Polarization rotation

$$\eta = f\left(\mathrm{Im}\{\Gamma\}, L\right)$$

Induced ellipticity
(circular dichroism)

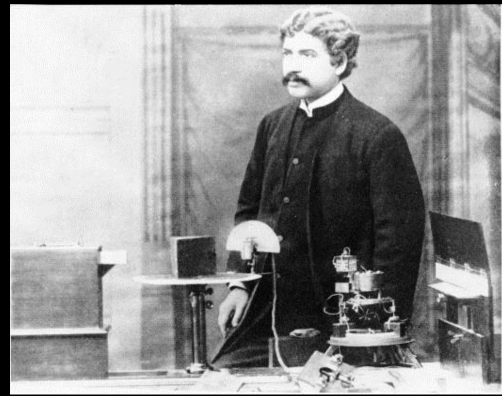
1^{st} Metamaterial (J.Bose, 1898)

"<u>In order to imitate</u> the rotation by liquids like sugar solutions, I made elements of <u>"molecules"</u> of twisted jute, of two varieties, one kind being twisted to the right (positive) and the other twisted to the left (negative)…"

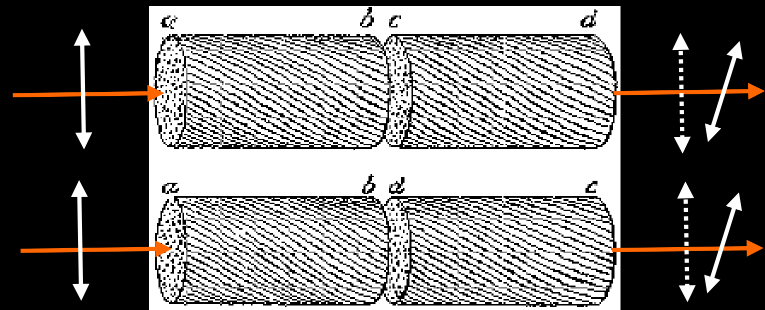


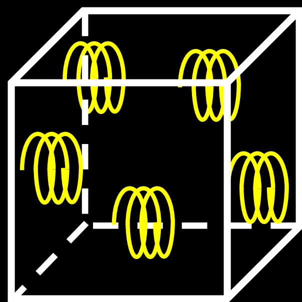
"The twisted structure [of jute] produces an optical twist of the plane of polarization"

J.Bose. Proc. Royal Soc. of London, **63**, 146 (1898)



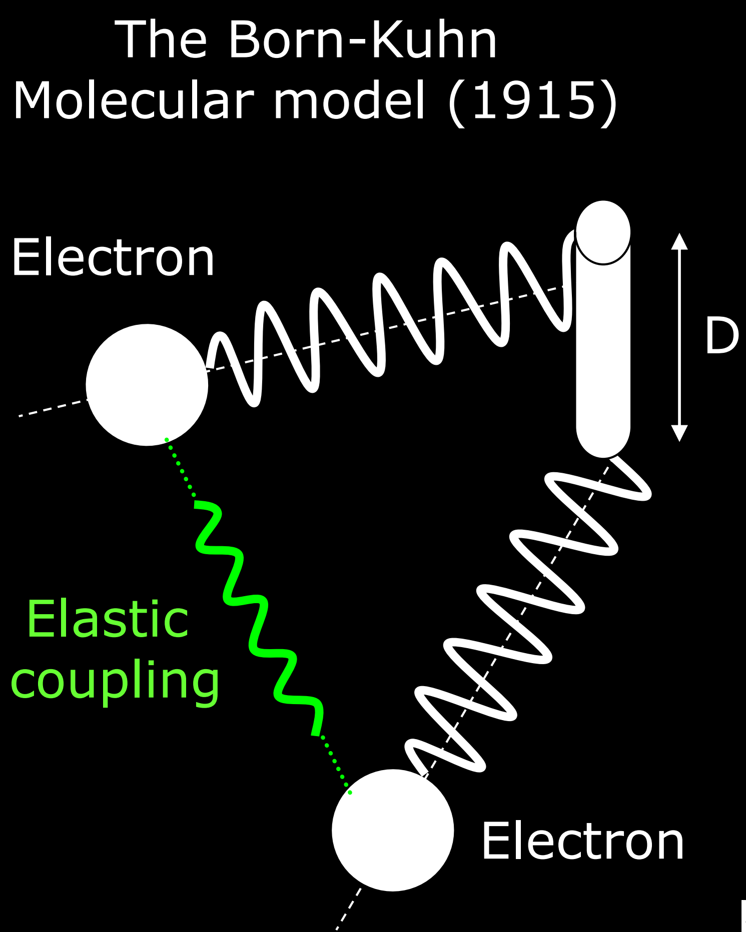
Polarization effect does not depend on the propagation direction

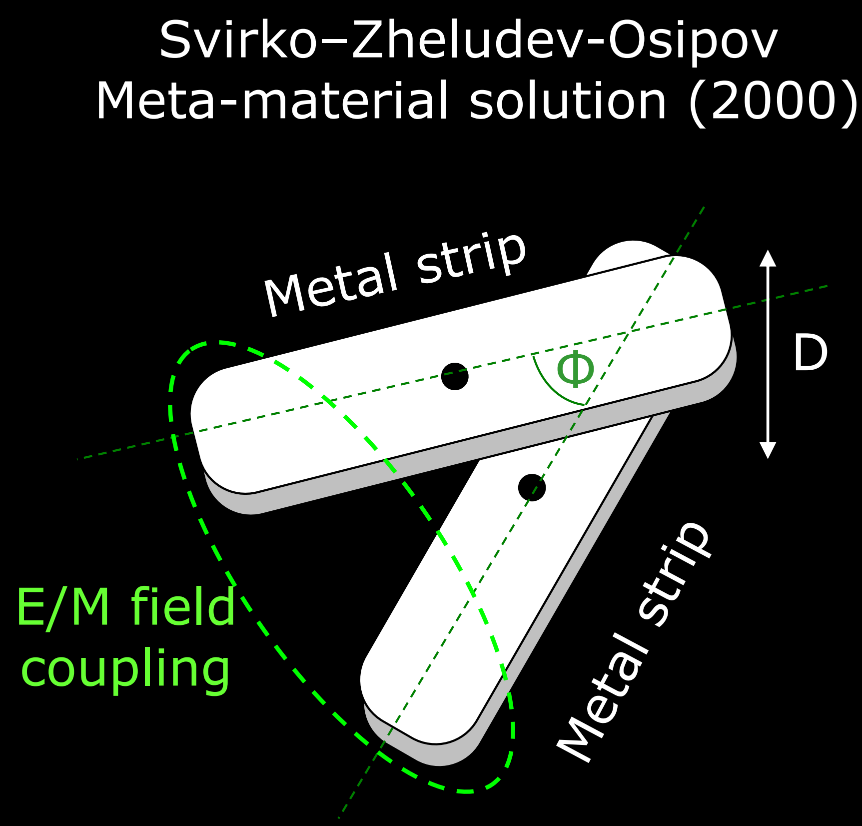


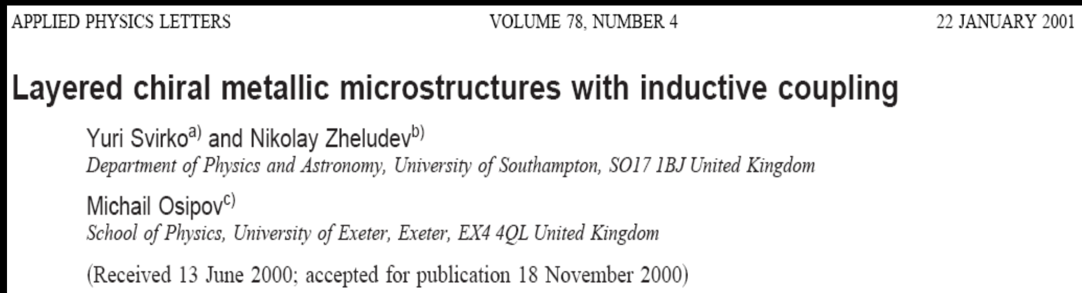


Karl Lindman (1920)

The First concept of Chiral Metal Metamaterial, 2000







APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 4 22 JANUARY 2001

Layered chiral metallic microstructures with inductive coupling

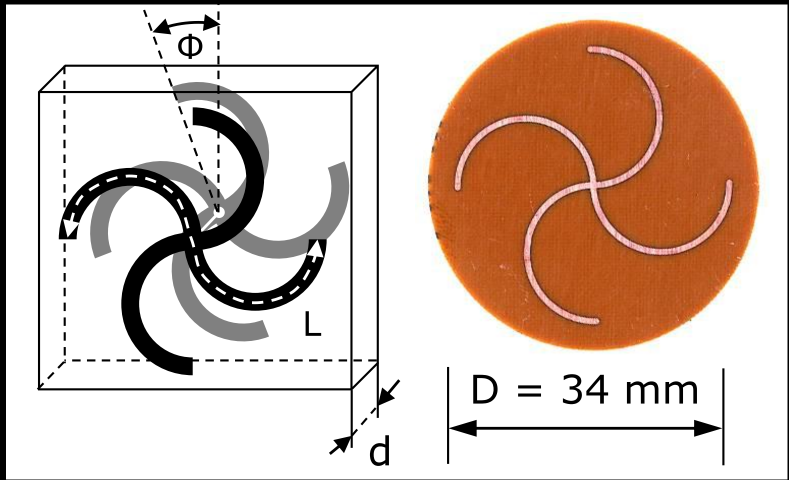
Yuri Svirko[a] and Nikolay Zheludev[b]
Department of Physics and Astronomy, University of Southampton, SO17 1BJ United Kingdom

Michail Osipov[c]
School of Physics, University of Exeter, Exeter, EX4 4QL United Kingdom

(Received 13 June 2000; accepted for publication 18 November 2000)

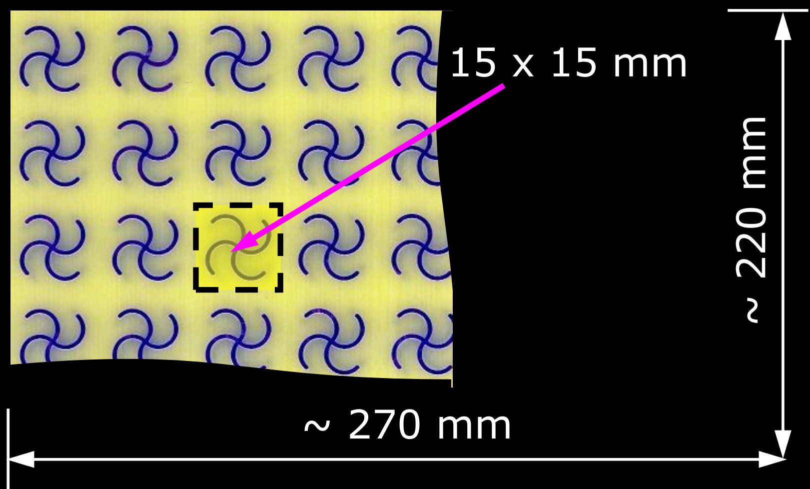
Microwave Chiral Metamaterails

Chiral Meta-molecule



Waveguide polarimeter

Chiral Metamaterial

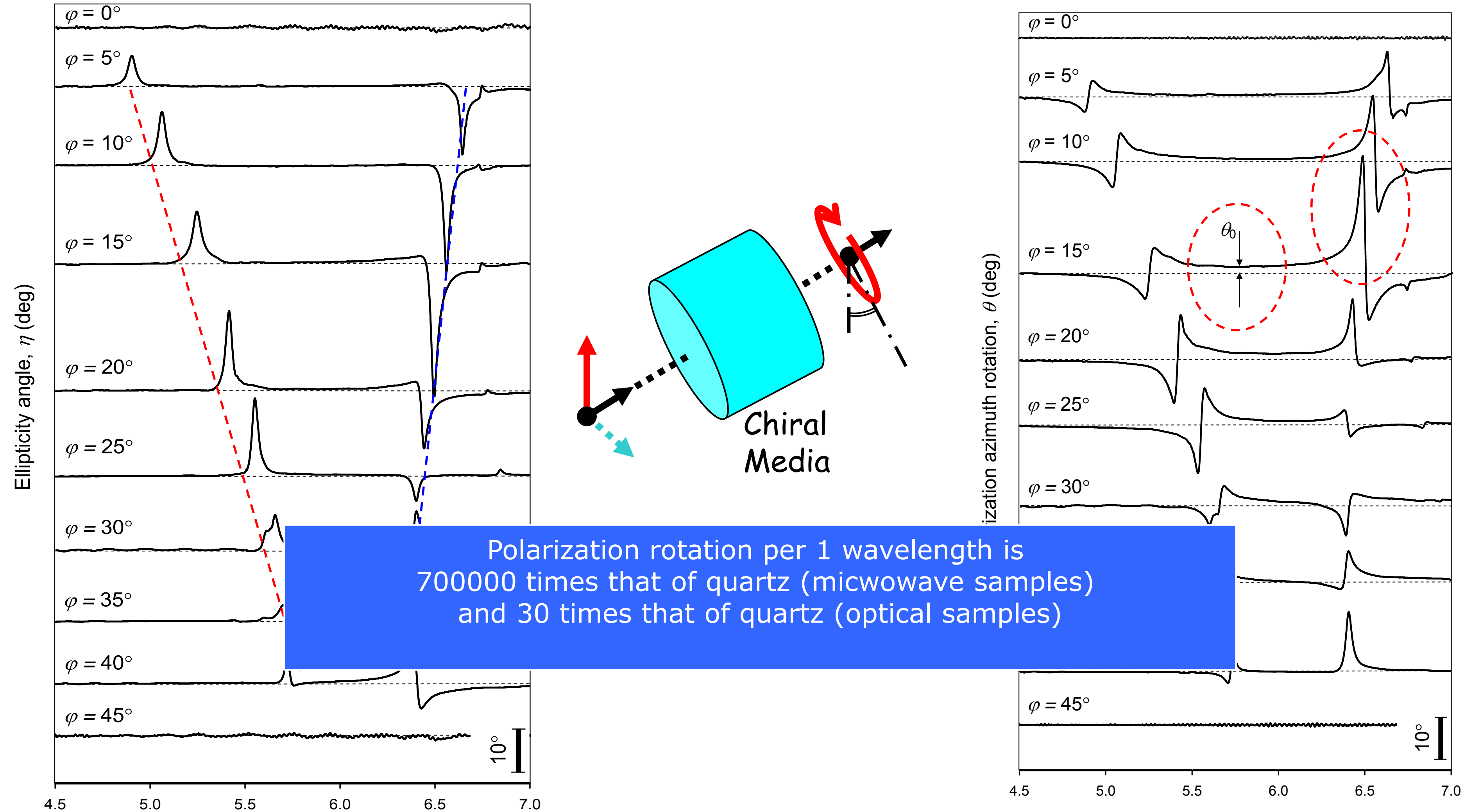


Anechoic chamber

Polarization rotation per 1 wavelength is 700000 times that of quartz (micwowave samples)
and 30 times that of quartz (optical samples)

Ellipticity and Polarization Rotation in Bi-layered Chiral Structure

Rogacheva, Fedotov,Schwanecke, and Zheludev. PRL, **97**, 177401 (2006)

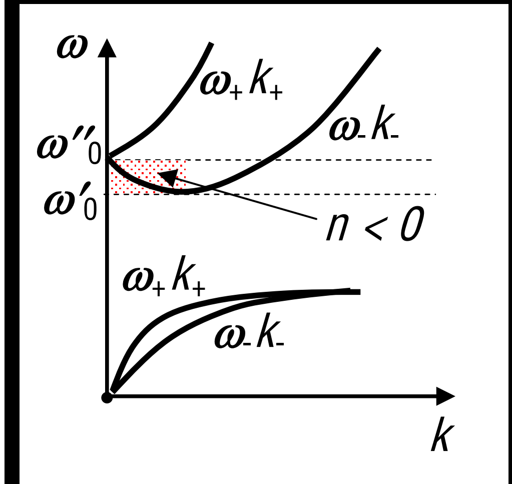


Polarization rotation per 1 wavelength is
700000 times that of quartz (micwowave samples)
and 30 times that of quartz (optical samples)

First Metamaterials Were Chiral

Rogacheva, Fedotov,Schwanecke, and Zheludev. PRL, **97**, 177401 (2006)

Chirality and Negative Refraction

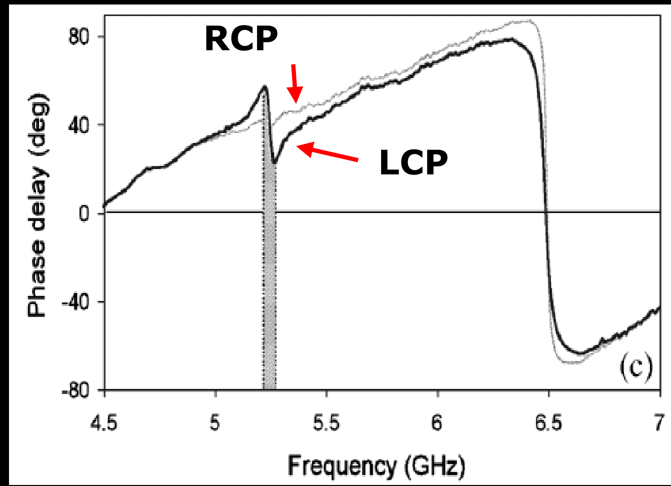


Tretyakov et al. (2003)
Pendry (2004)

In chiral materials strong chirality yields negative refraction for one circular polarization

$$\left(\frac{rotation}{ellipticization}\right) \propto N_0 \left(\frac{f(\omega)}{g(\omega)}\right) \mathrm{Im}\{R_{mn}\, d_{nm}\}$$

Phase delay in chiral metamaterial



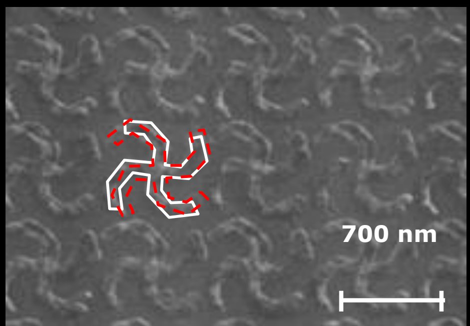
PRL 97, 177401 (2006) PHYSICAL REVIEW LETTERS week ending 27 OCTOBER 2006

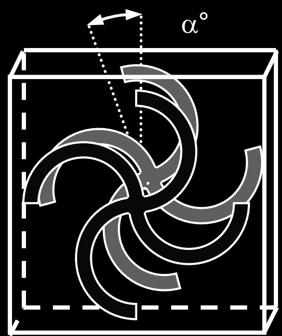
Giant Gyrotropy due to Electromagnetic-Field Coupling in a Bilayered Chiral Structure

A. V. Rogacheva, V. A. Fedotov,* A. S. Schwanecke, and N. I. Zheludev†

EPSRC NanoPhotonics Portfolio Centre, School of Physics and Astronomy, University of Southampton, SO17 1BJ, United Kingdom

(Received 7 April 2006; published 26 October 2006)





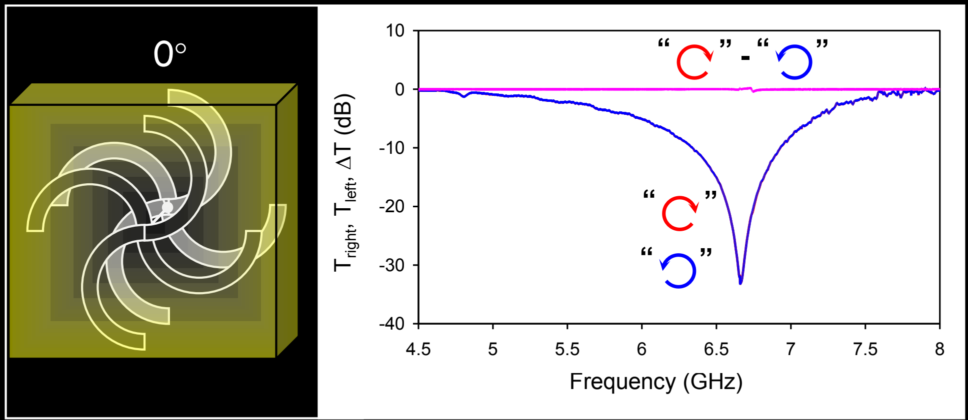
The first "stereo" photonics metamaterial (2007)

In the proximity of resonance the group velocity for right circular polarization in the sinistral structure has opposite sign to the phase velocity... this is a signature, or the necessary condition of negative refraction in chiral media.

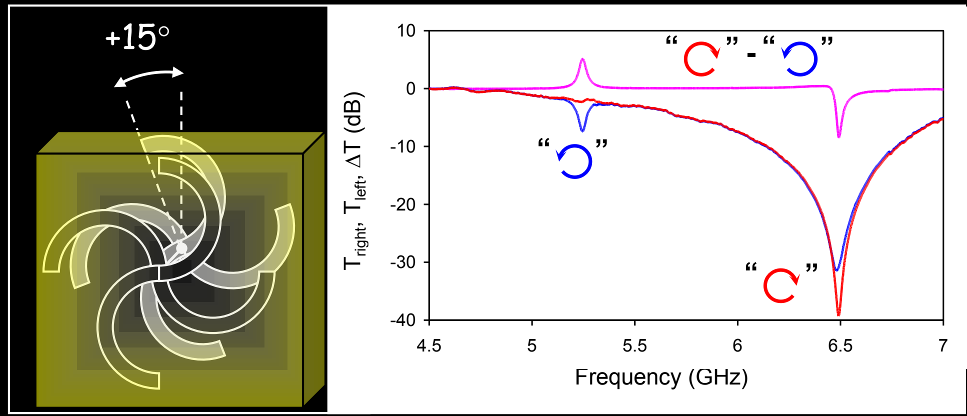
Plum, Zhou, Dong, Fedotov, Koschny, Soukoulis, Zheludev, *Phys. Rev. B* **79**, 035407 (2009)

Gyrotropy vs Chirality

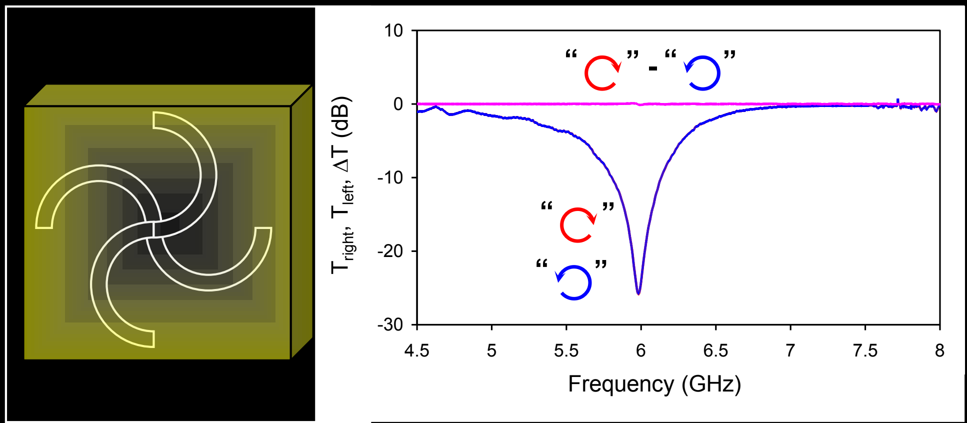
No gyrotropy



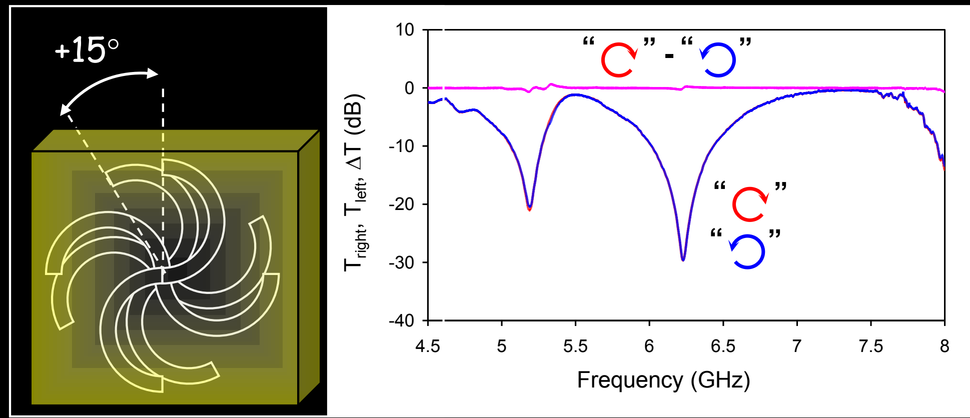
Yes gyrotropy



No gyrotropy



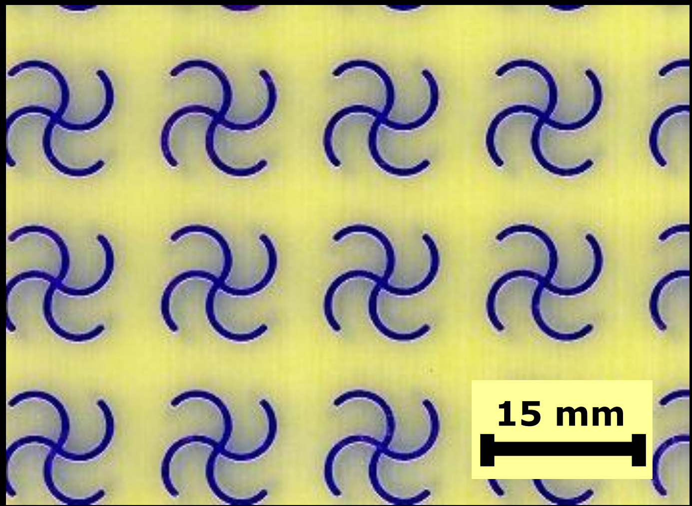
No gyrotropy



Polarization rotation per 1 wavelength is 700000 times that of quartz (micwowave samples) and 30 times that of quartz (optical samples)

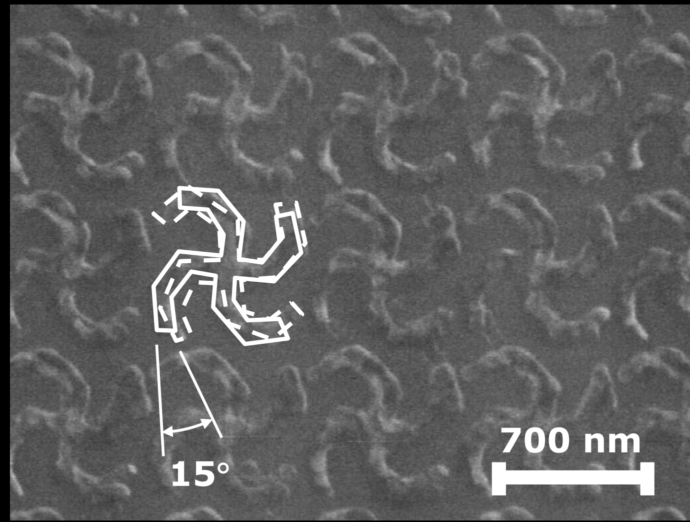
Light

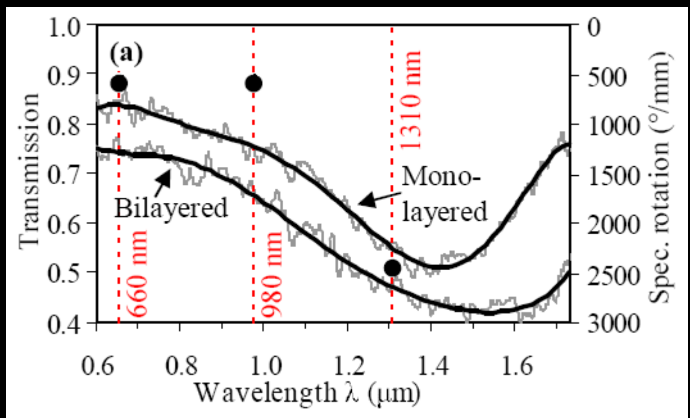
Photonic Chiral Bilayered (Stereo) Metamaterial

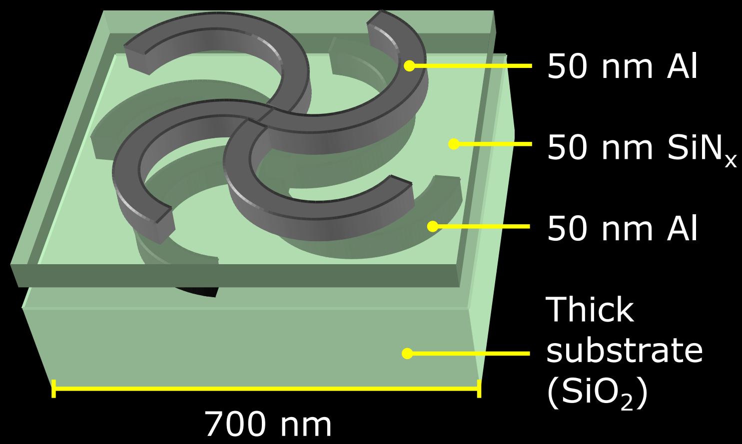


Scaling
1 : 21429

MW → near-IR



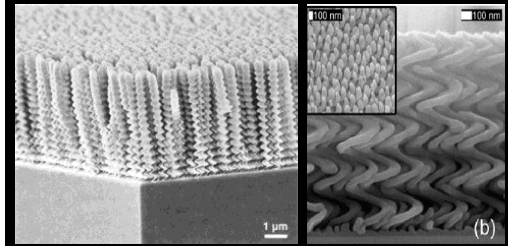




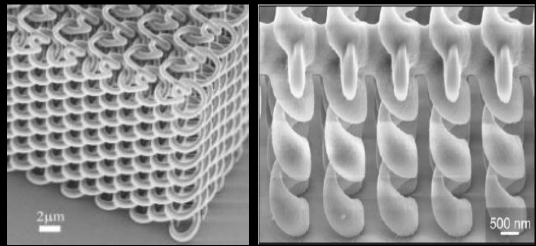
Fedotov, Plum, Schwanecke, Chen and Zheludev. APL **90**, 223113 (2007)

Key experimental results in 3D chiral metamaterials

Sculptured chiral photonic films & PCs

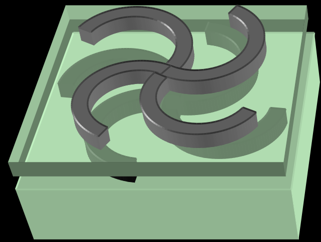


Young and Kowal (1956)
Robbie, Brett, Lakhtakia (1996)
Hrudey, Szeto, Brett (2006)



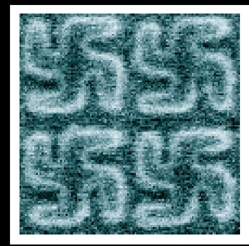
Kennedy, John et.al (2002)
Seet, Misawa et al (2005)
Pang, Sheng et.al (2005)
Thiel, Wegener et al (2007)

Negative refraction & NI in microwave Chiral MM



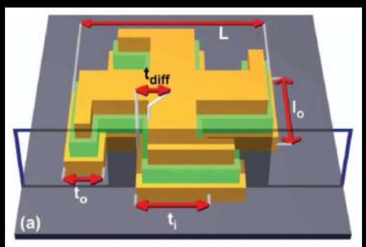
Rogacheva, Zheludev et al (2006)
Plum, Soukoulis, Zheludev (2009)

Gyrotropy in single-layered MM



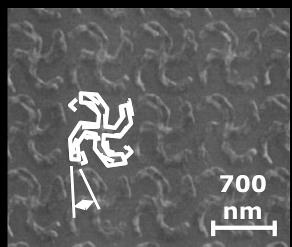
Kuwata-Gonokami et al (2005)

Strong dichroism in bi-layered structure



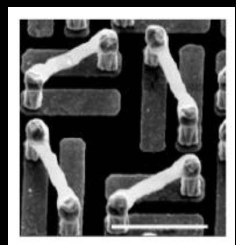
Decker, Wegener et al. (2007)

Stereo photonic metamaterials



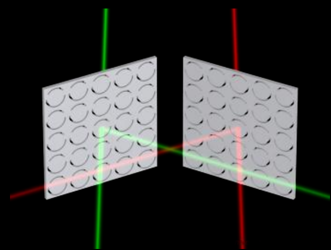
Plum, Zheludev et al (2007)

NI in THz



Zhang et al (2009)

Extrinsic Chirality & NR



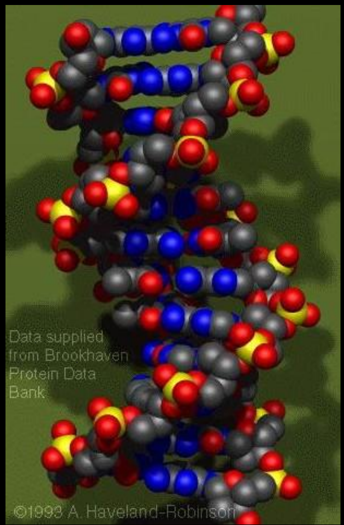
Plum, Zheludev et al (2008)

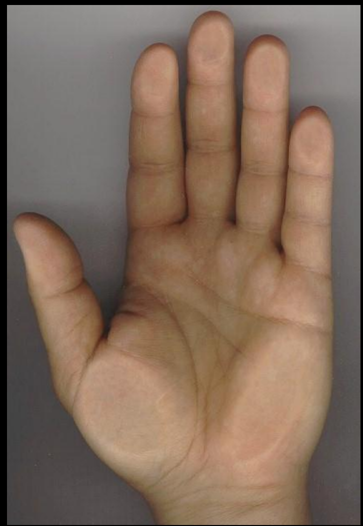
Volume Chiral NI Metamaterial

Wang, Souloulis et al (2009)

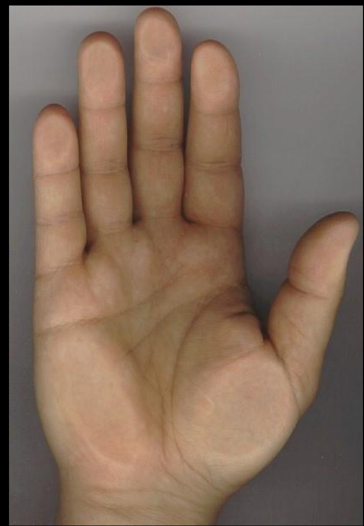
3D chirality (χιροσ)

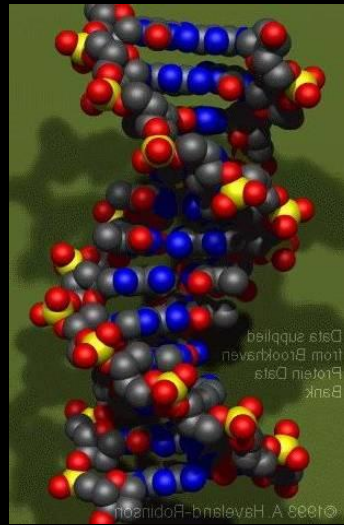
Enantiomeric forms of chiral structures

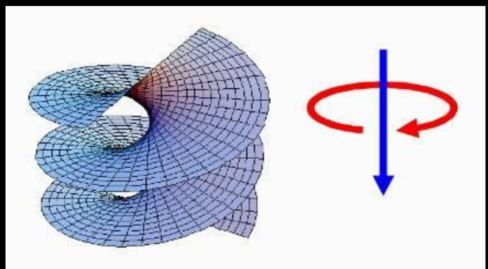


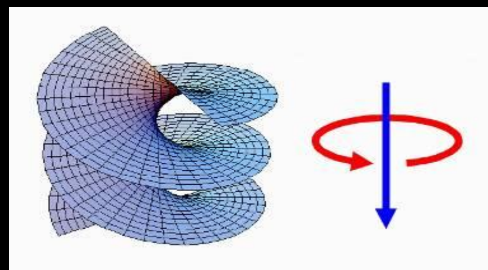


Plane of reflection









"Any man who, upon looking down at his bare feet, does not laugh, has either no sense of symmetry or no sense of humour" (Descartes)

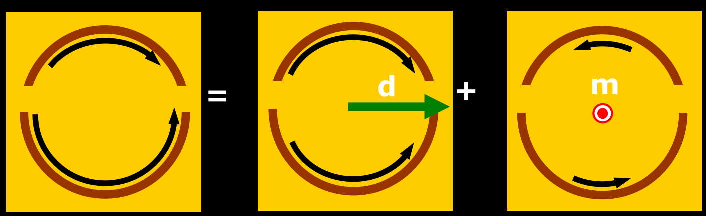
Is Molecular Chirality Needed for Optical Activity?

In randomly oriented ensembles of molecules molecular chirality IS needed for optical activity

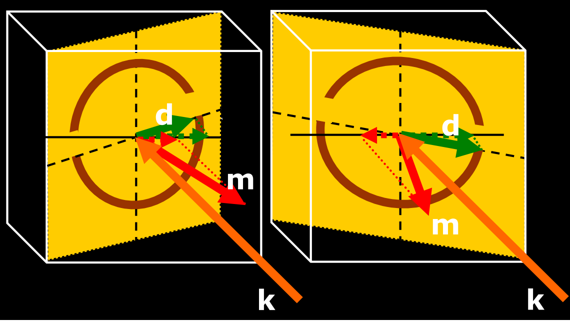
Intrinsic chirality
depends on symmetry of the medium

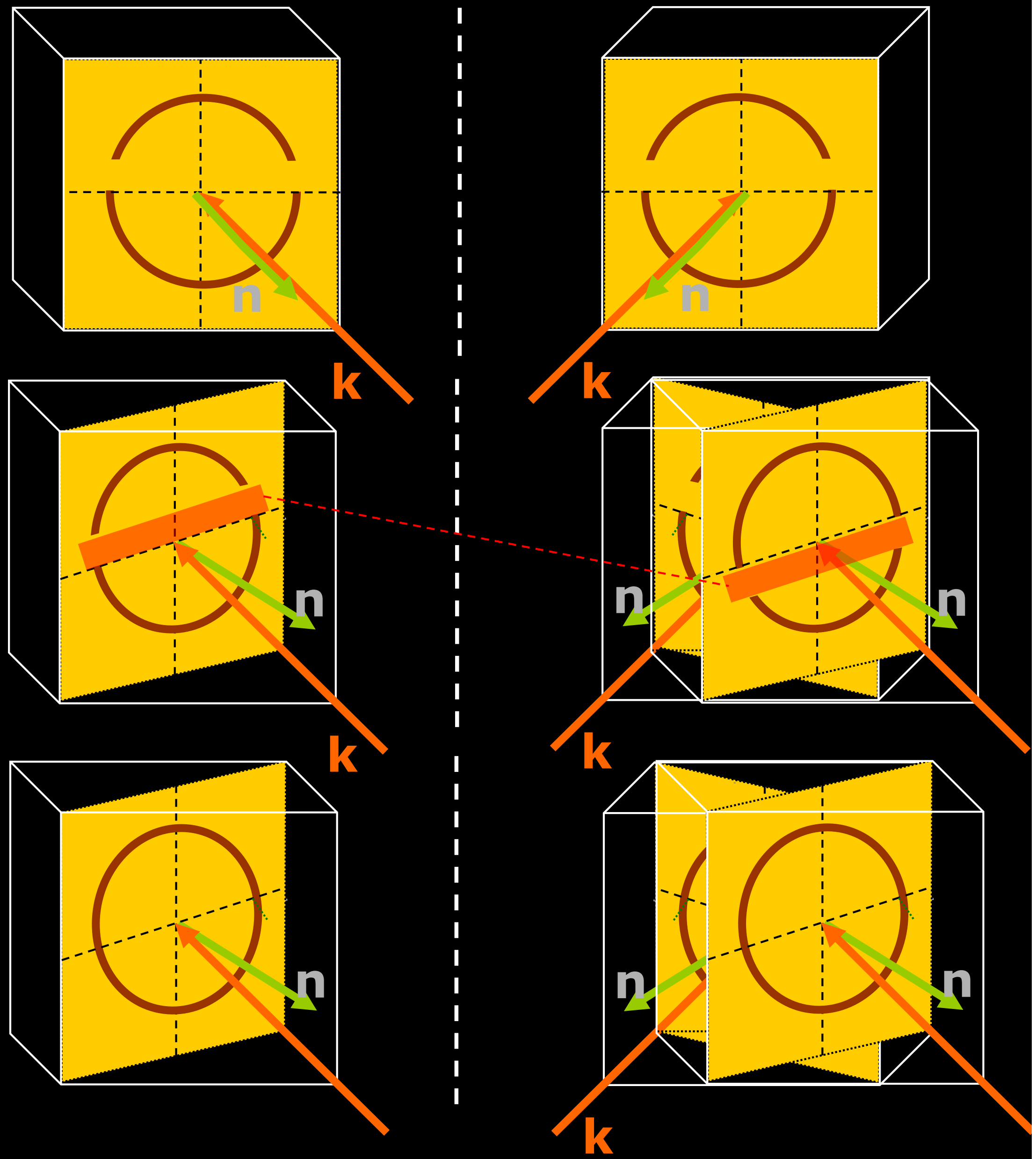
In ordered structures (crystal, meta-material) optical activity will be seen along a “screw direction” of light propagation

Extrinsic chirality
depends on combined symmetry of the medium and light wave



Oblique incidence

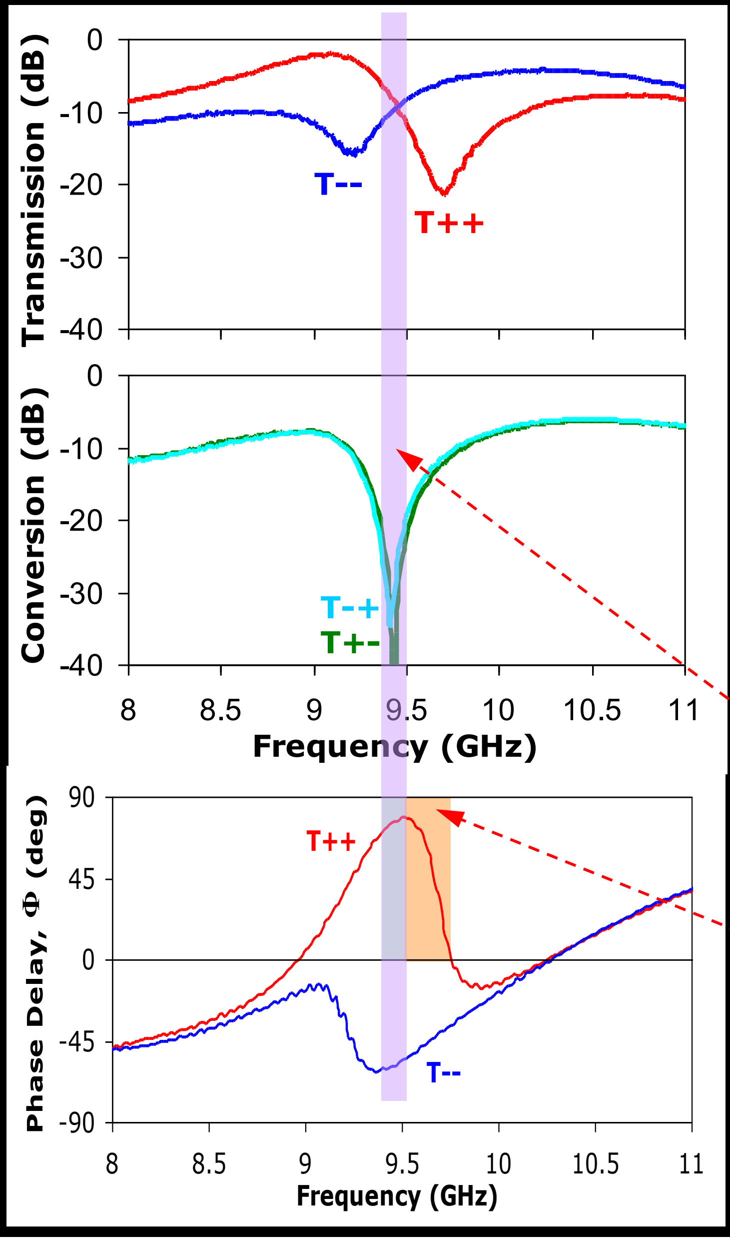


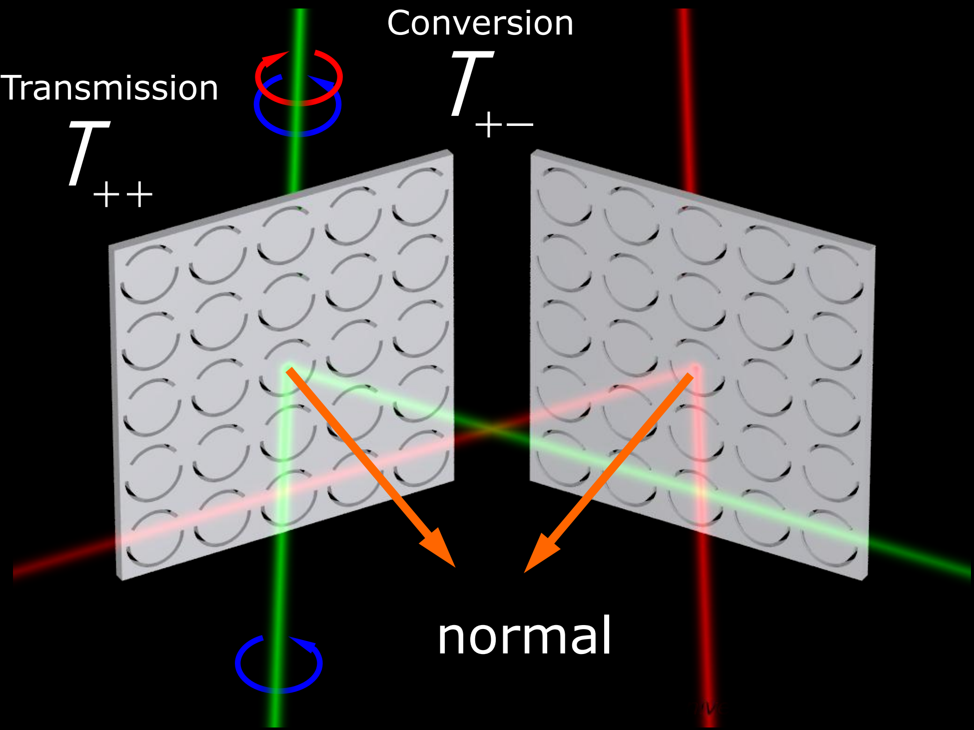


Metamaterials: optical activity without chirality

Plum, Liu, Fedotov, Chen, Tsai, and Zheludev, *PRL* **102**, 113902 (2009)

Extrinsic Chirality in Asymmetrically Split-ring Metamaterial



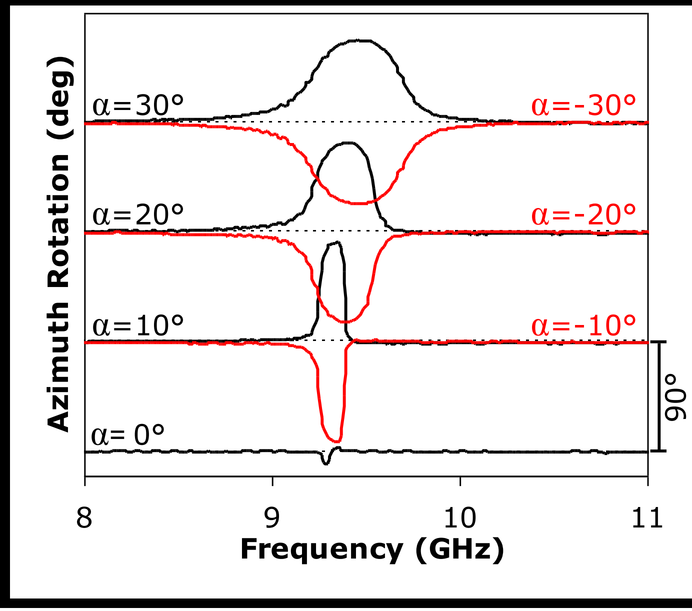


Almost circular eigenstates:

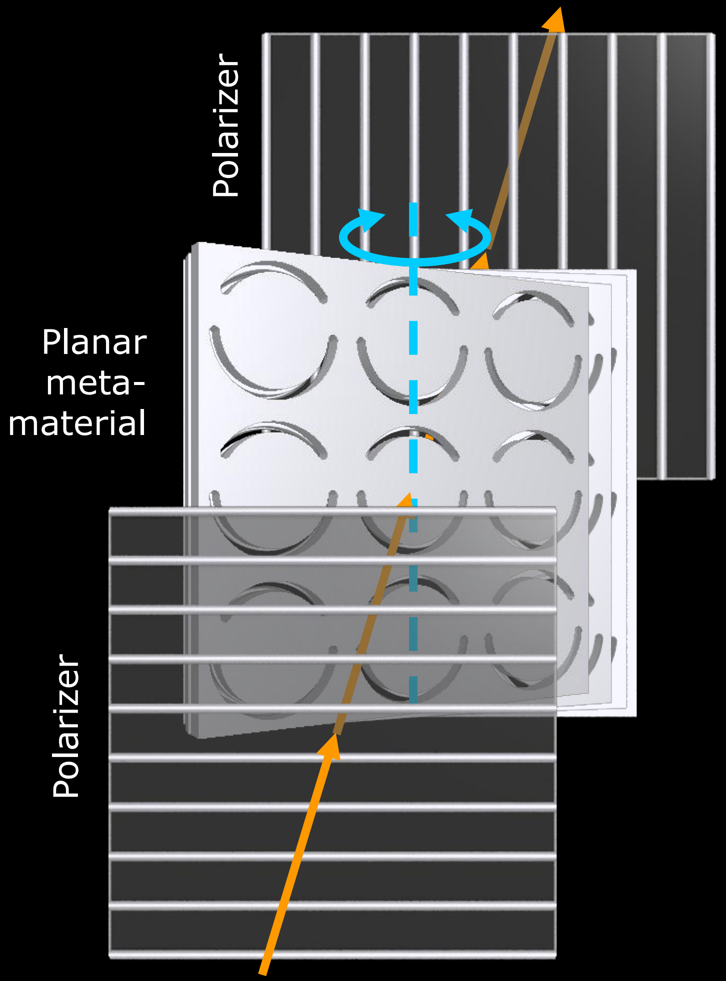
true optical activity

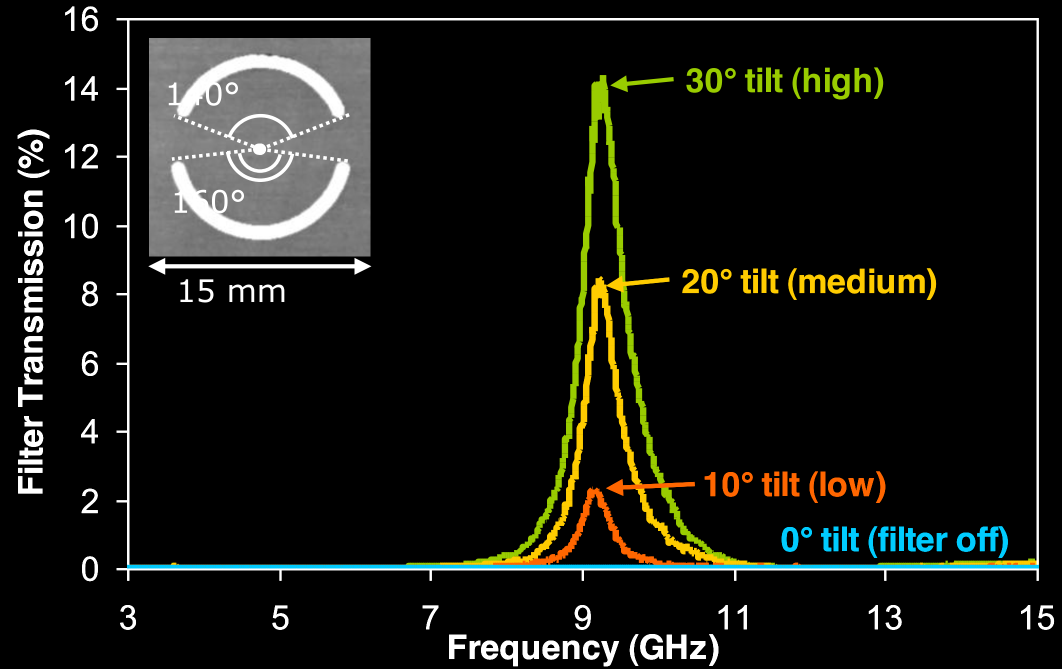
Negative

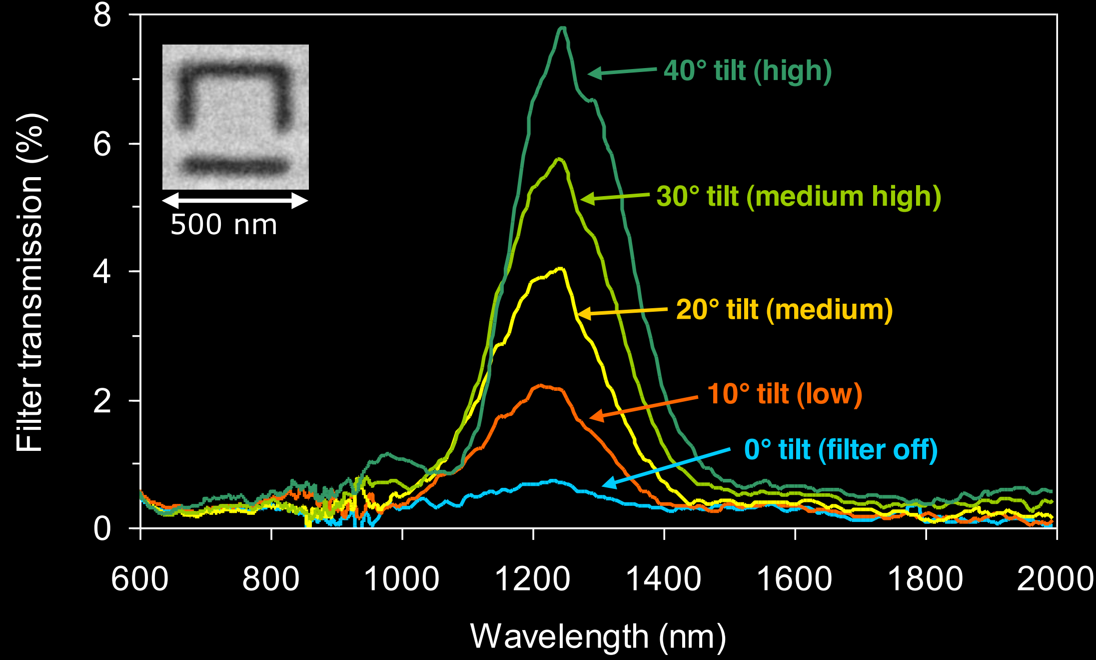
group velocity



Metamaterial isoindex chiral microwave, and optical filters



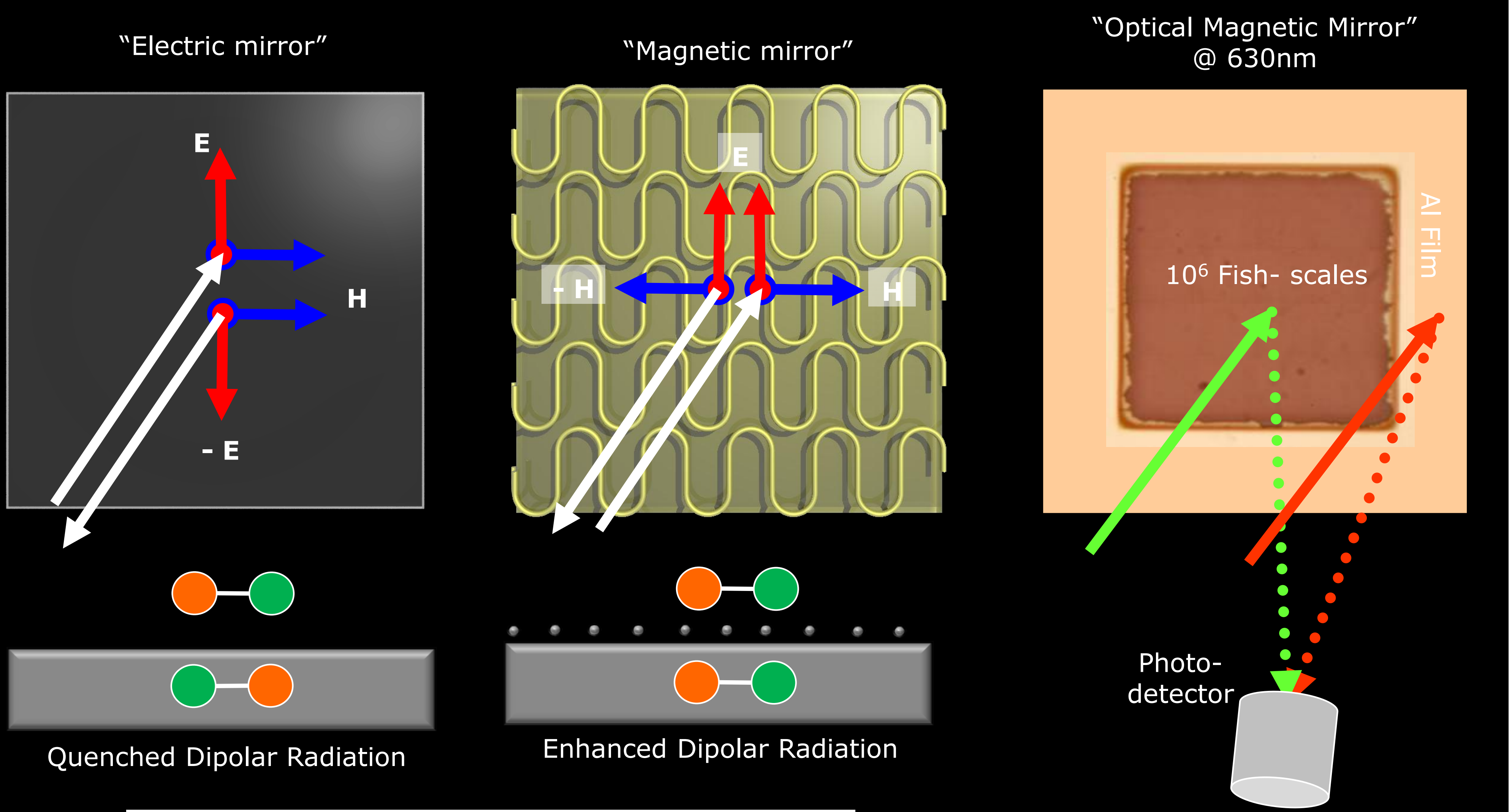




Tunable throughput
Well-isolated pass-band
simple planar metamaterial
Q-factors of >700 are achievable

Magnetic Mirror

Metamaterial Optical Magnetic Mirror (2005-2007)



APPLIED PHYSICS LETTERS **88**, 091119 (2006)

Mirror that does not change the phase of reflected waves

V. A. Fedotov, A. V. Rogacheva, and N. I. Zheludev[a)]

J. Opt. A: Pure Appl. Opt. **9** (2007) L1–L2

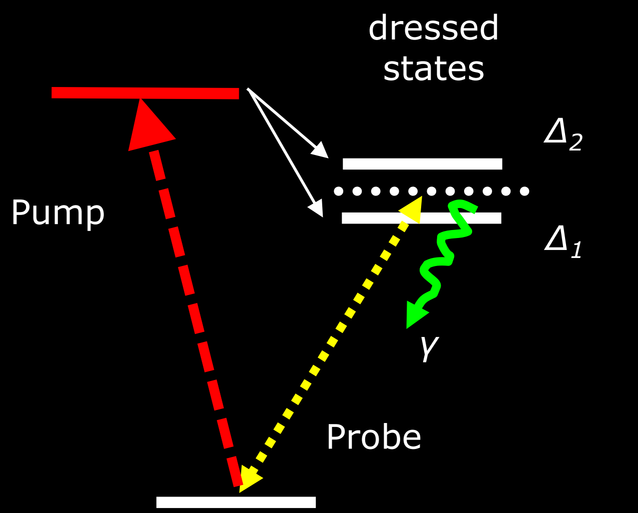
RAPID COMMUNICATION

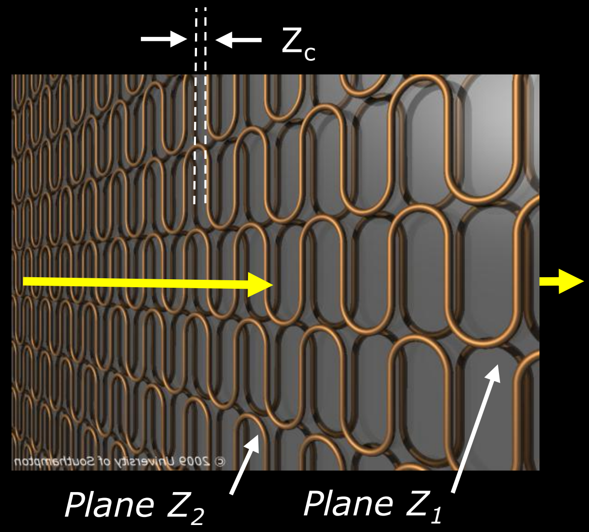
Optical magnetic mirrors

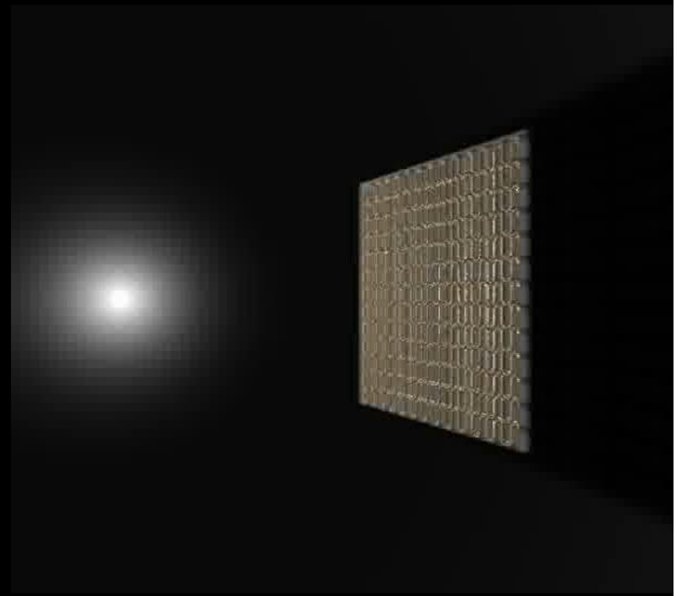
A S Schwanecke[1], V A Fedotov[1], V V Khardikov[2], S L Prosvirnin[2], Y Chen[3] and N I Zheludev[1]

Loss enhancement &
Optical Analogue of the Meissner effect (superconductivity)

Metamaterial Analog of EIT (2007)







Absorption Losses ~ $\dfrac{(\Delta_1+\Delta_2)^2}{\gamma^2\,(\Delta_1+\Delta_2)^{2}+(4\Delta_1\Delta_2)^2}$

Reflection Losses ~ $\dfrac{|Z_1+Z_2|^2}{|Z_c(Z_1+Z_2)+Z_1Z_2|^2}$

Quantum interference of probability amplitudes

Classical interference of electromagnetic fields

Slow light in metamaterials

PRL 101, 253903 (2008) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2008

Metamaterial Analog of Electromagnetically Induced Transparency

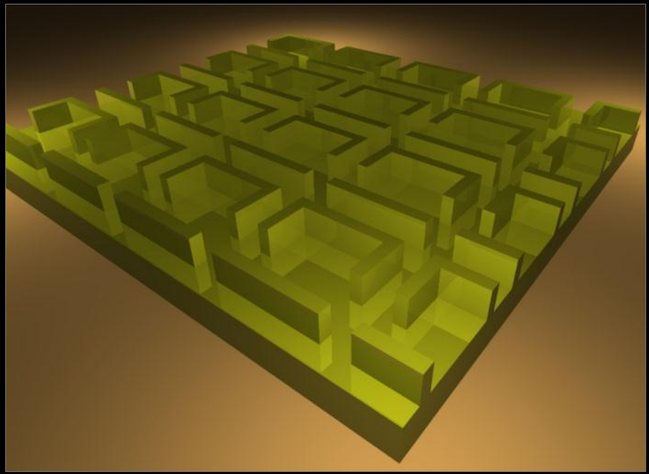
N. Papasimakis,* V. A. Fedotov, and N. I. Zheludev

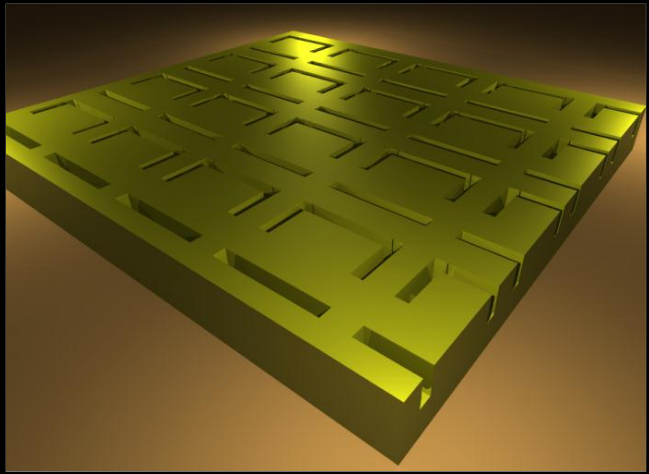
New classes of metamaterial: Bas-relief & Intaglio (2010)

(Continuous metallic metamaterials)

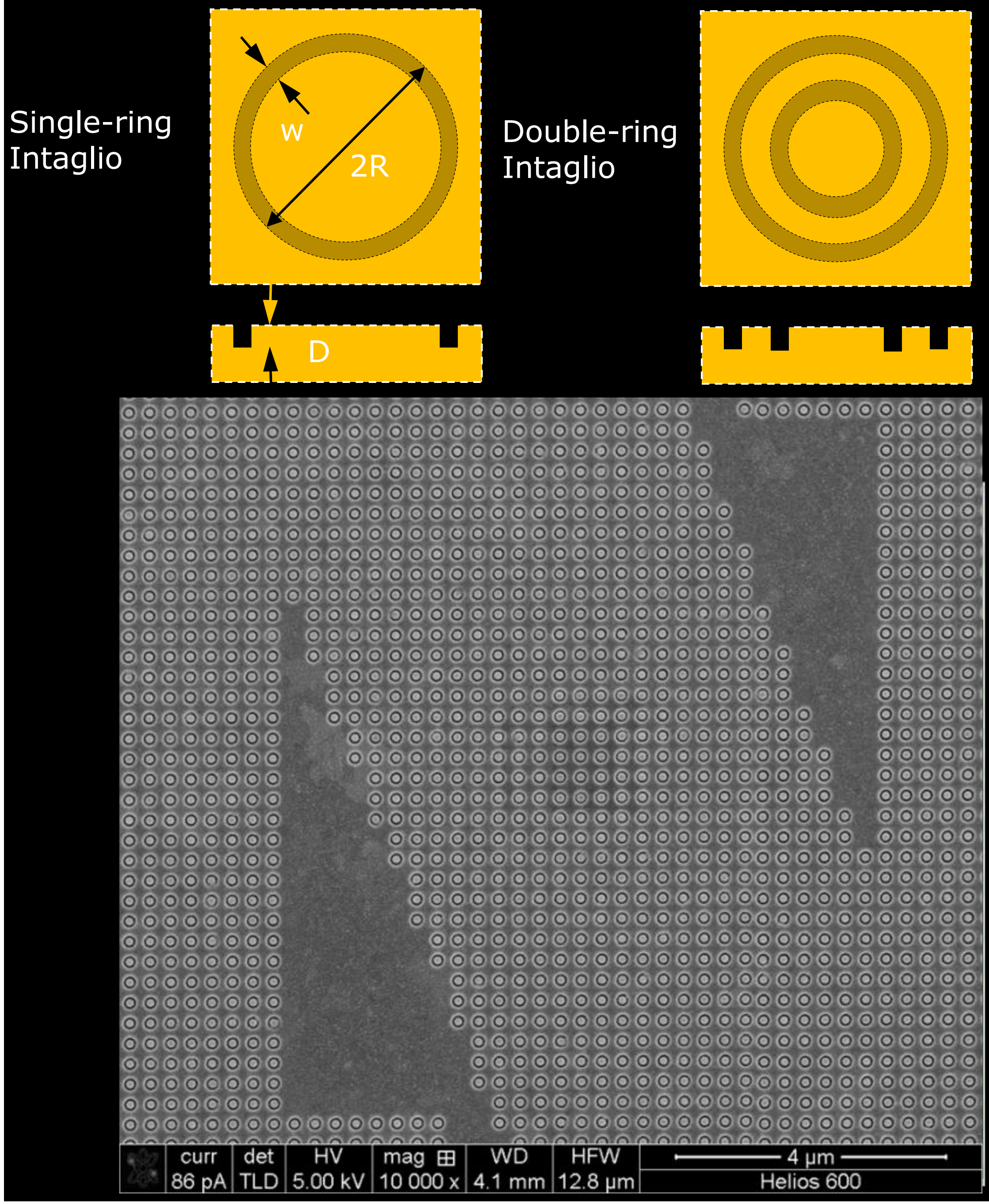
Bas-relief: Pattern raised above surface of the same material

Intaglio: Pattern inscribed in (not cut through) surface

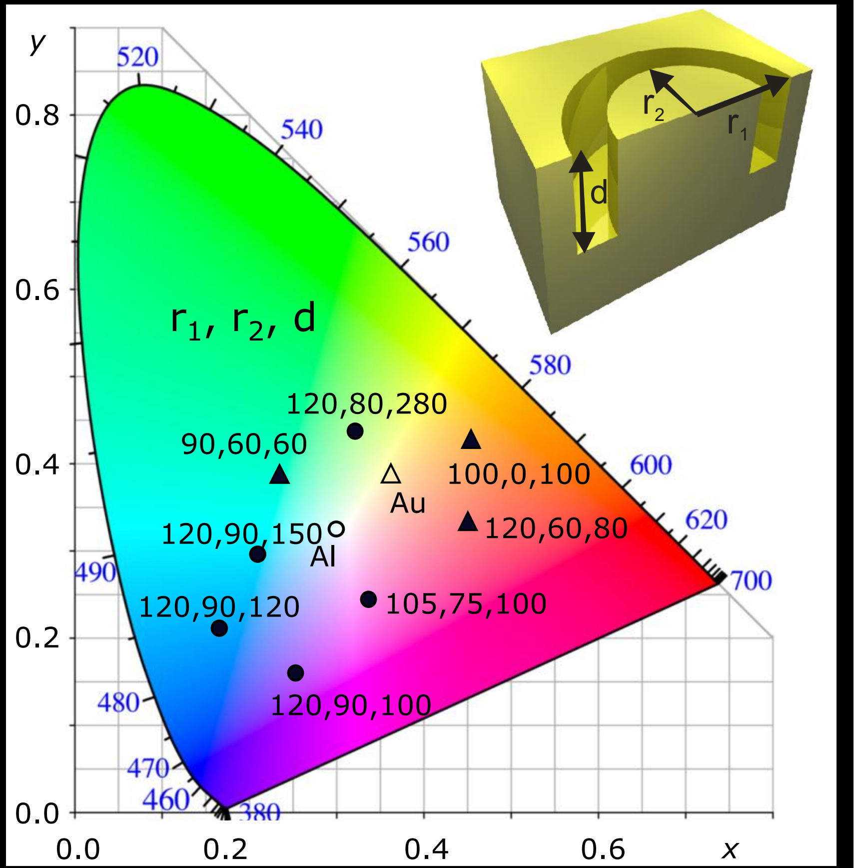




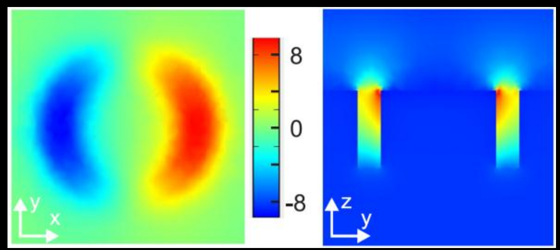
Bas-relief & Intaglio Metamaterials: Colour by design



International Commission on Illumination CIE1931 colour space chromaticity diagram



Plasmonic mode in intaglio Metamaterial



Would it be nice to have ...?

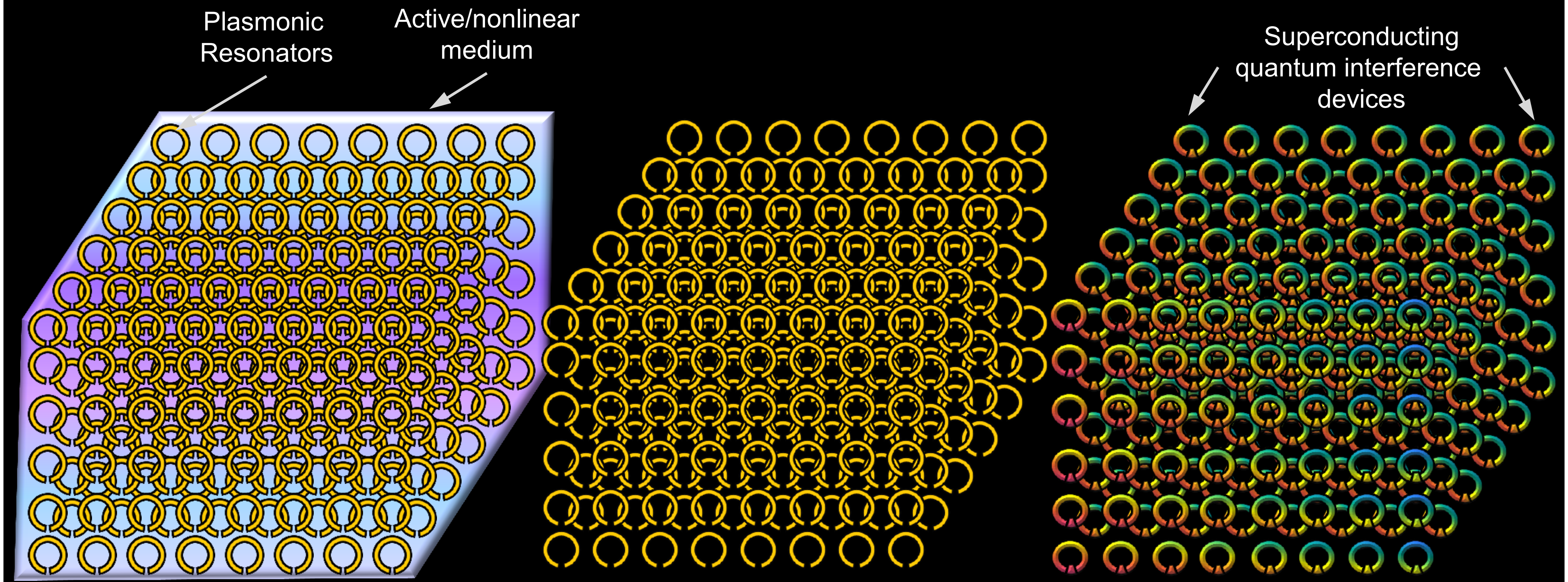
Tuneable magnetic mirror (for specroscopy ...)

Tuneable delay line (for telecoms ...)

Tuneable colour (for my watch dial ...)

Tuneable spectral filter (for my camera ...)

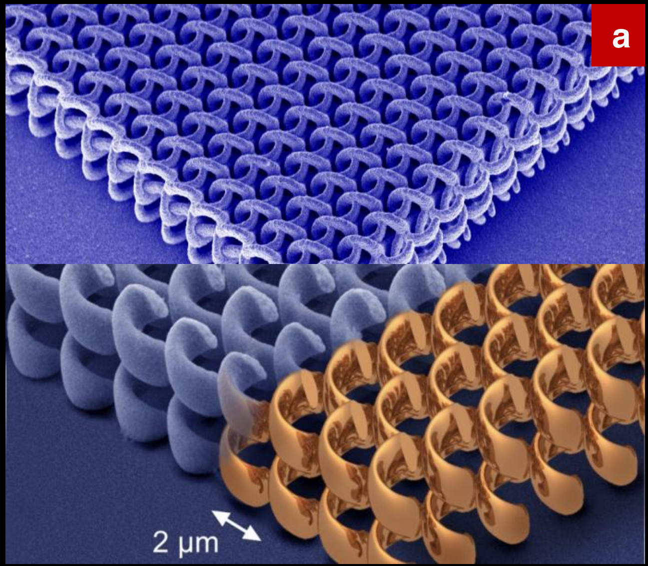
Metamaterials: mimicking Nature, step 2



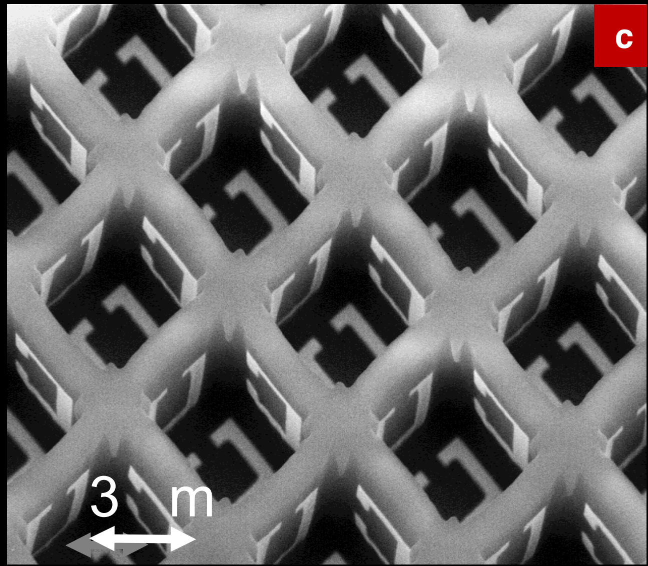
Electromagnetic Metamaterial

Reconfigurable metamaterial

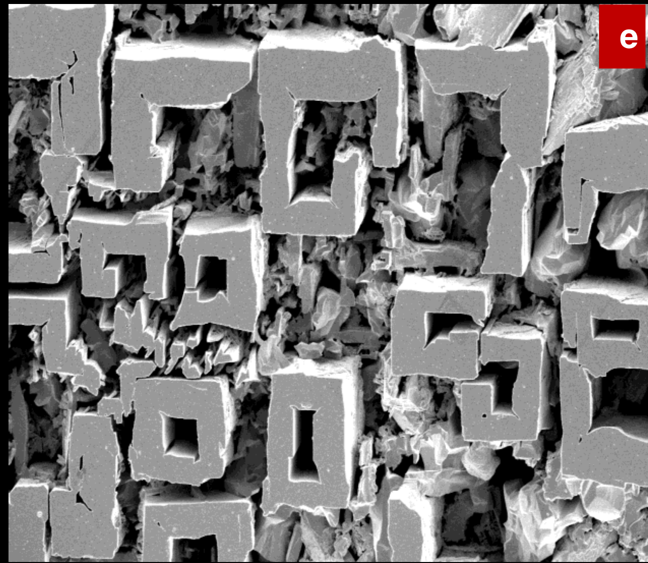
"Quantum" Metamaterial



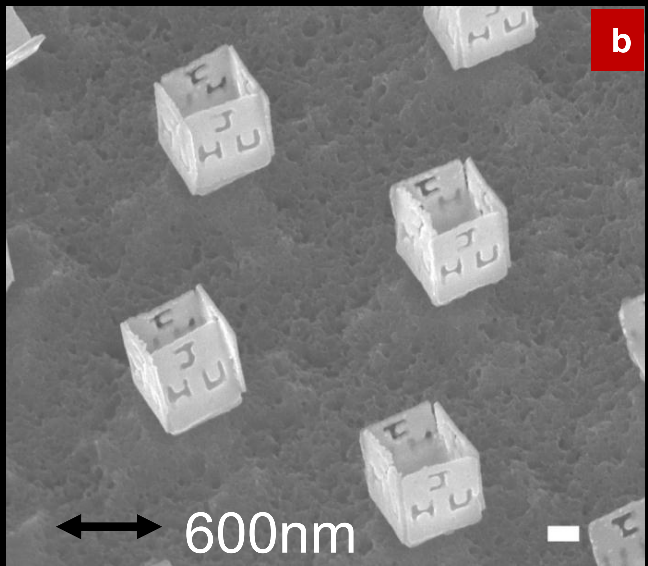
Laser Lithography,
Stuttgart & Karlsruhe



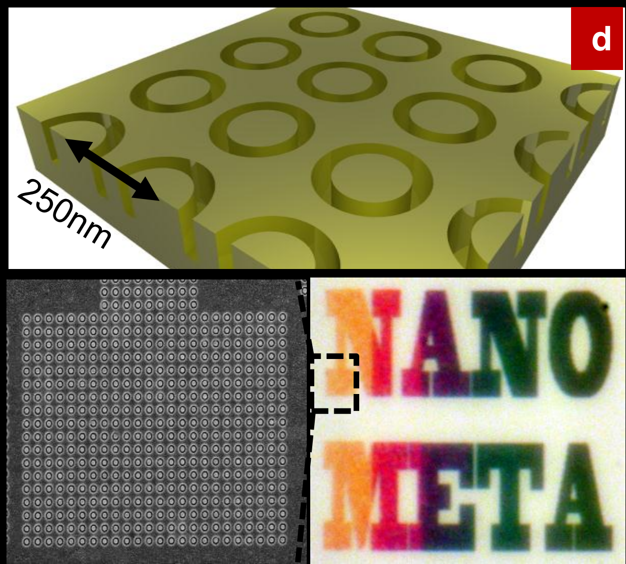
Projection lithography,
Sandia



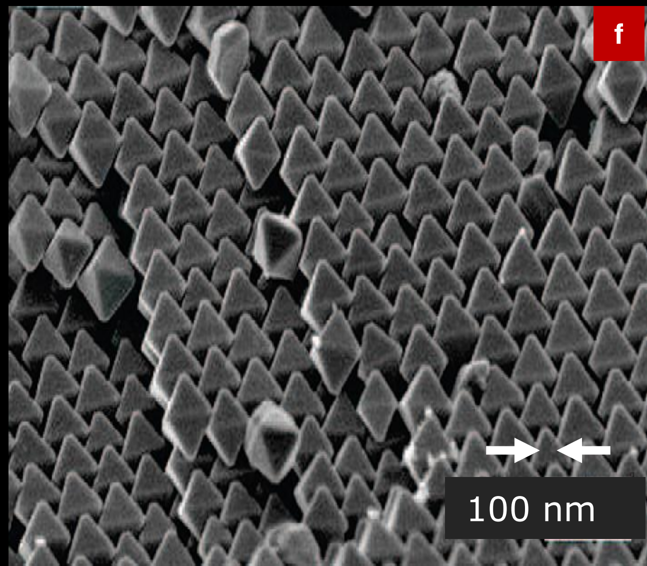
Directional solidification of eutectic,
IEM, Warsaw



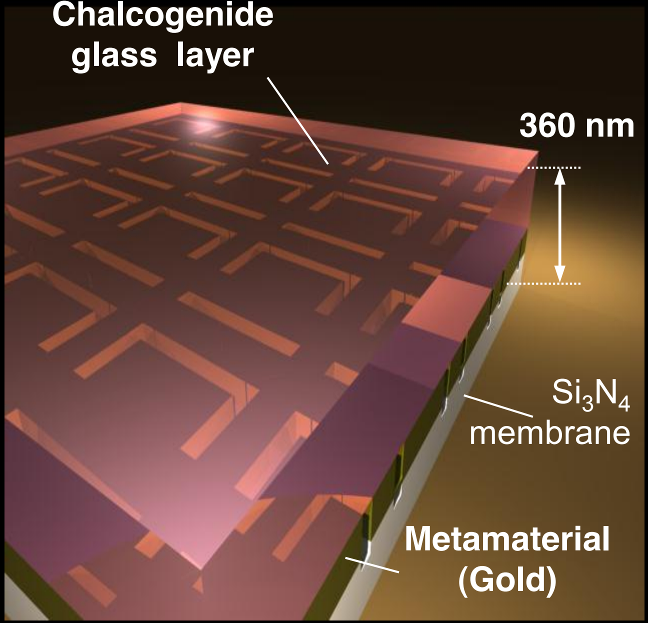
Self-assembled hinged pattern,
John Hopkins



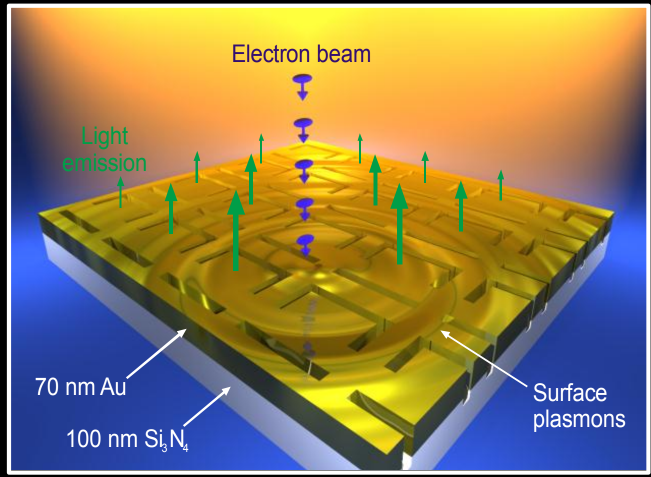
"Intaglio" all-metal metamaterial,
Southampton



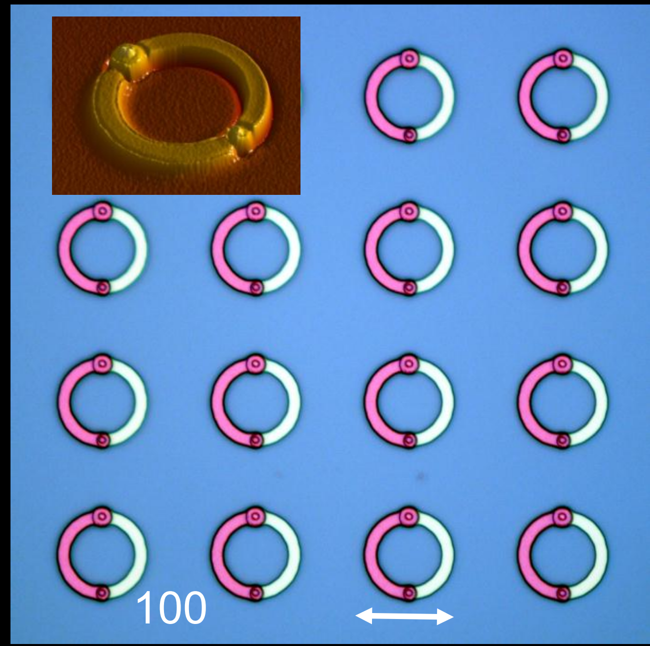
Colloidal nanocrystal arrays,
Berkeley



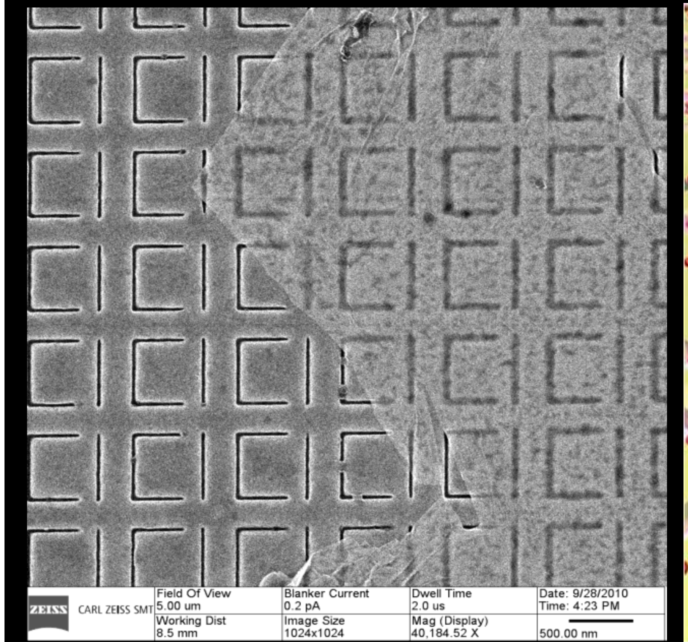
Switchable metamaterial (ChG), Southampton



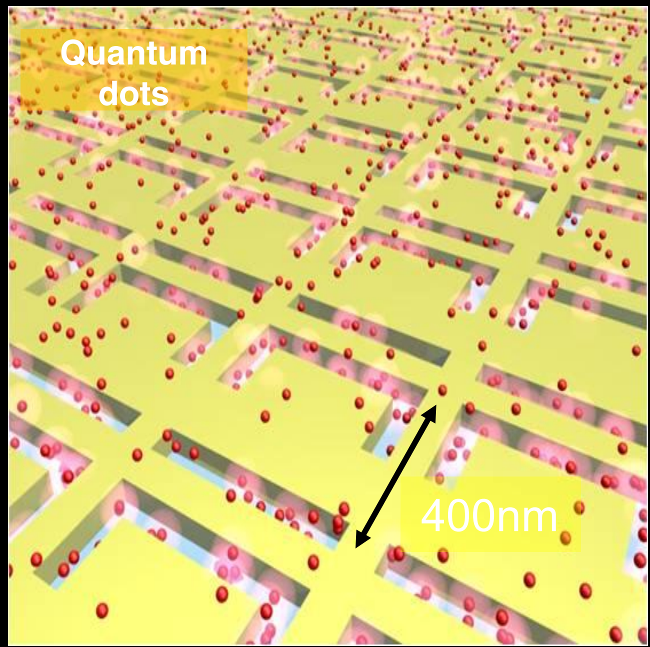
Electron-beam driven light source Southampton



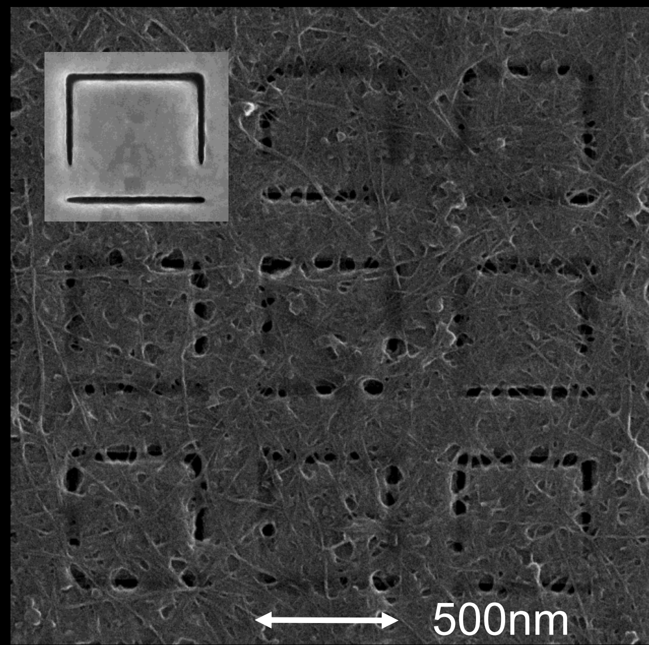
Quantum metamaterial, Southampton



Nonlinear metamaterial & Graphene Southampton & NTU, Singapore



Switchable metamaterial (QDs), Southampton



Nonlinear metamaterial (CNTs), Southampton

MEMS & NEMS reconfigurable Metamaterials

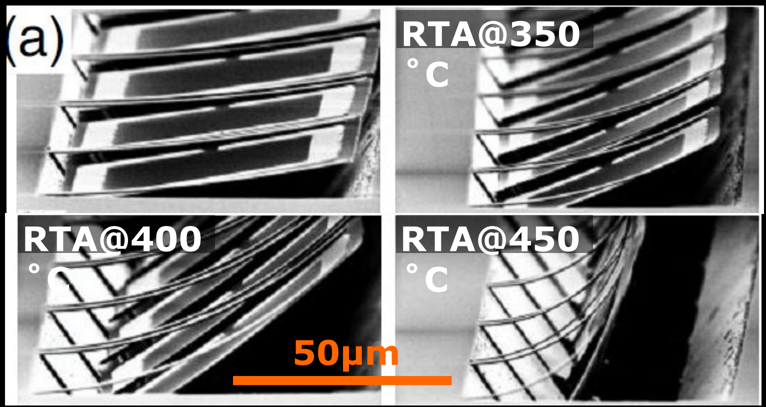
Switchable & tuneable metamaterials

Goal:
switchable and controllable properties

Applications:
modulators, adaptable surfaces

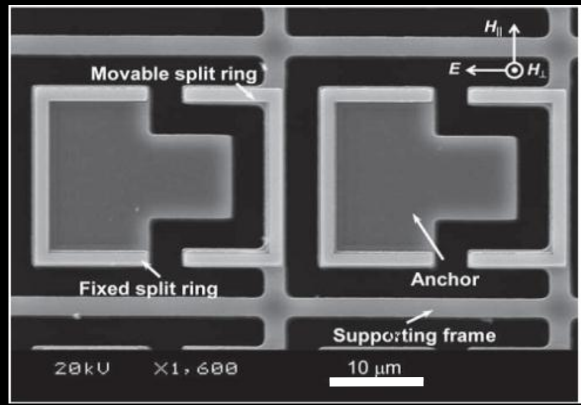
Reconfigurable Metamaterials

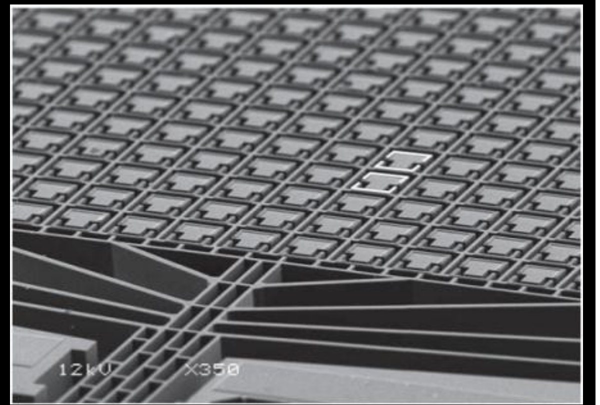
Rapid thermal annealing



H. Tao, Padilla, Averitt et al (2009)

MEMS reconfigurable meta-molecules

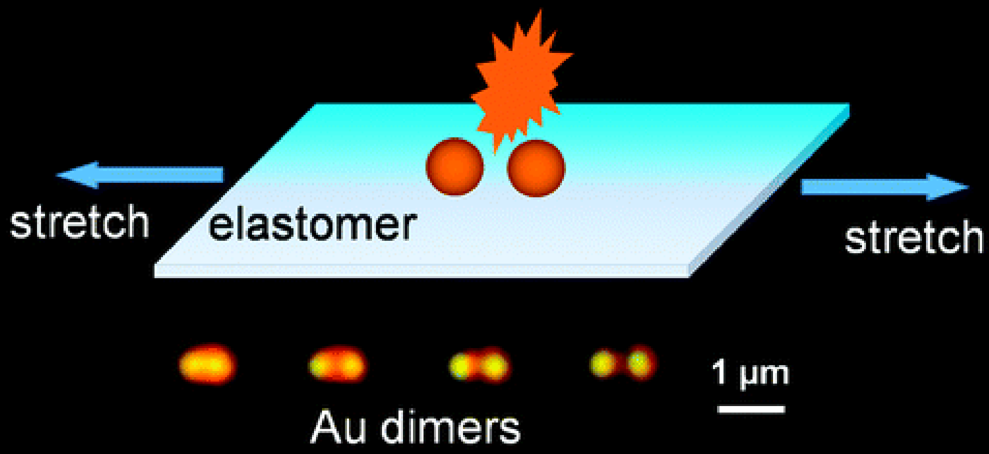




W.M. Zhu, *Ai Qun Liu* et al. (2011)

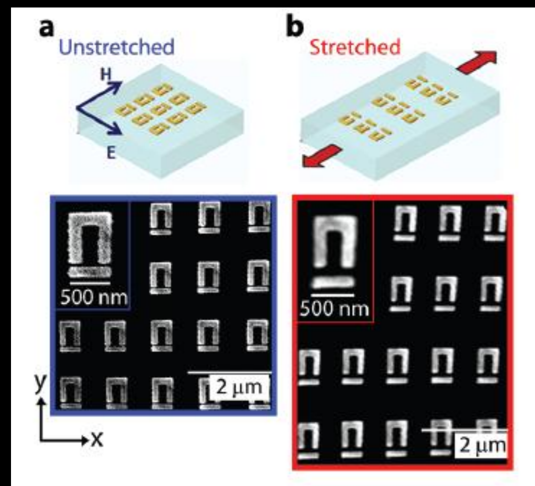
Nanoscale features & movements are required for photonic metamaterials

Stretchable substrate



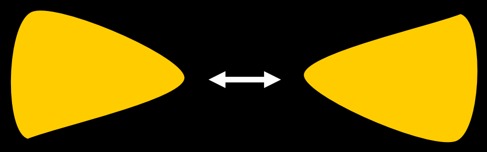
Huang & Baumberg (2010)

Stretchable substrate

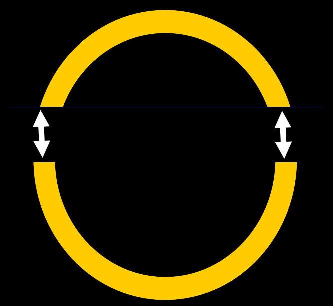


Pryce, Atwatter et al. (2010)

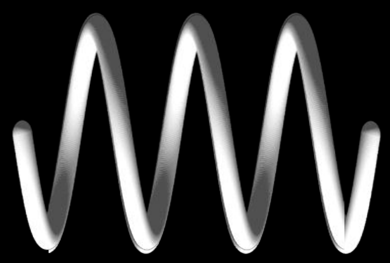
From controlling meta-molecules to controlling arrays



Tunable nano-Antenna

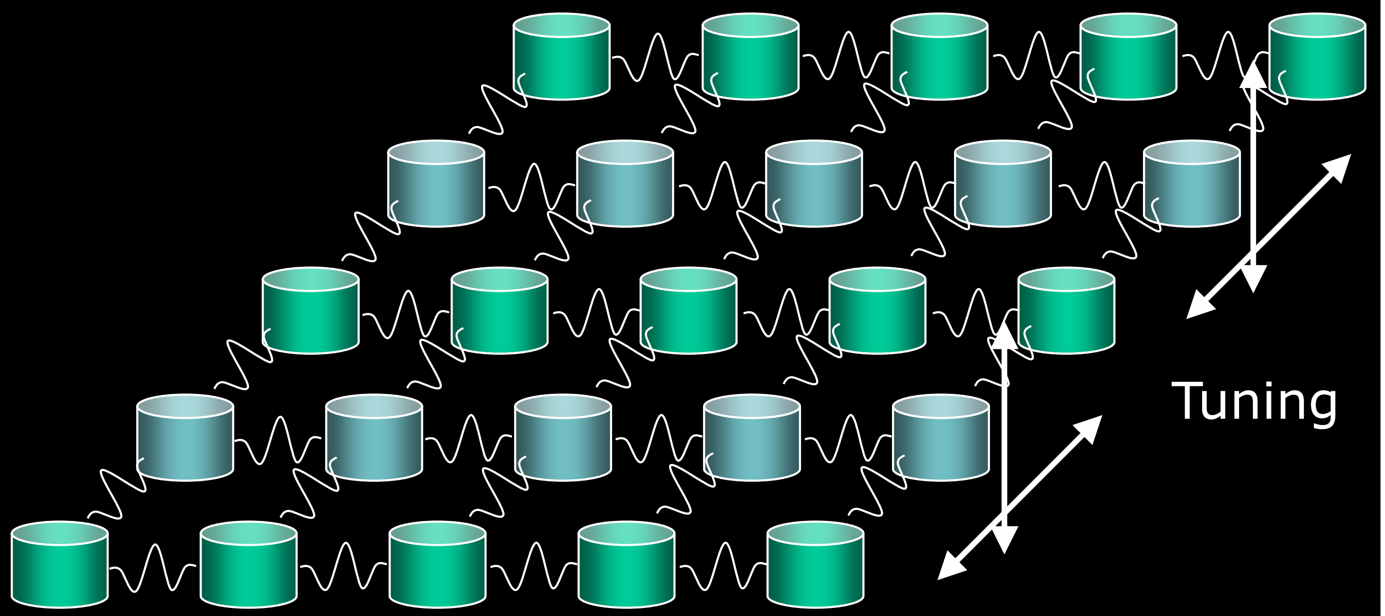


Tunable split-ring

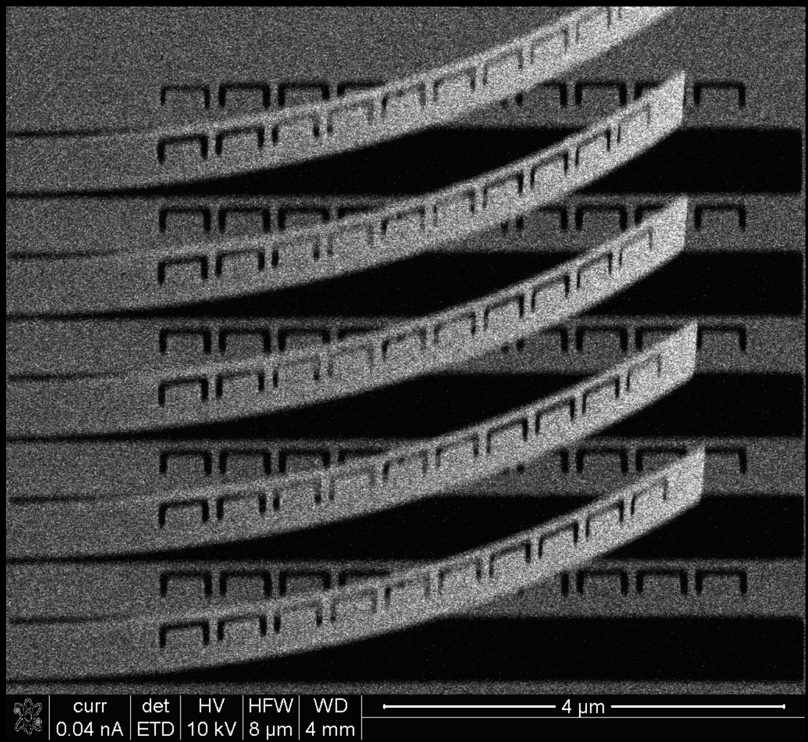


Chiral meta-molecule

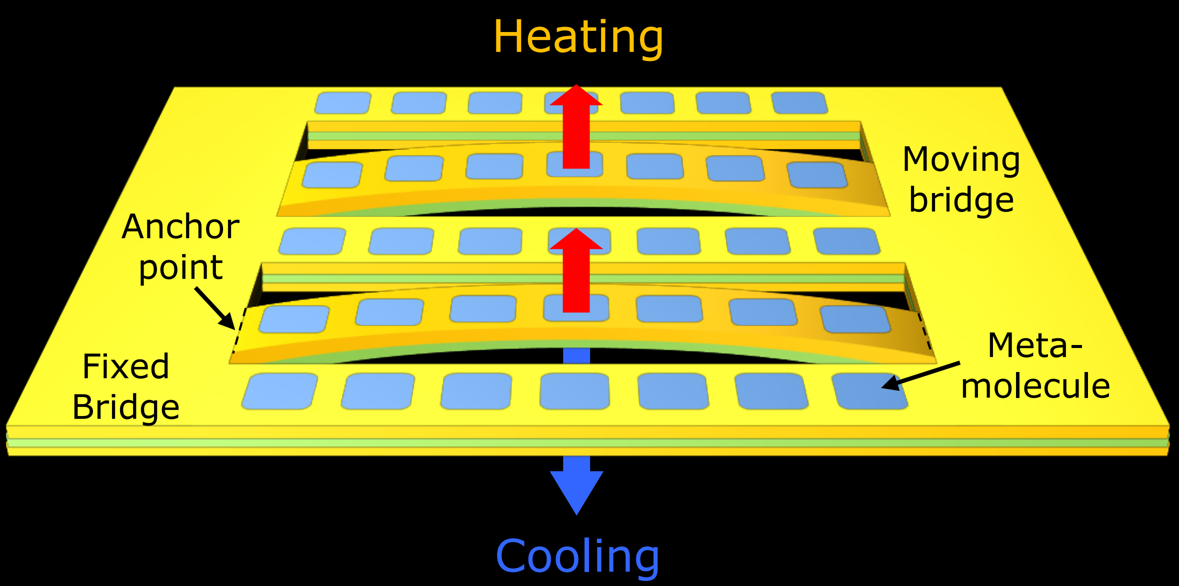
Meta-molecular spacing controls optical properties

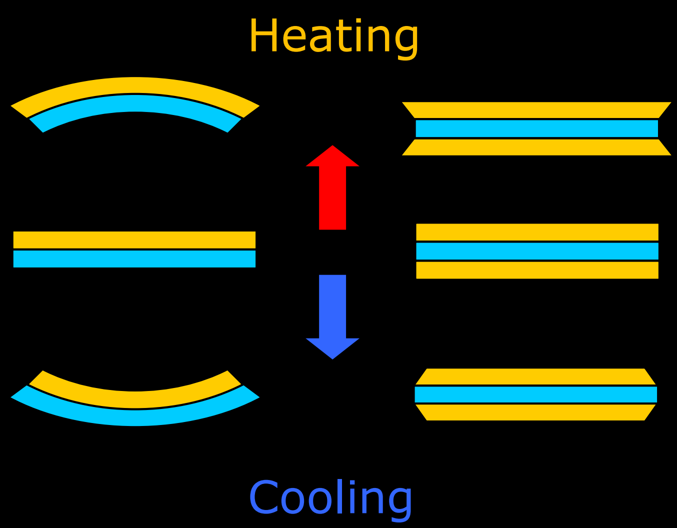


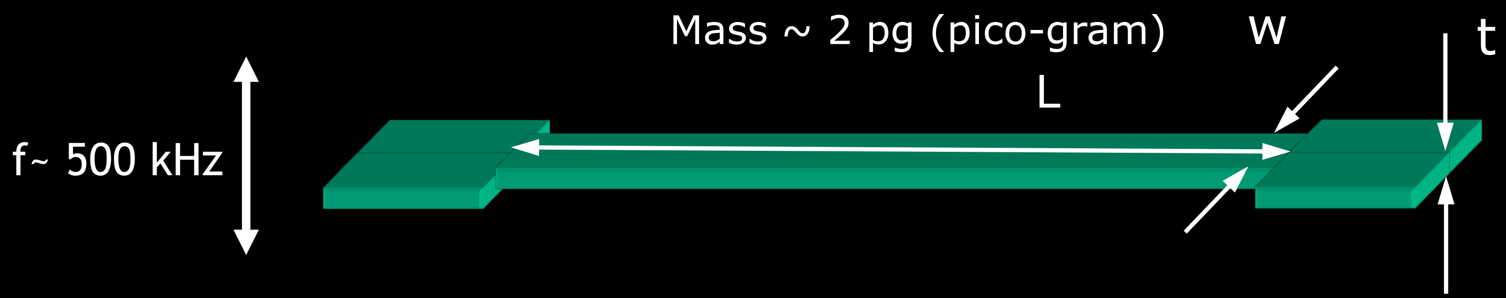
Temperature-Controlled Photonic Metamaterials



Temperature-Controlled RPMs: Concept







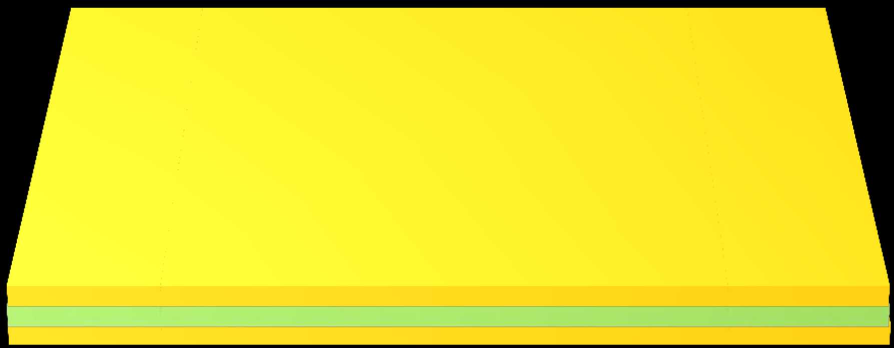
Mechanical resonance frequency:

Silicon nitride bridge

L =25μm; t= 50nm; E=260 GPa, ρ=3.44 g/cm³

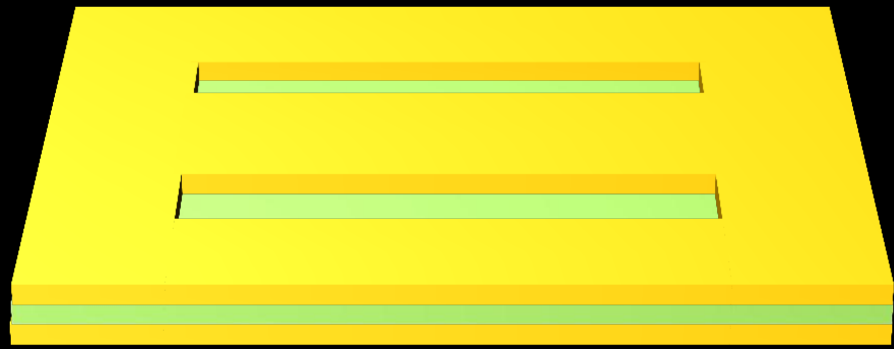
$$f = \frac{1}{2\pi}\frac{t}{l^2}\sqrt{\frac{185}{12}\frac{E}{\rho}}$$

Temperature-Controlled RPM: Fabrication

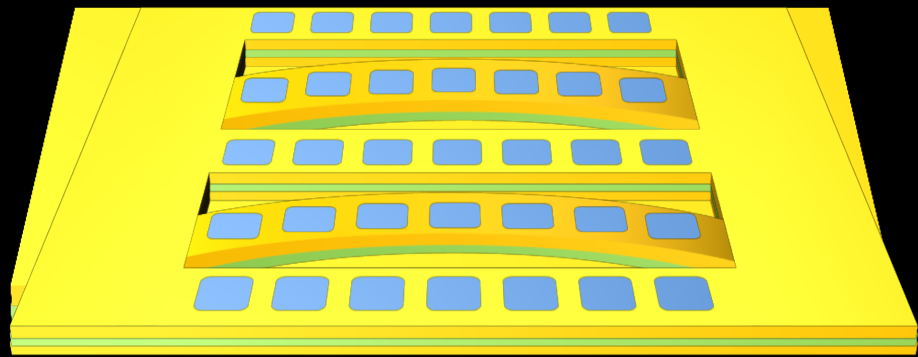


Au on both sides of Si_3N_4 membrane

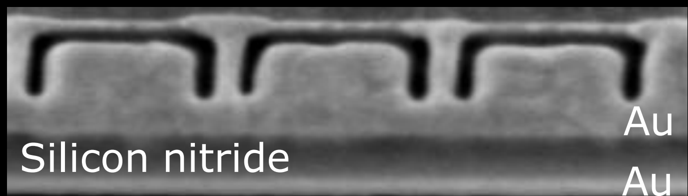
Alternating Gold slits removed by FIB



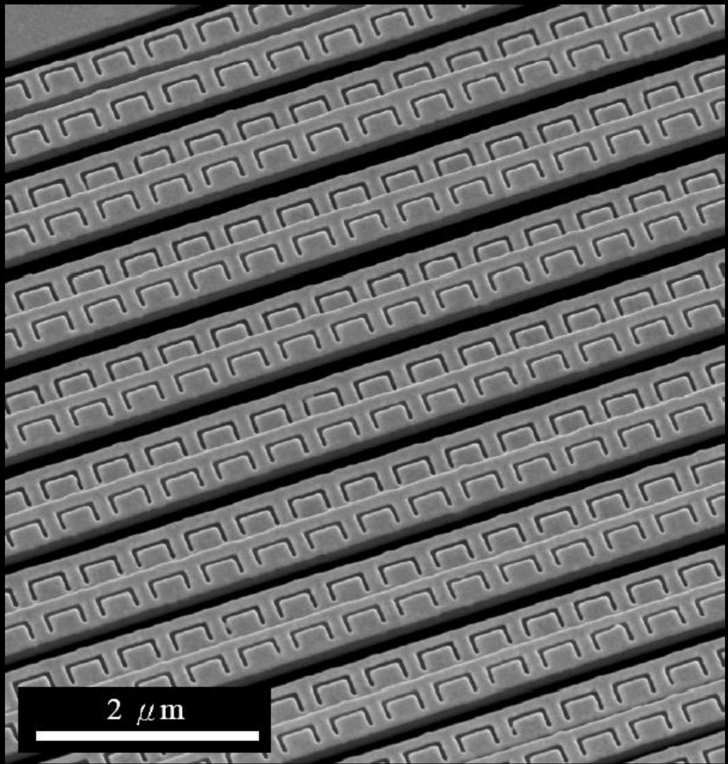
Flip Sample

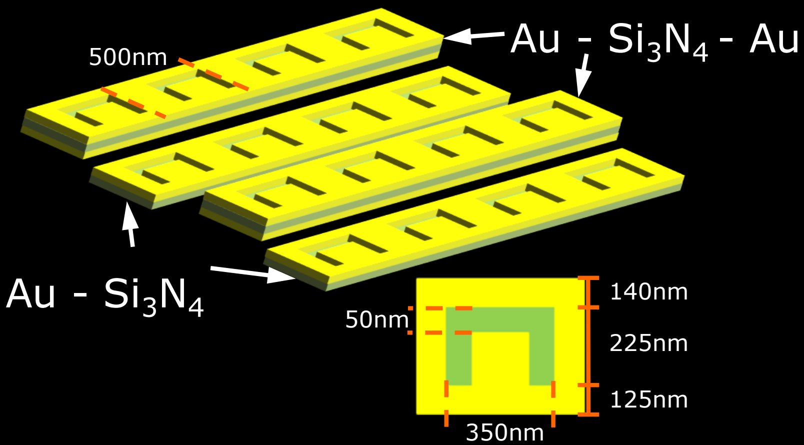


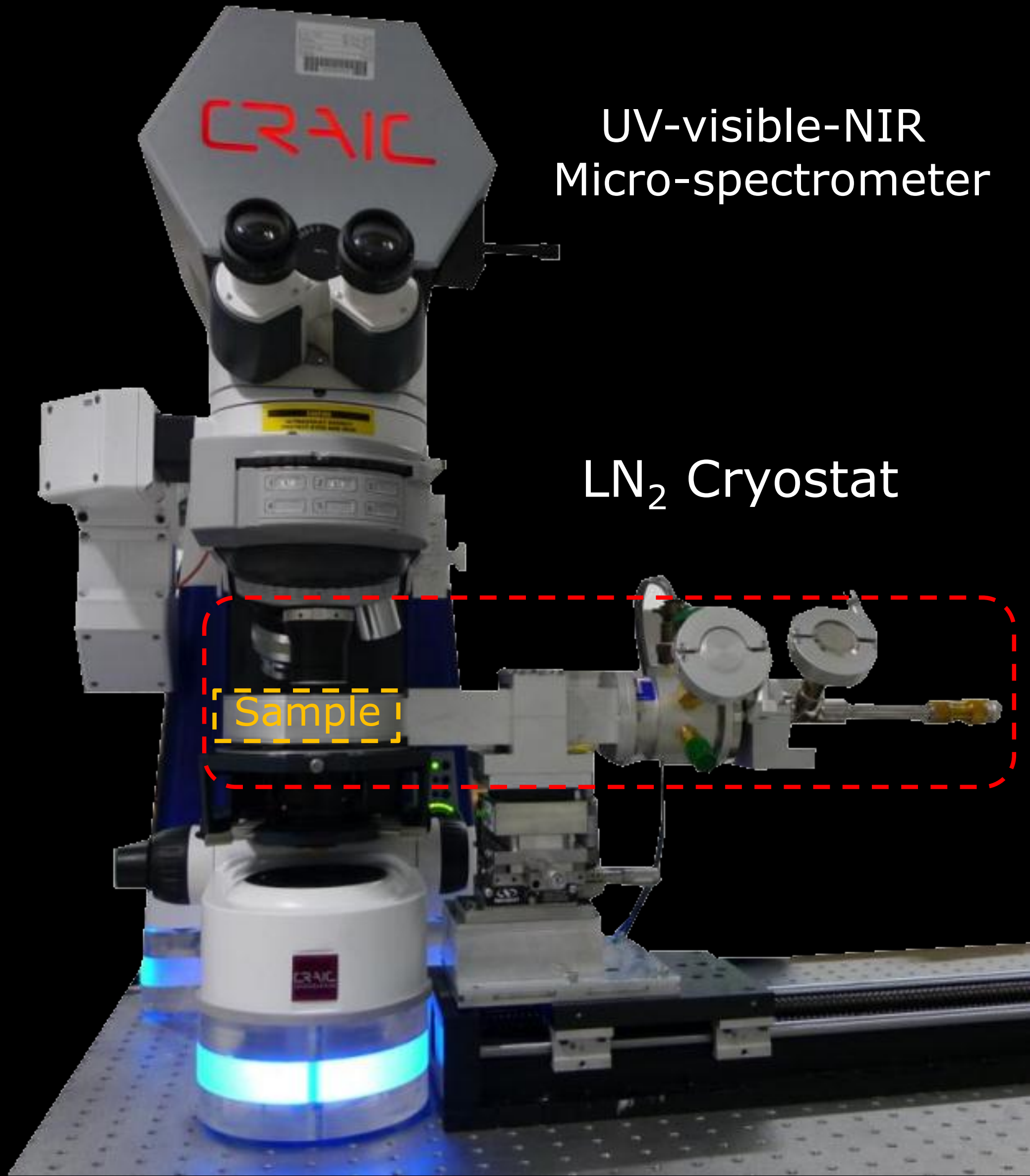
Meta-molecules patterning by FIB
Bridges cut through



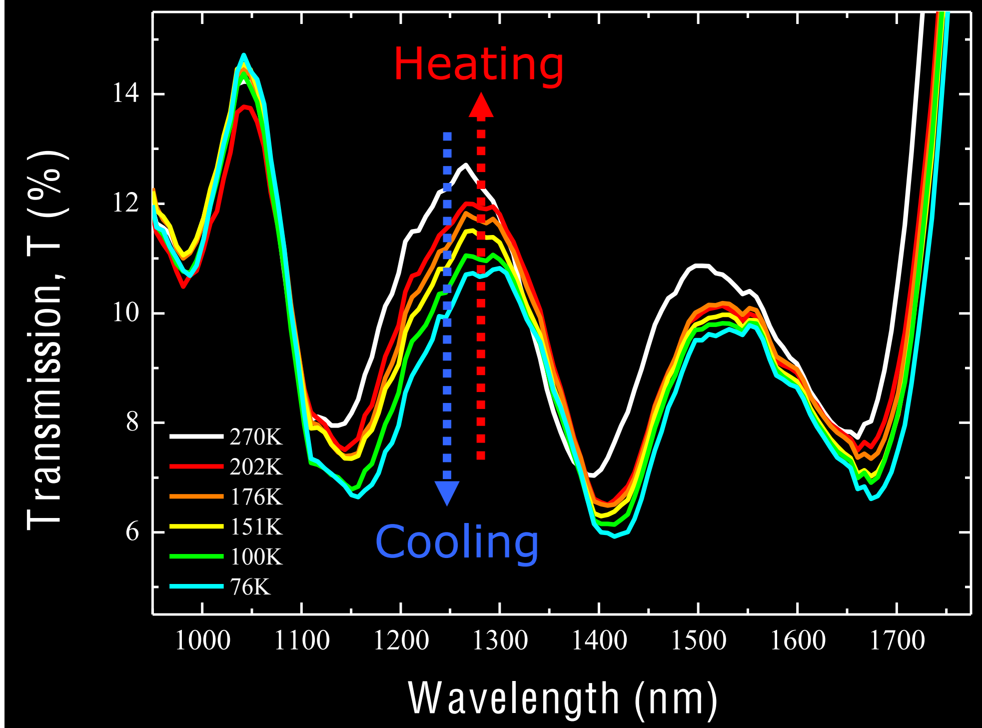
Temperature-Controlled RPM: Optical Characterization

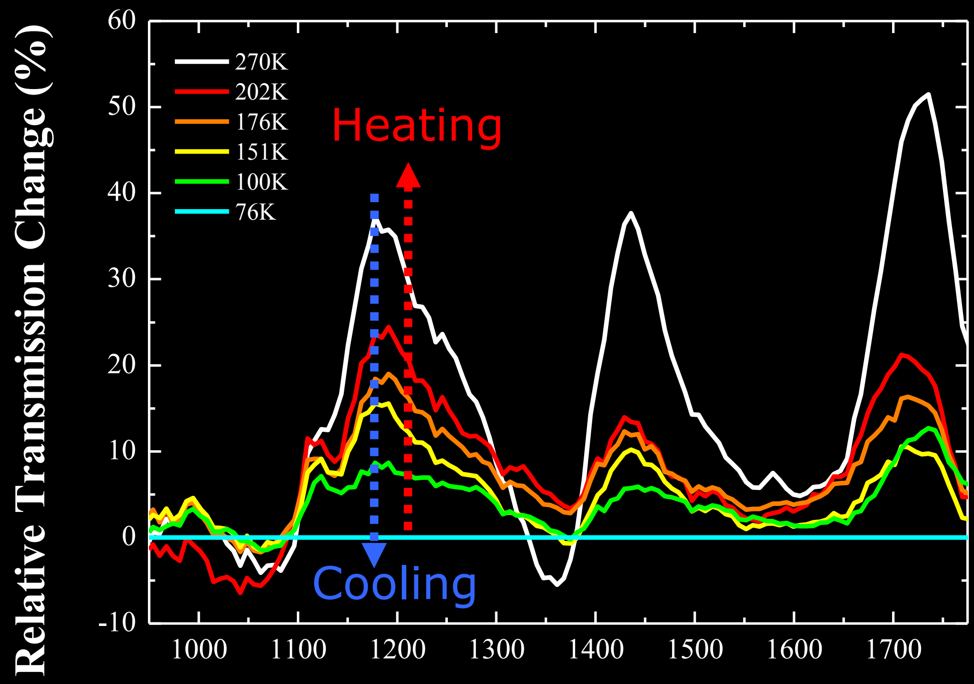






Temperature-Controlled RPM: Performance





Reversible continuous tuning by cooling/heating
Relative changes in transmission up to **50%**

Optical Forces in Metamaterials

Goal:
Controlling adhesion forces

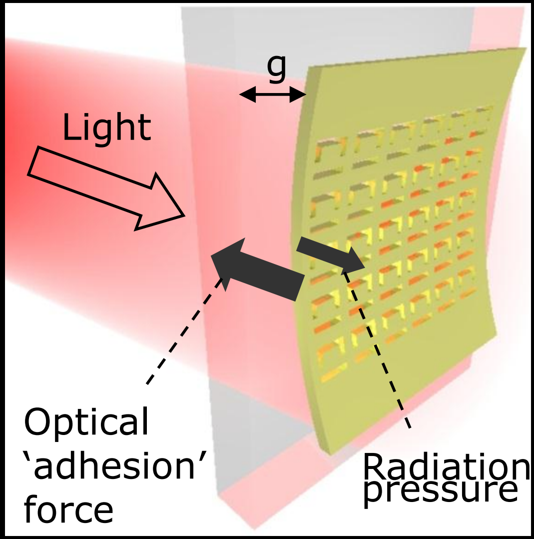
Applications:
Handling of small objects

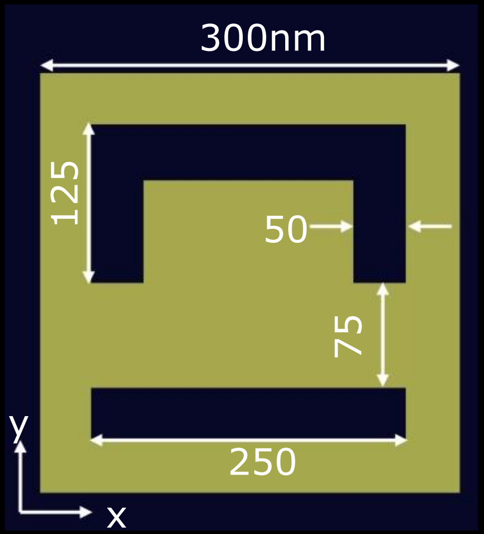
Light

Optical 'Gecko Toe'

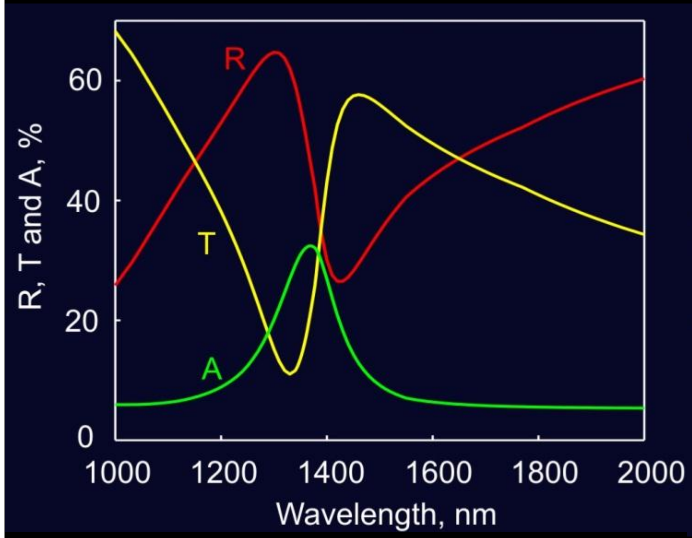
Gecko toes

Optical 'adhesion' force

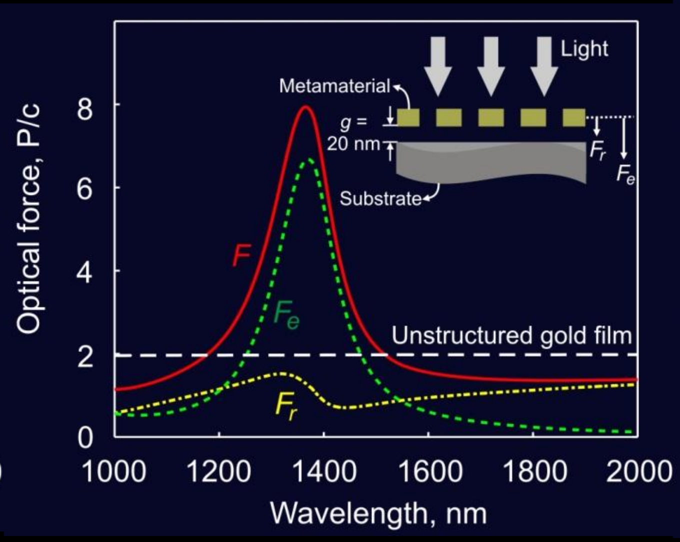


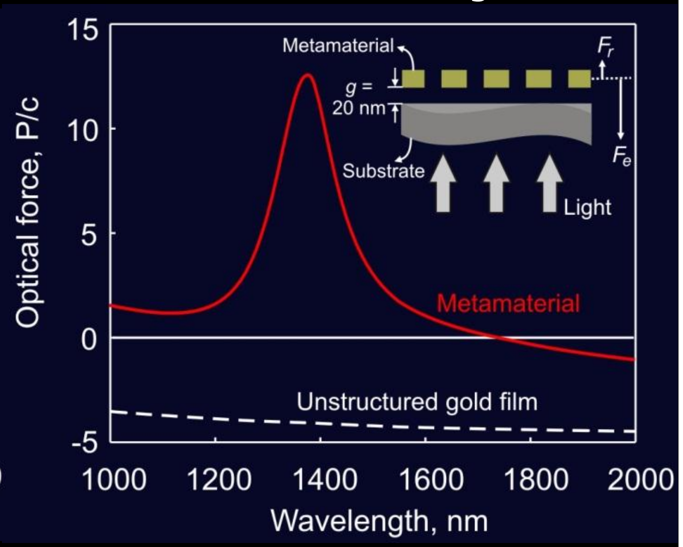


Simulated spectra for y-polarization



Optical force for light impinges from air side and through substrat





Nonlinear & Switchable Metamaterials

Applications:

all-optical data processing
telecom switching
data storage
Displays
Lasers (modeloking/q-switcing)
Optical limiting and conditioning

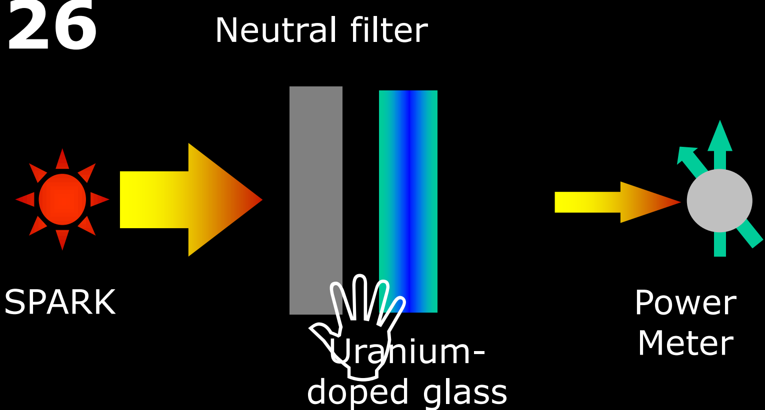
Violation of the Superposition Principle

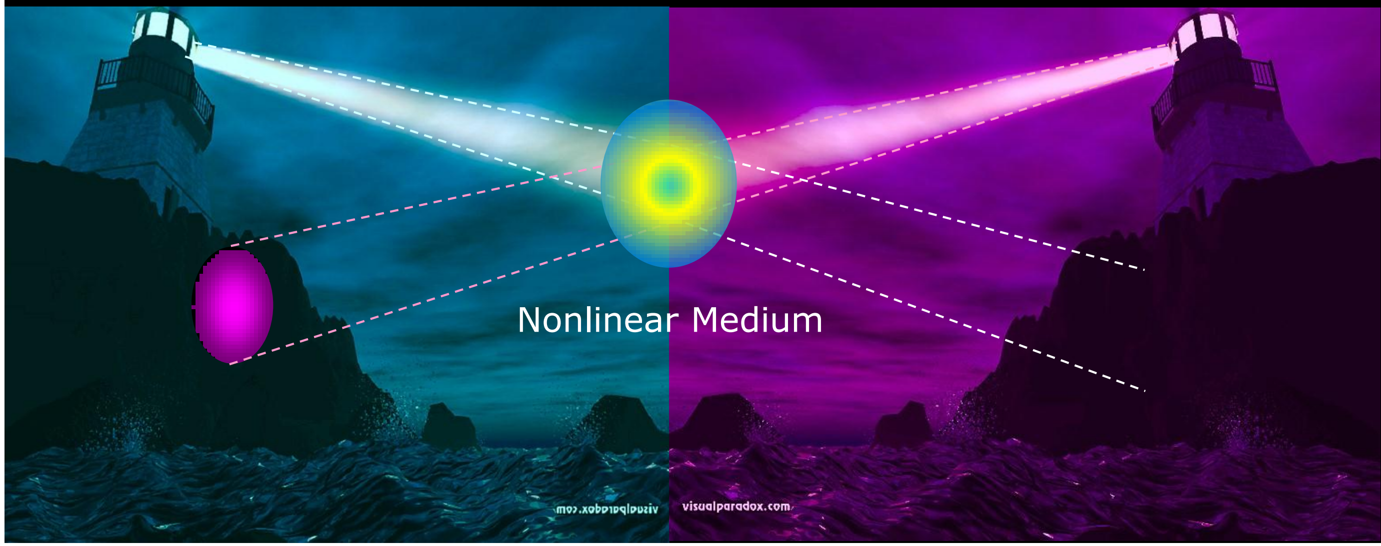
Christian Huygens
1629 - 1695

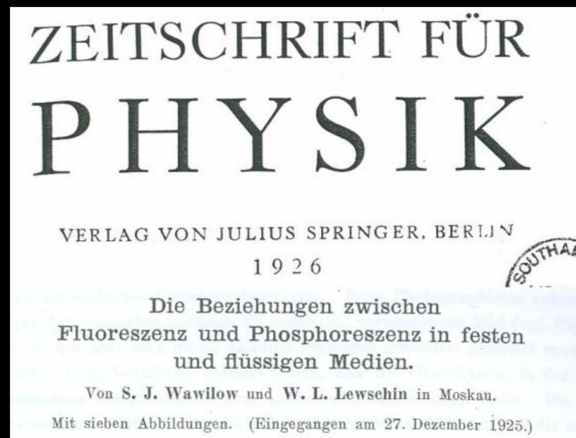
"The most remarkable property of light is that light beams travelling in different and even opposite directions pass though one another without mutual disturbance"
"Abhandlung über das Licht" 1678

V.L.Levshin (1896-1969)
& S.I.Vavilov (1891-1951)

1926







ZEITSCHRIFT FÜR
PHYSIK

VERLAG VON JULIUS SPRINGER, BERLIN
1926

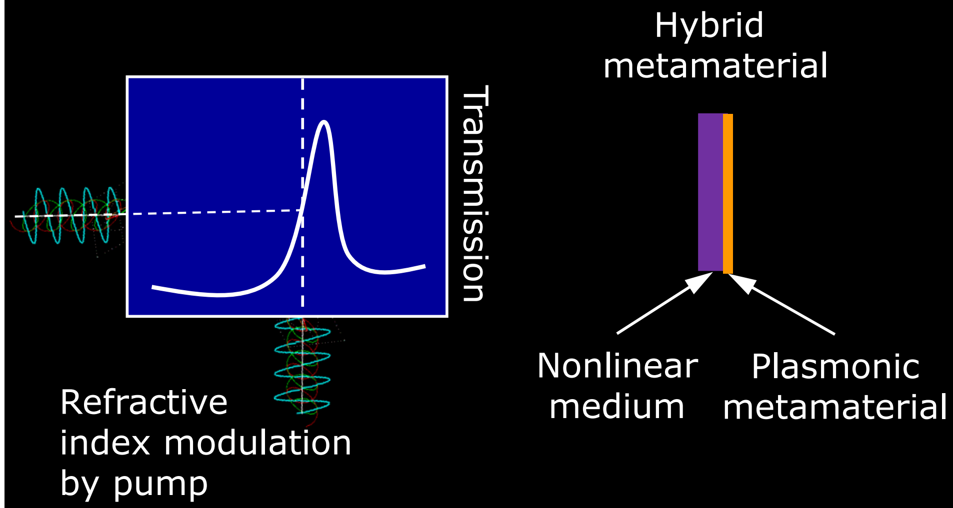
Die Beziehungen zwischen
Fluoreszenz und Phosphoreszenz in festen
und flüssigen Medien.

Von S. J. Wawilow und W. L. Lewschin in Moskau.

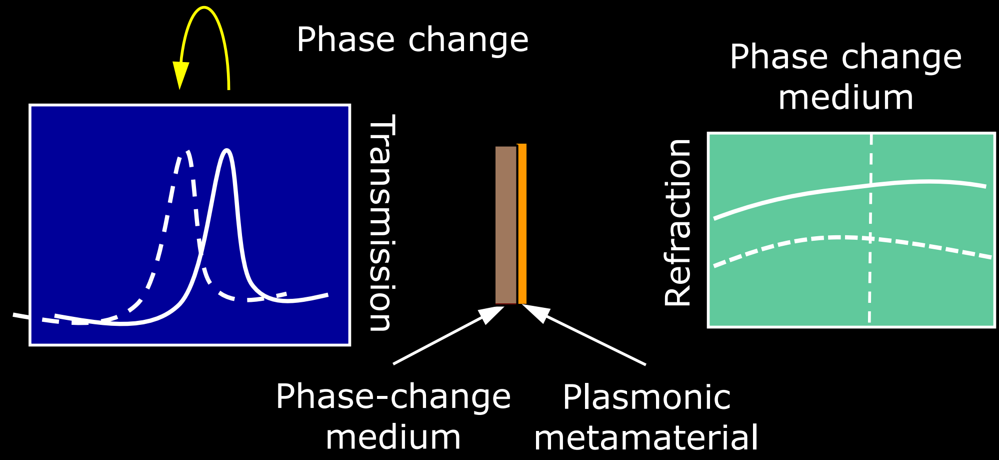
Mit sieben Abbildungen. (Eingegangen am 27. Dezember 1925.)

Giant nonlinearity and switching with photonic metamaterials

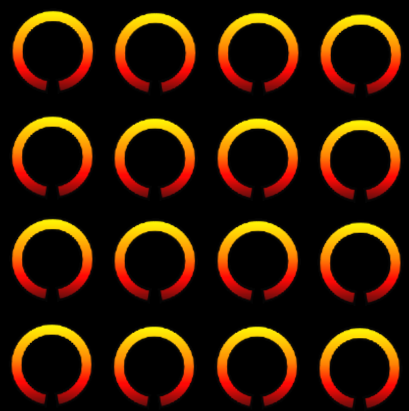
Resonant enhancement of nonlinearity In Metamaterials



Phase Change Metamaterials

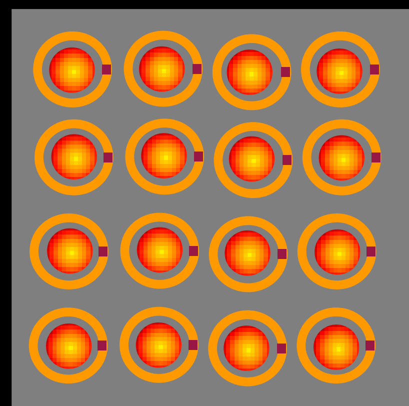


Reconfigurable MM



Flux quantization MM

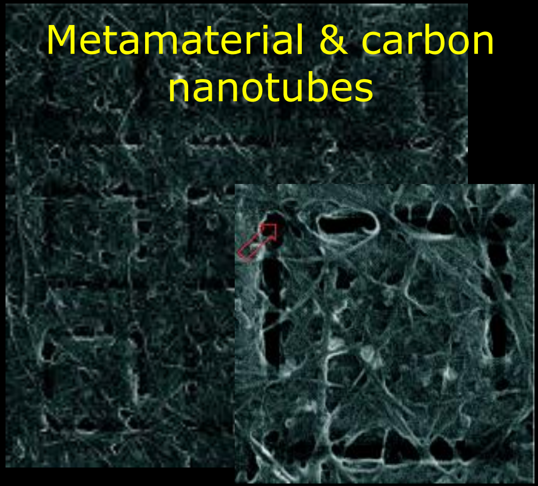
Josephson SQIDs



Quantum-level nonlinearity

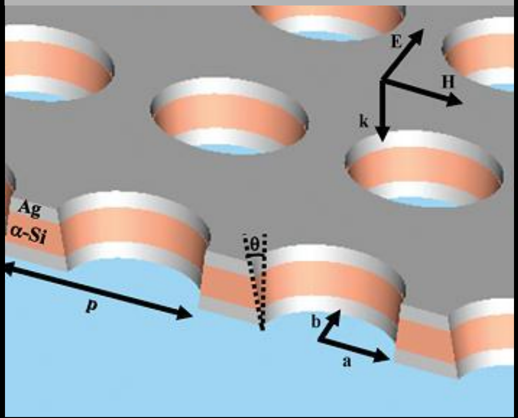
Plasmonic enhanced cubic nonlinearity

Metamaterial & carbon nanotubes



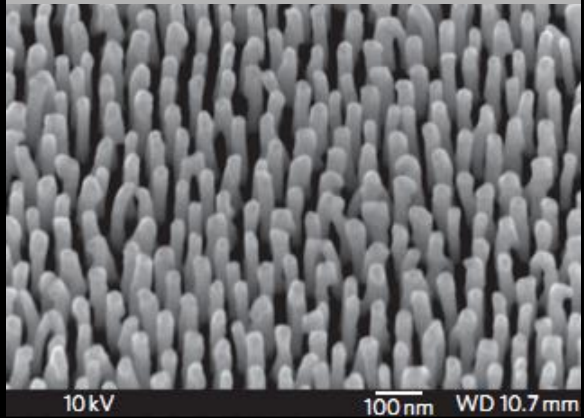
Nikolaenko, Angelis, Boden, Papasimakis, et. al. Phys. Rev. Lett. 104, 153902 (2010)

Si & metamaterial

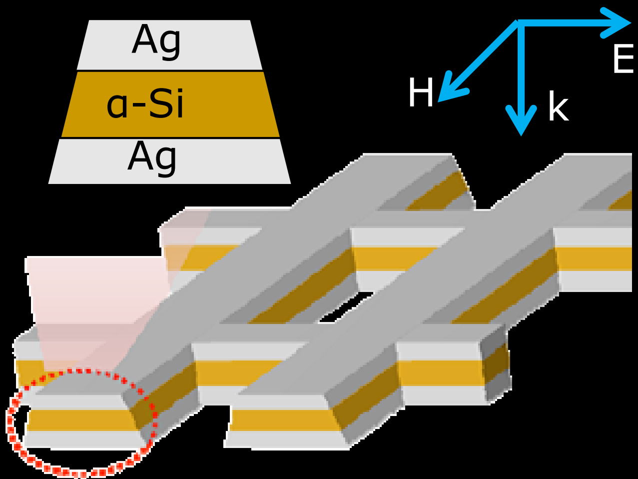


Dani, Ku, Upadhya, Prasankumar, Brueck, Taylor Nano Lett. 9, 3565 (2009)

Gold nanorods

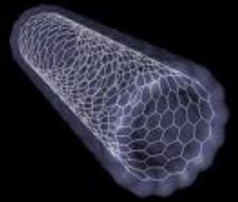


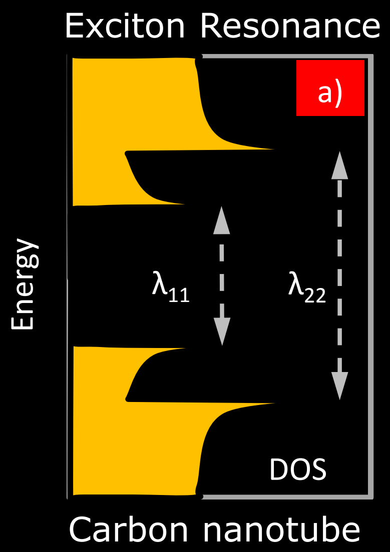
Wurtz, Pollard, Hendren, Wiederrecht, et. al. Nat. Nanotech. 6, 107 (2011)



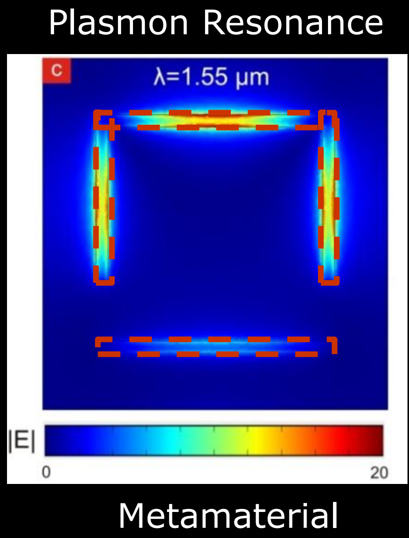
Cho, Wu, Ponizovskaya, Chaturvedi, Bratkovsky, Wang, Zhang, Wang and Shen Opt. Express 17, 17652 (2009)

Ultrafast Nonlinear Metamaterials with Carbon Nanotubes through plasmon- exciton coupling

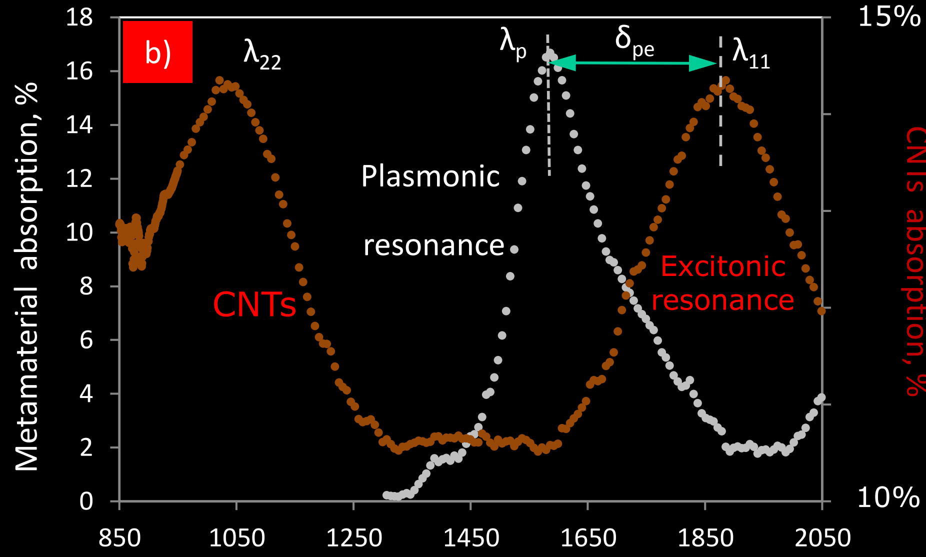


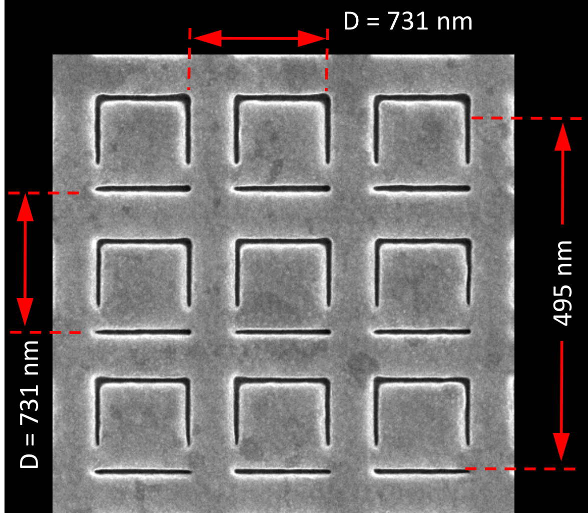


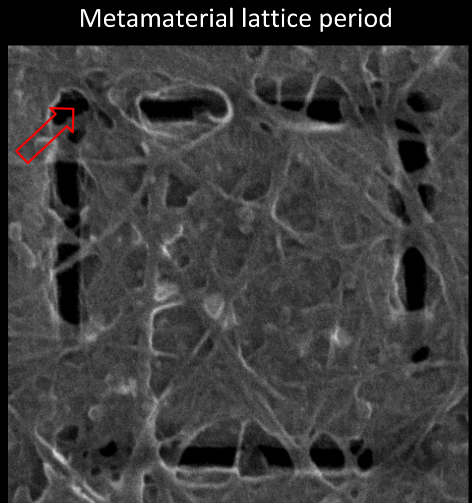
+



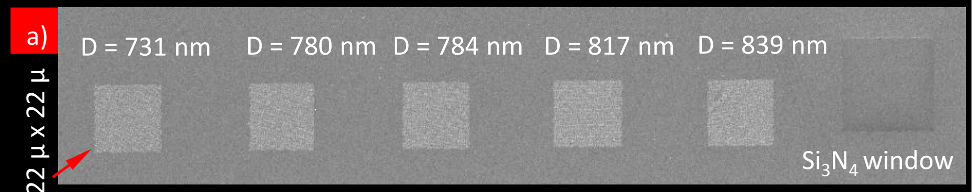
Plasmonic & Excitonic absorption lines







Combinatorial approach to metamaterials research

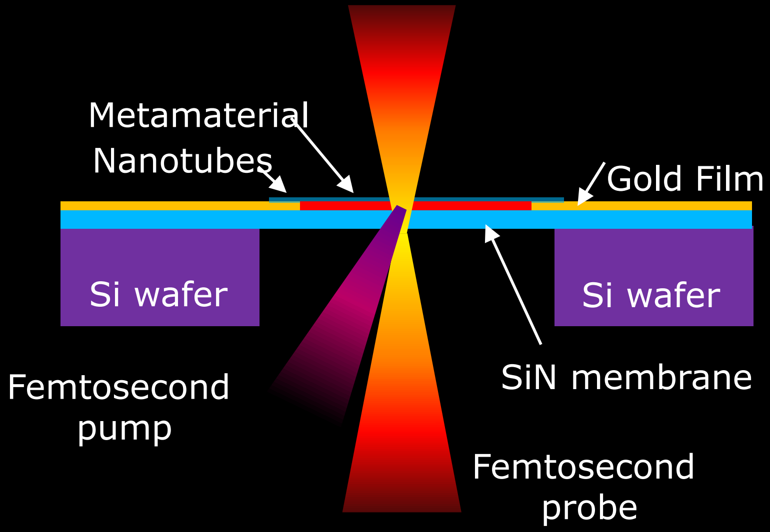


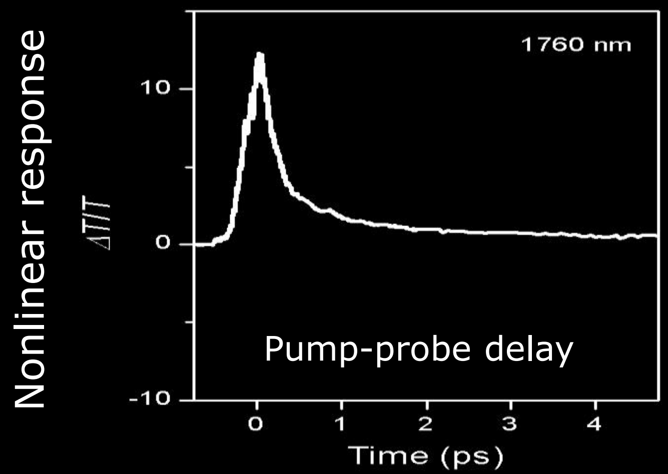
PRL 104, 153902 (2010) PHYSICAL REVIEW LETTERS week ending 16 APRIL 2010

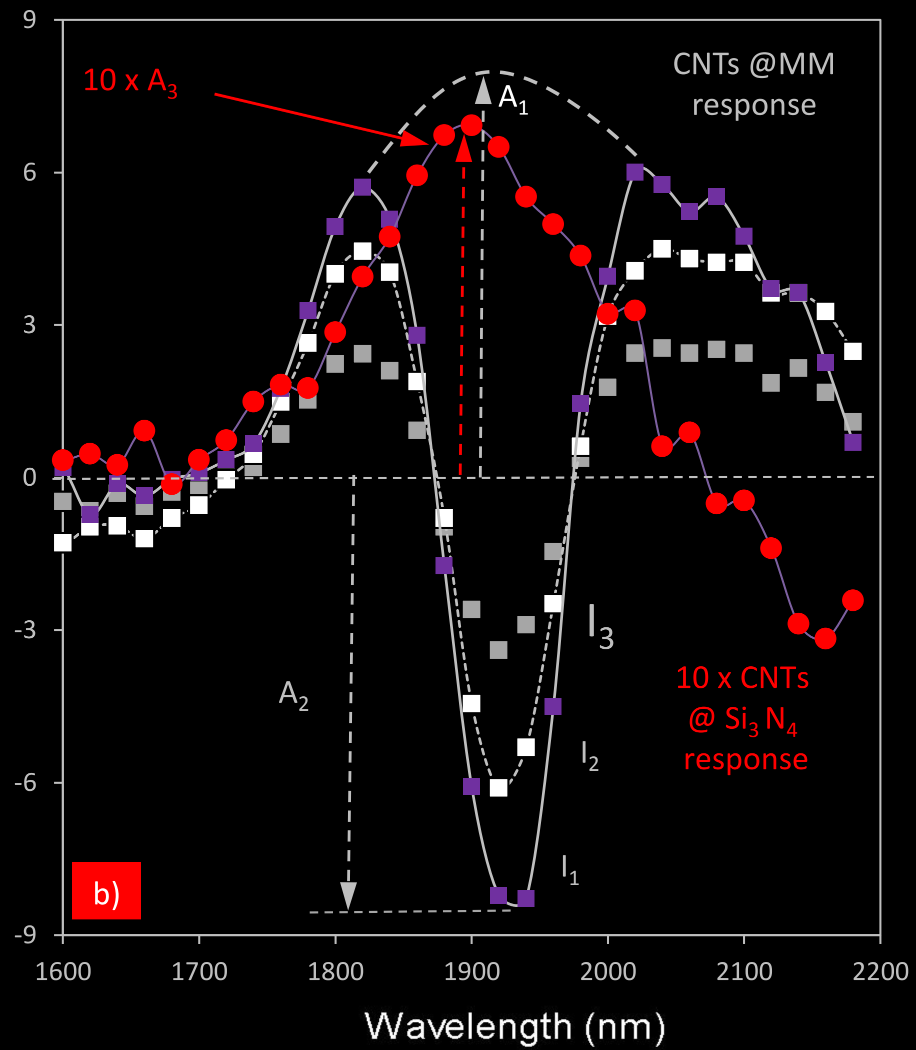
Carbon Nanotubes in a Photonic Metamaterial

Andrey E. Nikolaenko,[1] Francesco De Angelis,[2] Stuart A. Boden,[3] Nikitas Papasimakis,[1] Peter Ashburn,[3] Enzo Di Fabrizio,[2] and Nikolay I. Zheludev[1]

Giant Nonlinearity through plasmon-exciton coupling





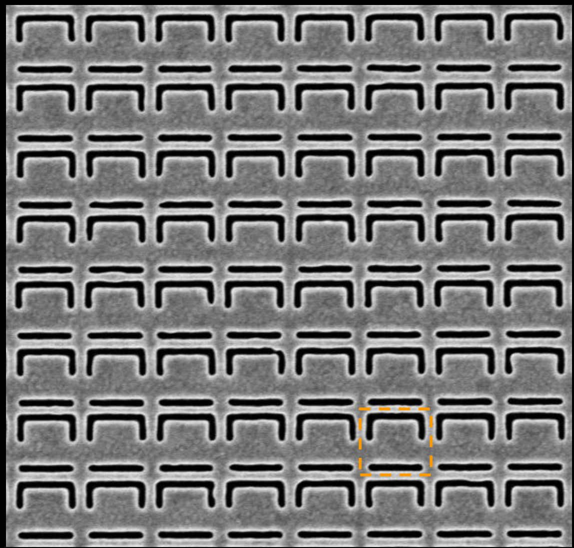


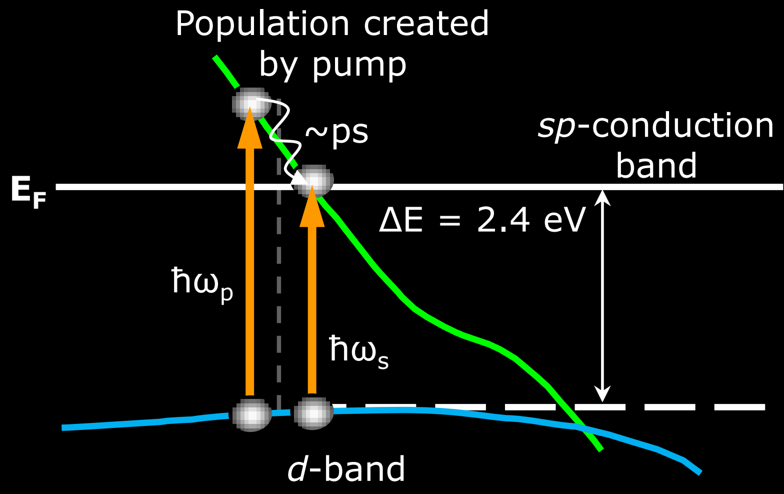
System	% T modulation	Fluence, μJ/cm²	Response time, fs	J x fs/cm²
Metamaterial + CNTs PRL,104, 153902 (2010)	10 %	40	~500fs	0.02

Nonlinearity of the Metamaterial’s framework

Gold Nonlinear Metamaterial

Metamaterial nanostructure

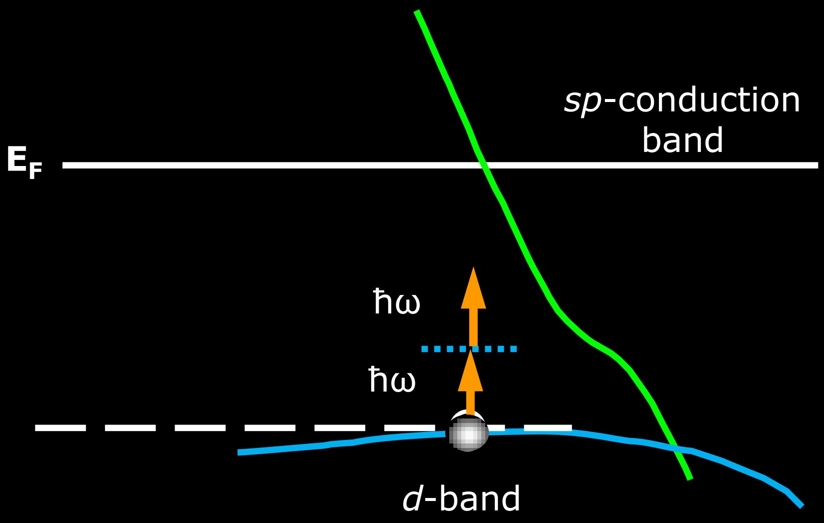




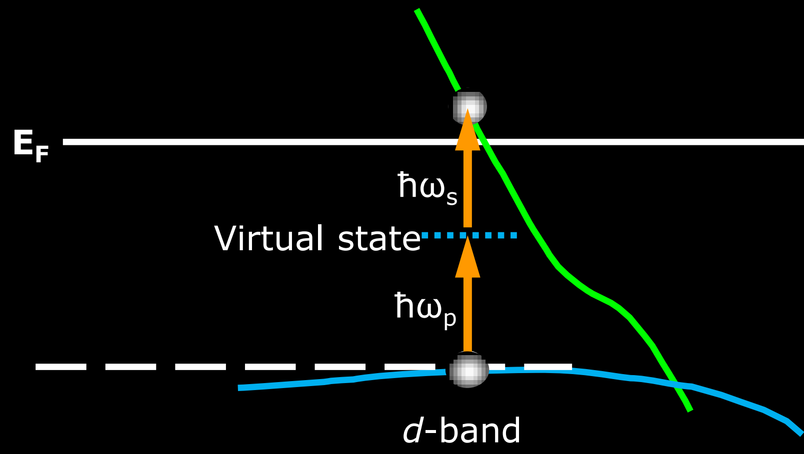
Fermi Smearing Nonlinearity $\hbar\omega$~2.4eV

β ~10^{-5} m/W peaking at ~516 nm

Few ps response (hot e- thermalization)



Au Nonlinear Absorption is negligible for 2$\hbar\omega$<2.4eV



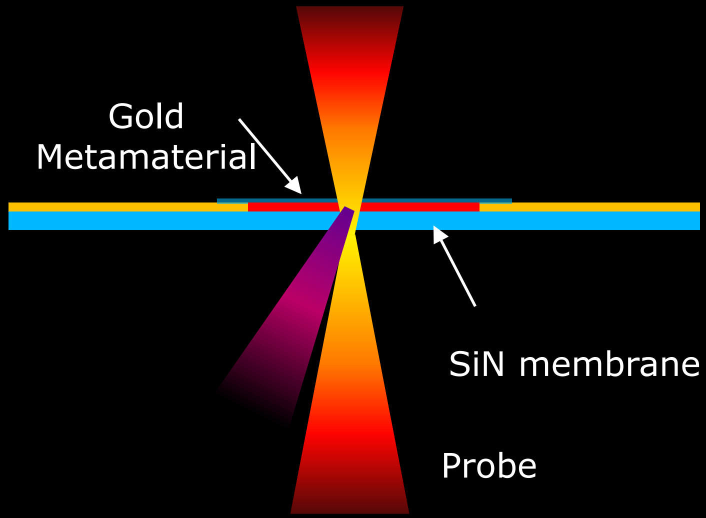
Two Photon Absorption nonlinearity

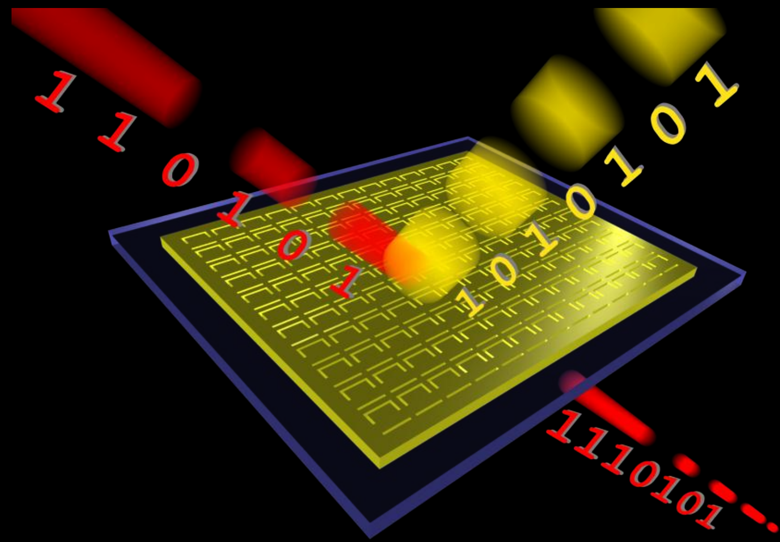
2.4eV>$\hbar\omega$>1.2eV

β ~10^{-8} m/W, Virtual level lifetime ~2$\hbar/\Delta E$ < 1 fs

Nonlinear Metamaterial: THz optical modulation bandwidth

100fs Z-Scan and Pump-probe





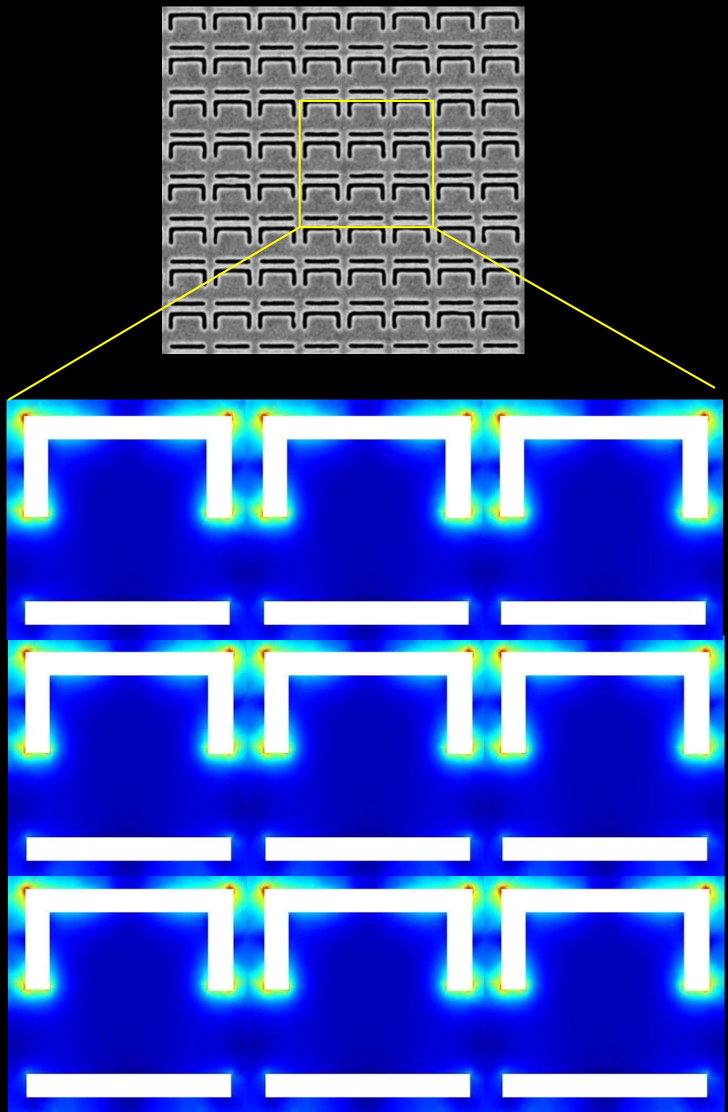
Average Laser power ~ 3 mW

Ren, Zheludev et.al.
Adv. Mat. DOI: 10.1002/adma.201103162

System	% T modulation	Fluence, μJ/cm^2	Response time, fs	J x fs/cm^2
Gold metamaterial	40 %	270	~ 40fs	0.01

Strong Resonant Field Localization (in the metal itself!)

Metamaterial nanostructure



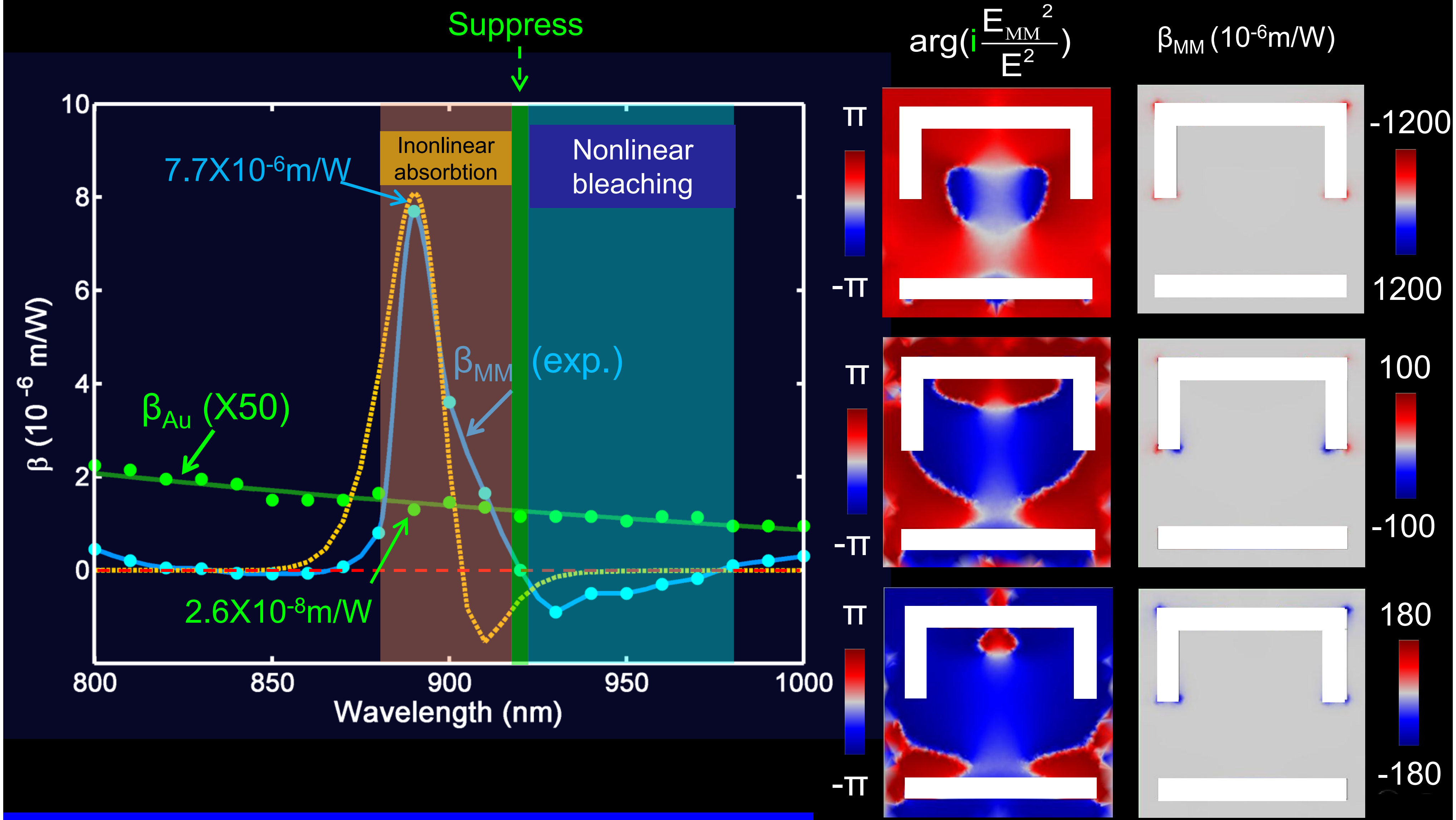
Nonlinear absorption coefficient of plasmonic metamaterial

$$\beta_{eff} = \beta_{Au} \frac{n^2}{n_{eff}^2} \mathrm{Re}\left\{ \frac{\int E_{loc}^2 |E_{loc}|^2 dv}{E_0^2 |E_0|^2 V} \right\}$$

Local field

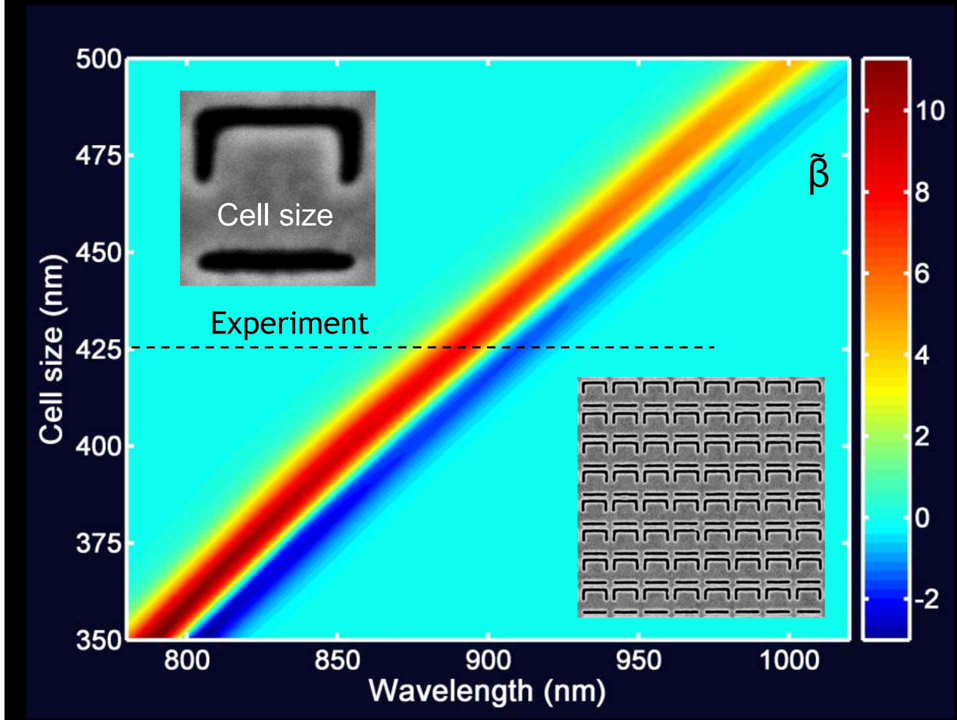
Incident field

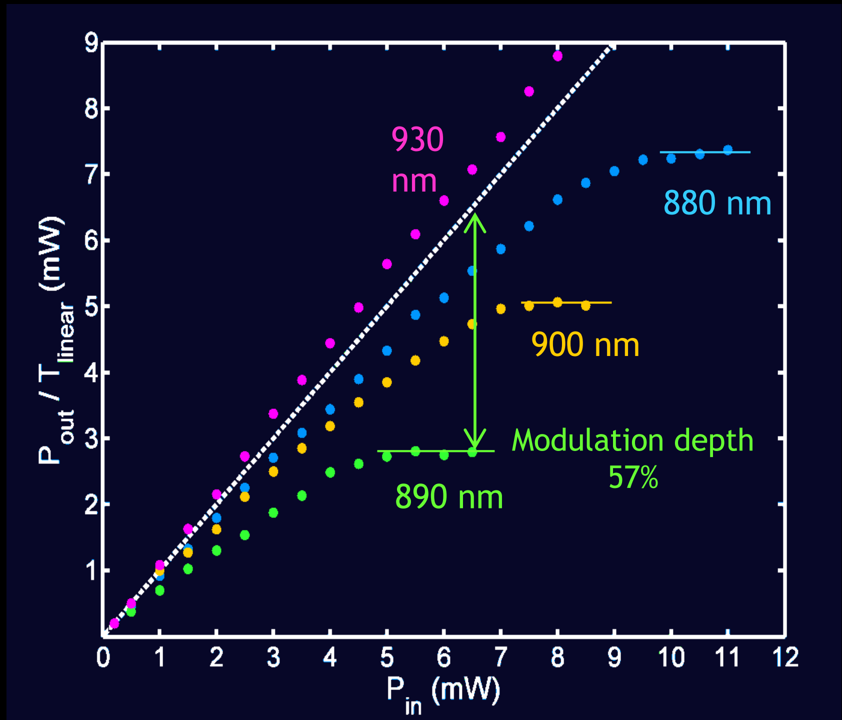
Nonlinearity control: enhancement OR loss compensation



Ren, Jia, Ou, Plum, Zhang, MacDonald, Xu, Gu, Nikolaenko, and Zheludev . Adv. Mat. DOI: 10.1002/adma.201103162

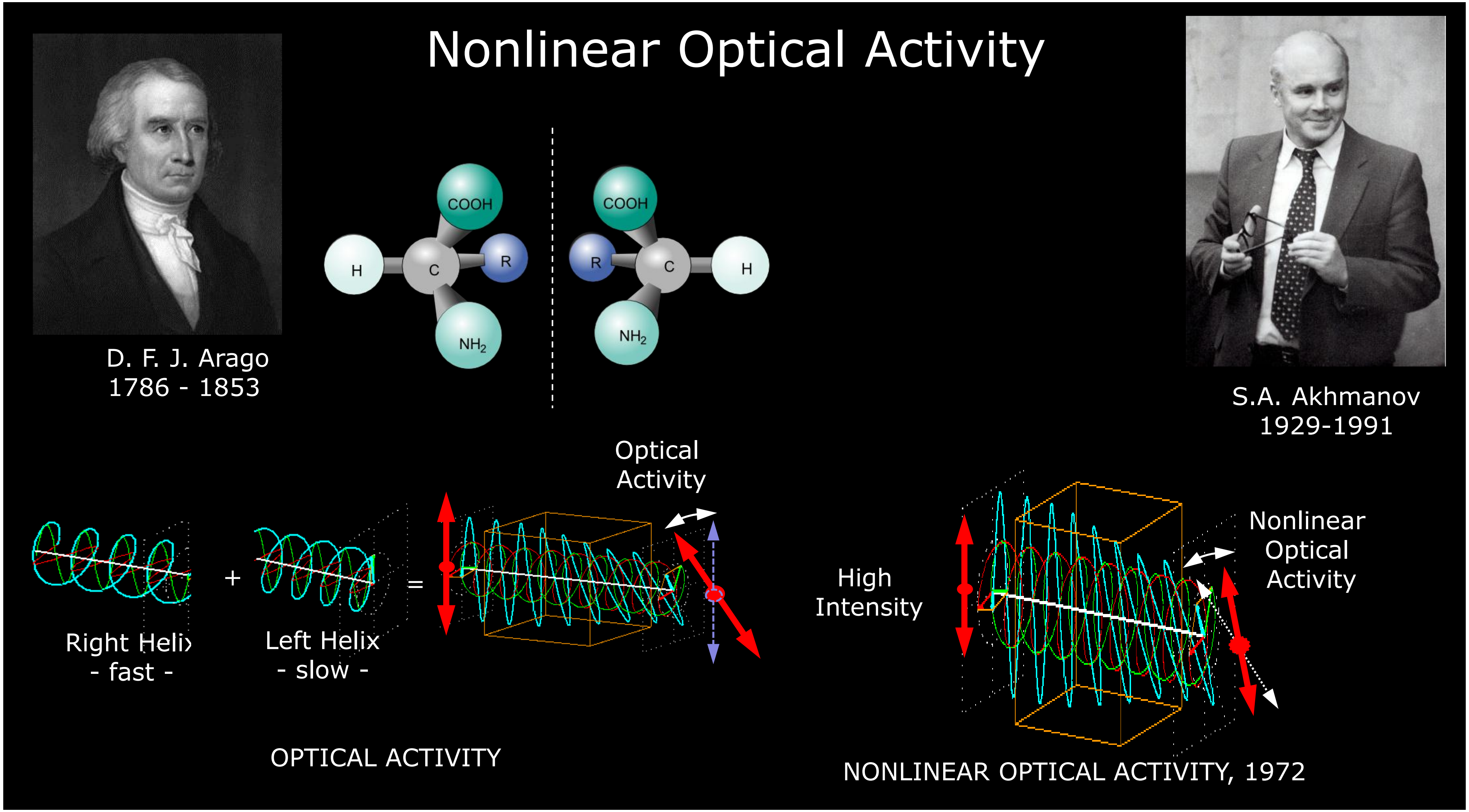
Ultrafast Au metamaterial: Tuneability & Application





System	% T modulation	Fluence, μJ/cm²	Response time, fs
Gold metamaterial	**40 %**	**270**	**~ 40fs**
Metamaterial + a-Si Opt. Exp. 17, 17652 (2009)	**30 %**	**300**	**>750fs**
Metamaterial + CNTs PRL,104, 153902 (2010)	**10 %**	**40**	**~500fs**
Plasmonic nanorods Nature NanT 6,107 (2011)	**80 %**	**7000**	**~1ps**

From Nonlinear Optics to Nonlinear Plasmonics

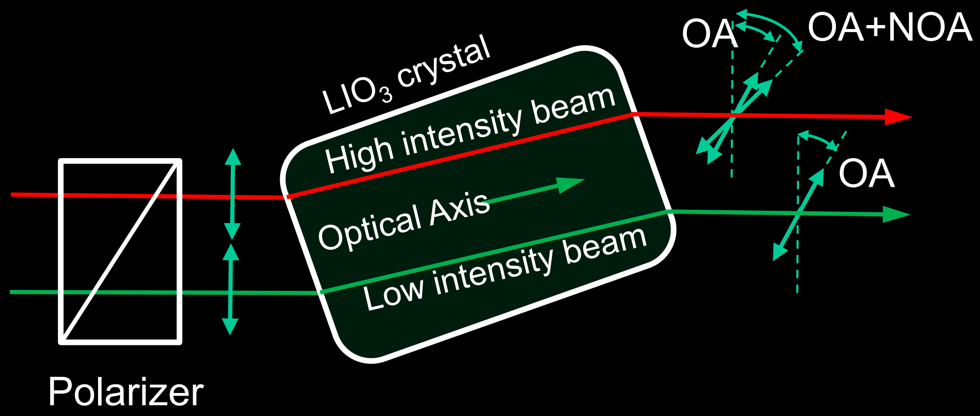


$$P_i = \frac{1}{4\pi}\left(\varepsilon_{ij} - \delta_{ij} + i\, k_n \Gamma^{(1)}{}_{ijn}\right) E_j + \left(\chi^{(3)}{}_{ijkl} + i k_n \Gamma^{(3)}{}_{ijk\ln}\right) E_j E_k E_l^*$$

$$\Theta = \Theta_0 + \frac{2\pi L}{\lambda^2}\mathrm{Re}\left\{\Gamma^{(1)}\right\} + \frac{64\pi^4 L}{c\lambda^2(1+n)^2}\mathrm{Re}\left\{\Gamma^{(3)}{}_{xxxyz}\right\} I$$

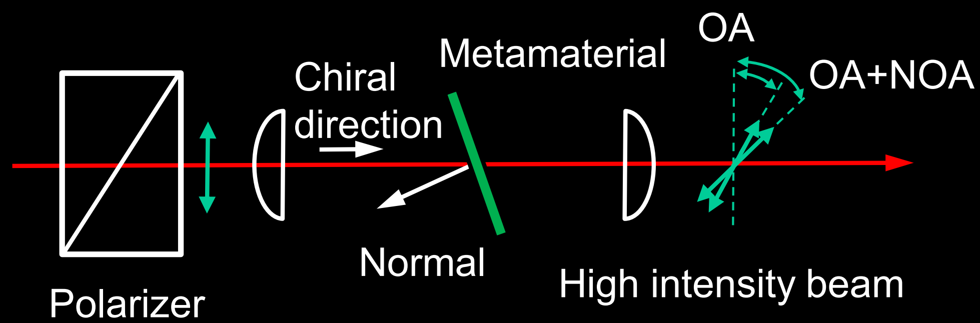
Nonlinear optical activity:
10^7 times stronger than natural media

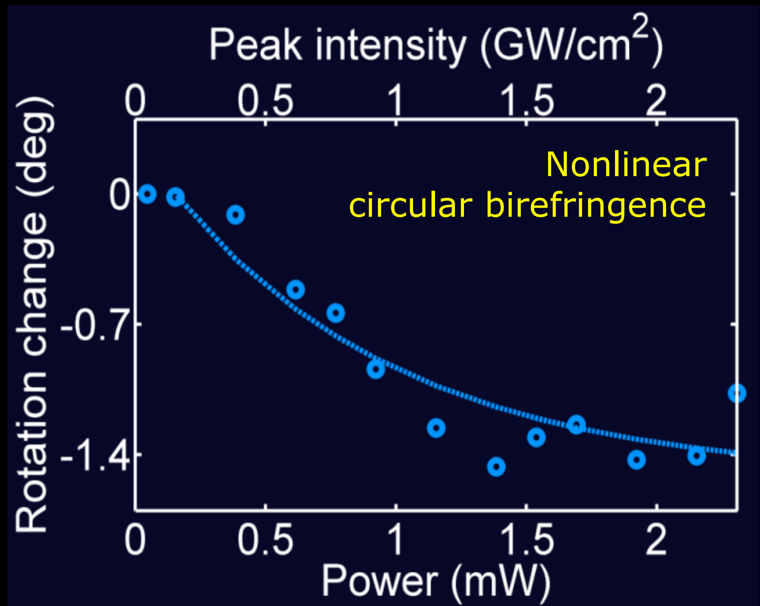
1979: Ahmanov, Zheludev et.al, JETP Lett, 29, 5 (1979)



FOM ~ 10^{-11}deg·cm/W

2011: Ren, Plum Zheludev, TBP





FOM ~ 10^{-4}deg·cm/W

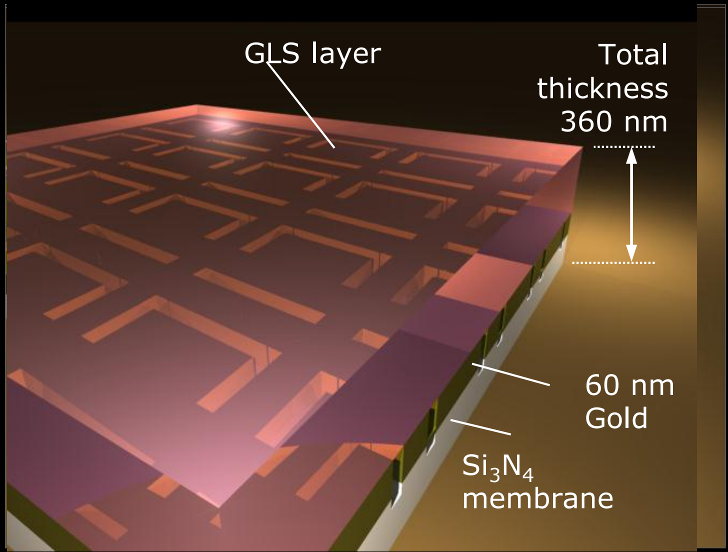
Phase Change Metamaterials

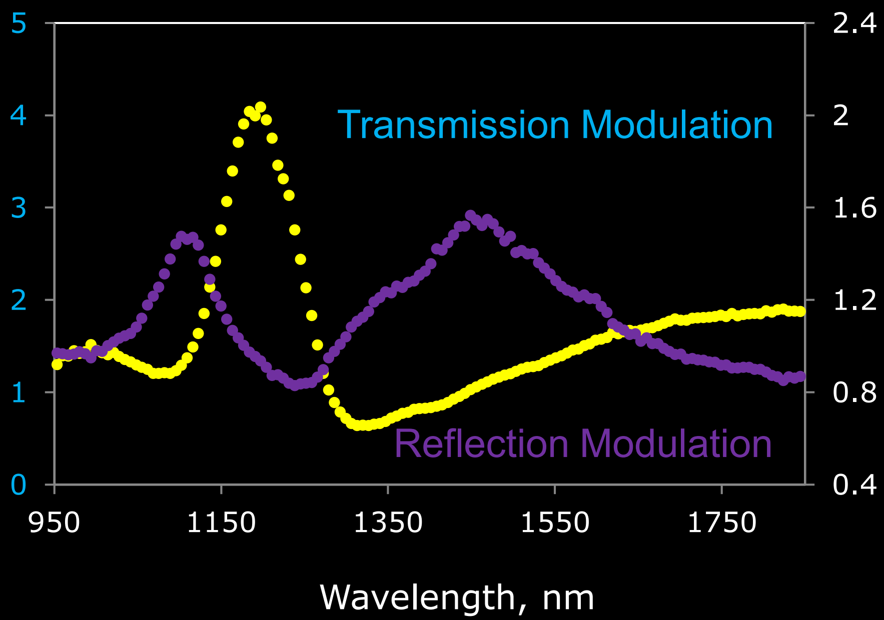
Phase change metamaterials

Goal:
Non-volitile switching

Applications:
data storage,
displays

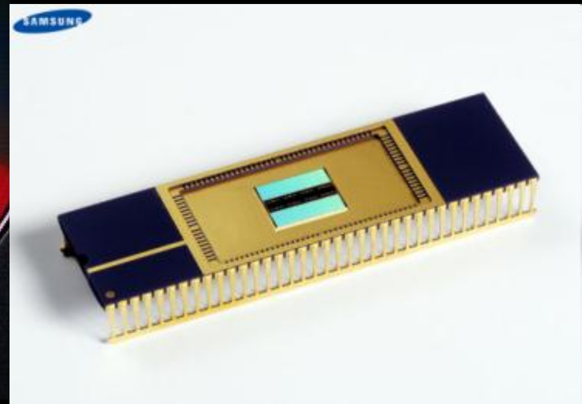
Nanoscale Thickness Electro-optical Modulator: Chalcogenide Glass @ Metamaterial





Optical discs

Next electronic memory



nature materials | REVIEW ARTICLE
PUBLISHED ONLINE: 23 AUGUST 2010 | DOI: 10.1038/NMAT2810

The Fano resonance in plasmonic nanostructures and metamaterials

Boris Luk'yanchuk[1], Nikolay I. Zheludev[2], Stefan A. Maier[3], Naomi J. Halas[4], Peter Nordlander[5*], Harald Giessen[6] and Chong Tow Chong[1,7]

APPLIED PHYSICS LETTERS **96**, 143105 (2010)

Metamaterial electro-optic switch of nanoscale thickness

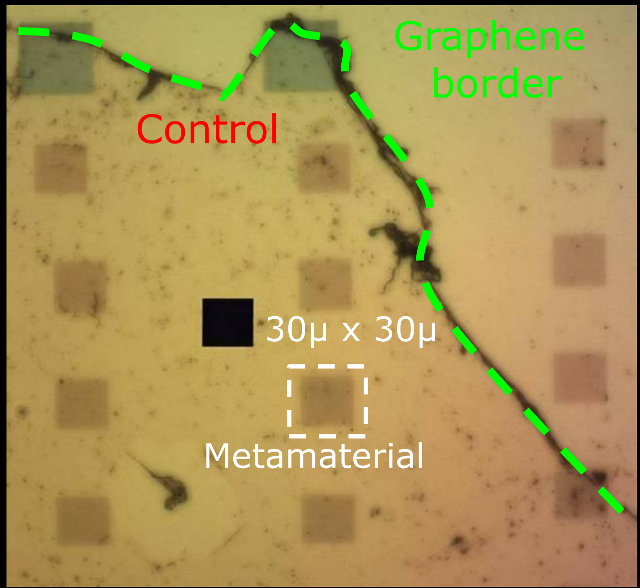
Z. L. Sámson,[1] K. F. MacDonald,[1,a)] F. De Angelis,[2] B. Gholipour,[1] K. Knight,[1] C. C. Huang,[1] E. Di Fabrizio,[2] D. W. Hewak,[1] and N. I. Zheludev[1]

Graphene @ Metamaterials

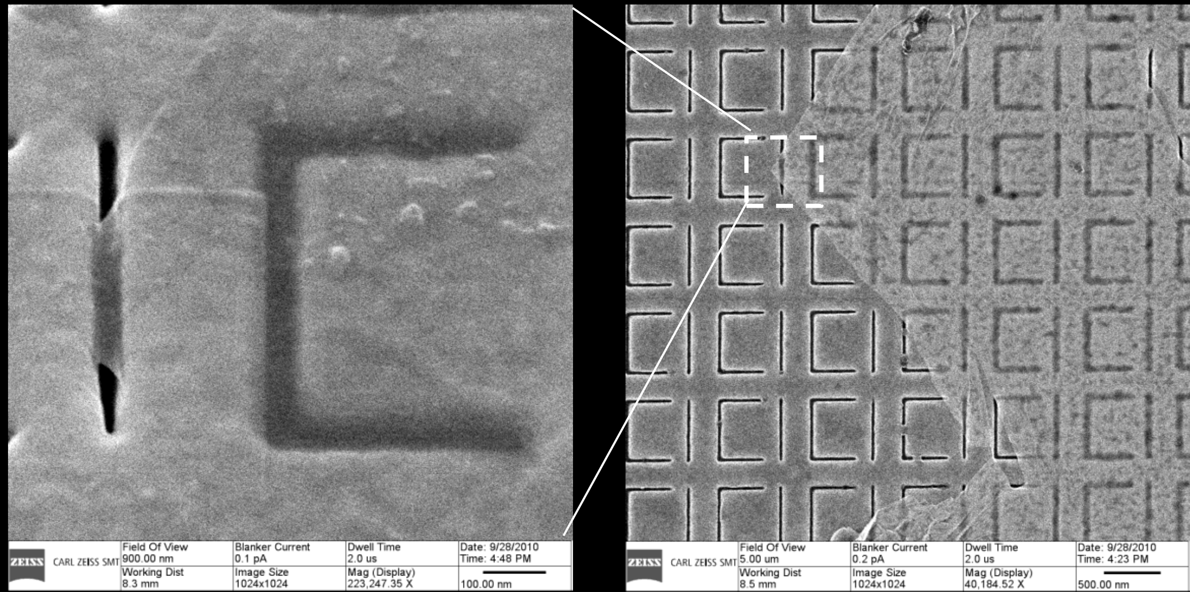
Graphene in a photonic metamaterial

12 April 2010 / Vol. 18, No. 8 / OPTICS EXPRESS 8353

Nikitas Papasimakis,[1] Zhiqiang Luo,[2] Ze Xiang Shen,[2] Francesco De Angelis,[3,4] Enzo Di Fabrizio,[3,4] Andrey E. Nikolaenko,[1] and Nikolay I. Zheludev[1]*

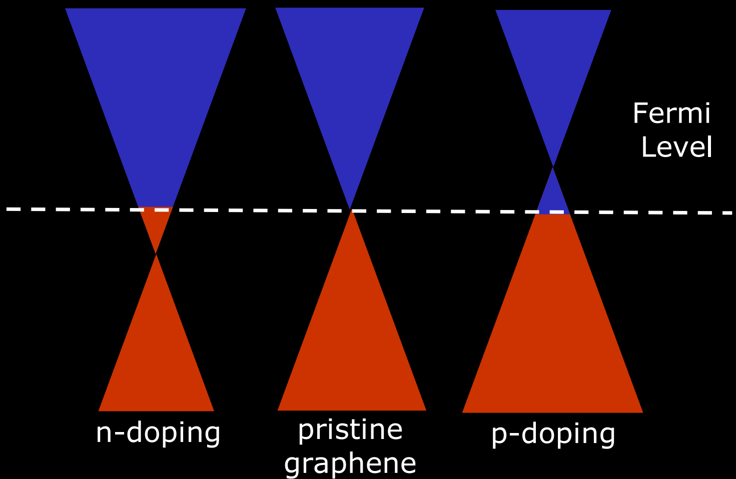


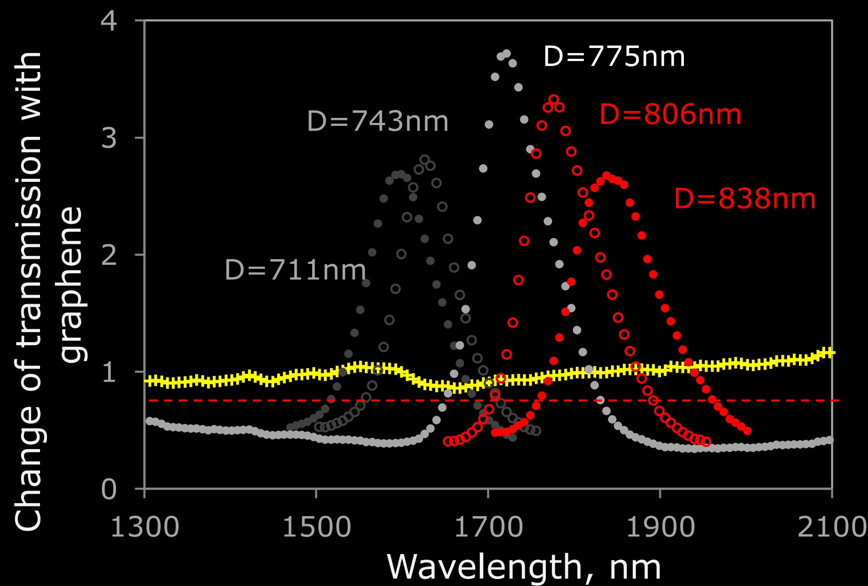
Optical microscope images



Helim-Ion microscope images

Modulating graphene properties by carrier injection





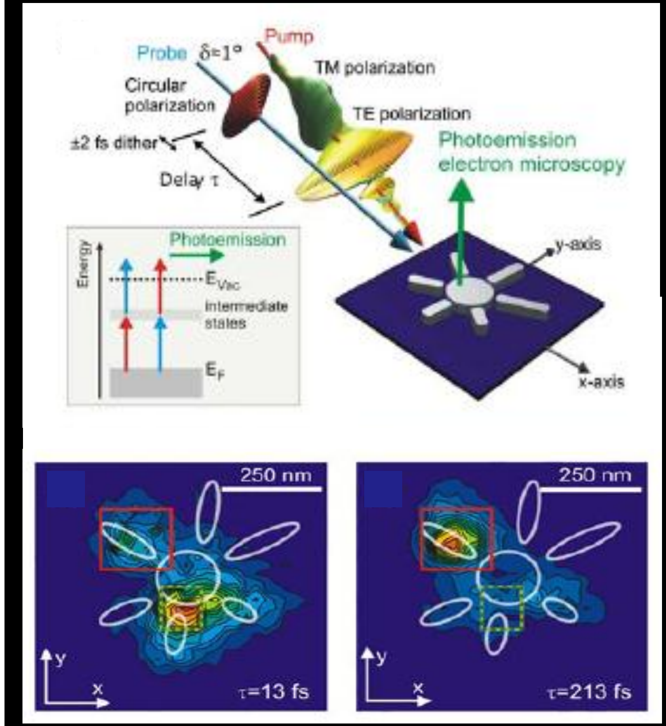
Nanoscale light localization in metamaterials

Goal:
Controlable hot-spots in metamaterials

Applications:
Imaging & data storage, routing

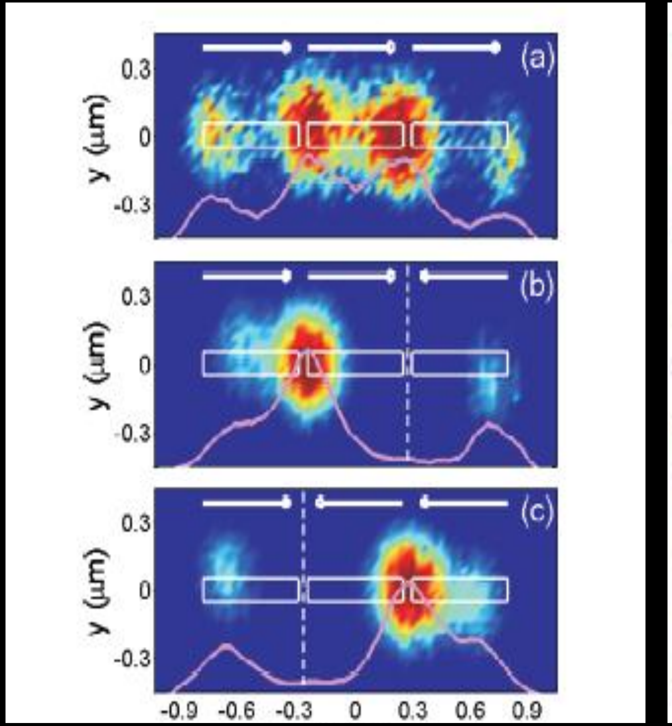
Manipulation of nanoscale optical fields

Ultrafast coherent control



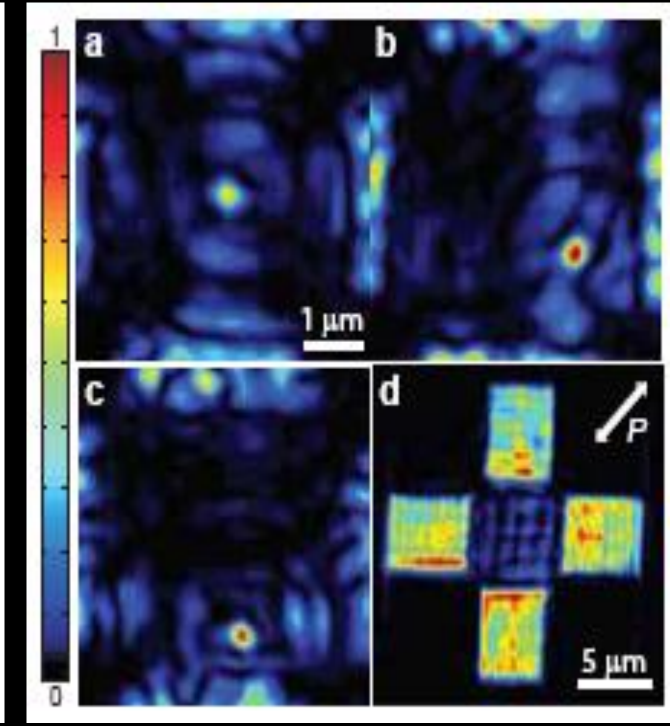
M. Stockman, M. Aeschlimann, *et. al,* (2006-2010)

Spatial phase-shaped beams



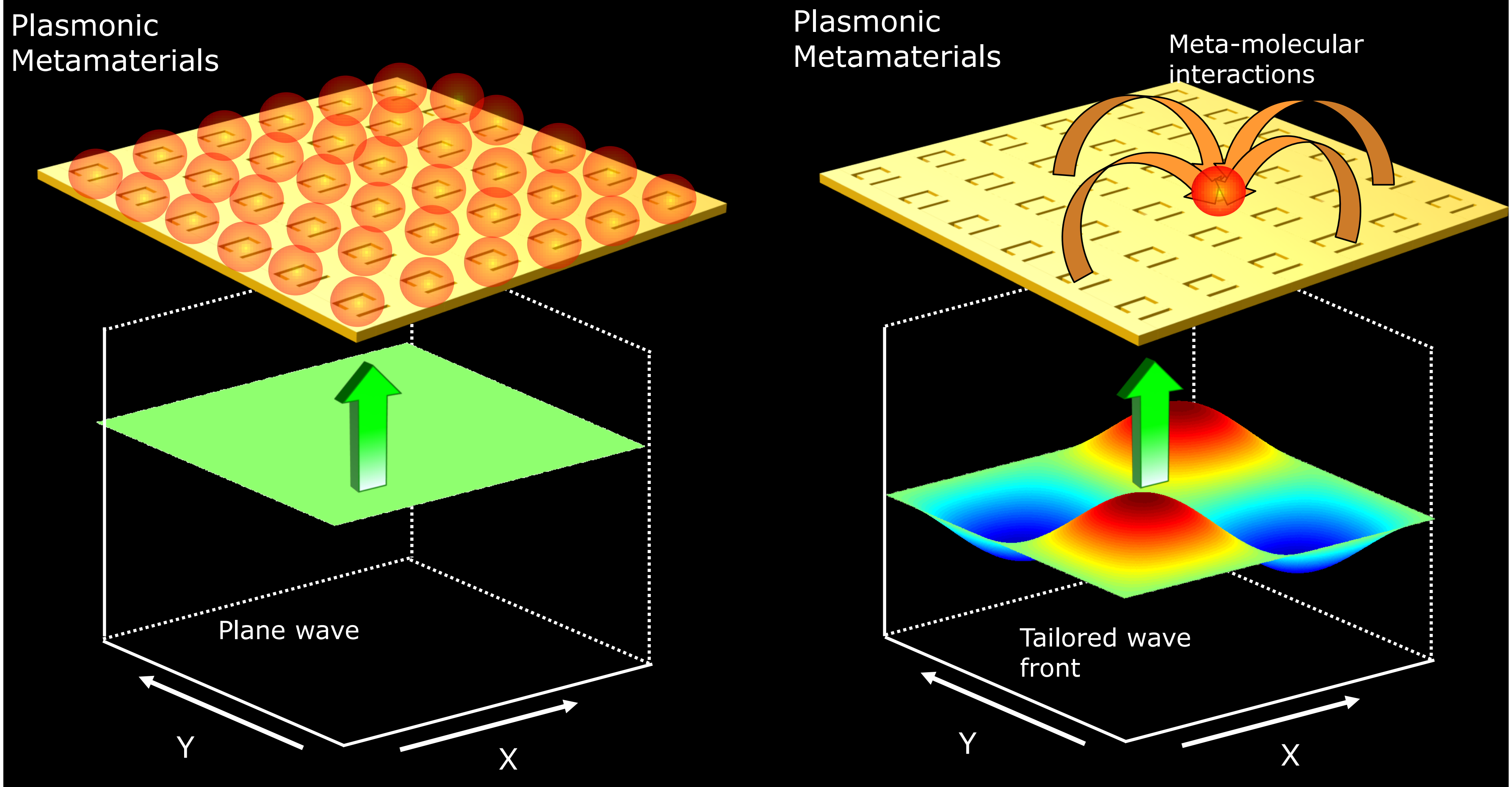
G. Volpe, *et. al,* (2009)

Tailored plasmon interference



B. Gjonag, *et. al,* (2011)

Coherent control of nanoscale field localization

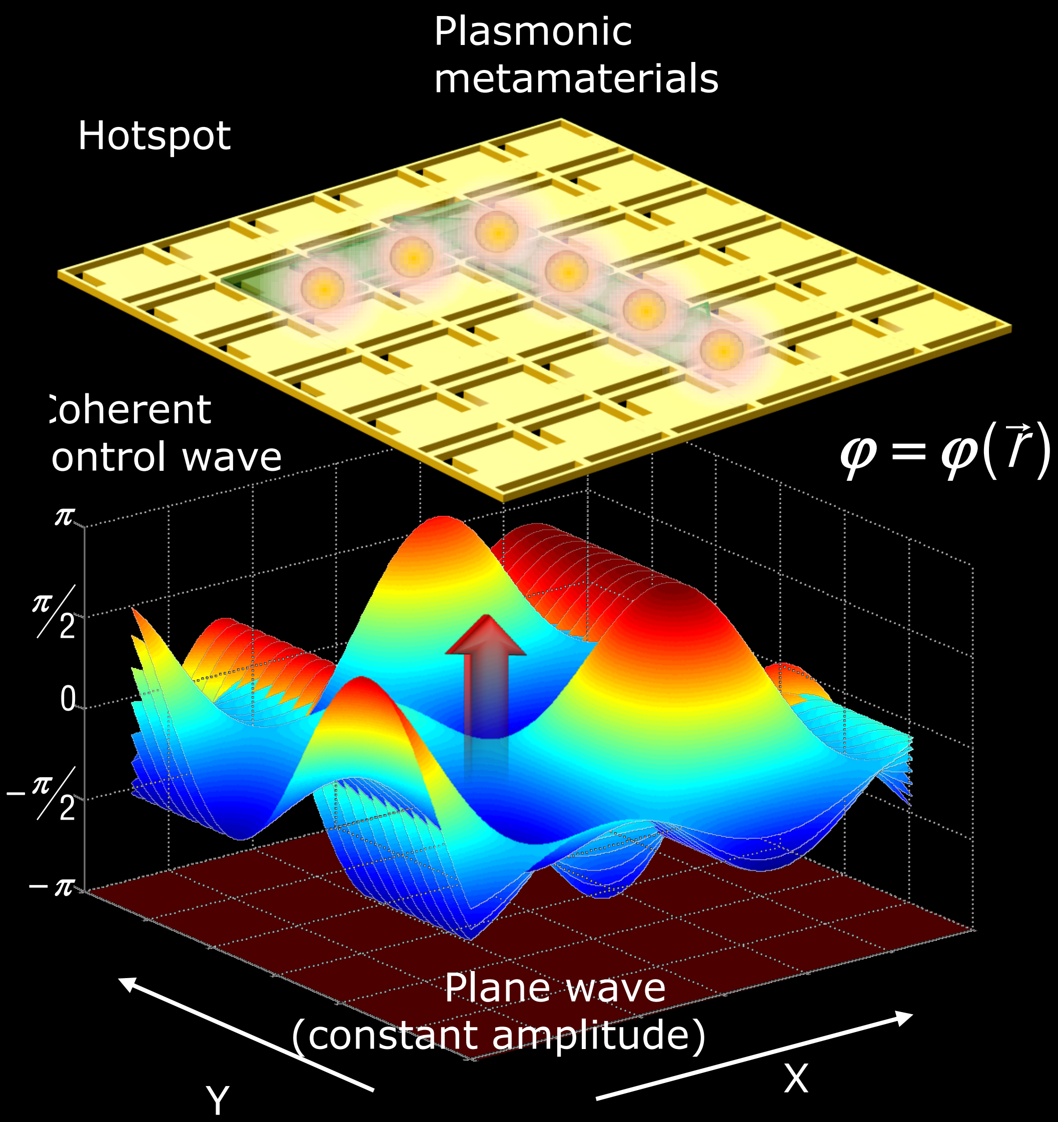


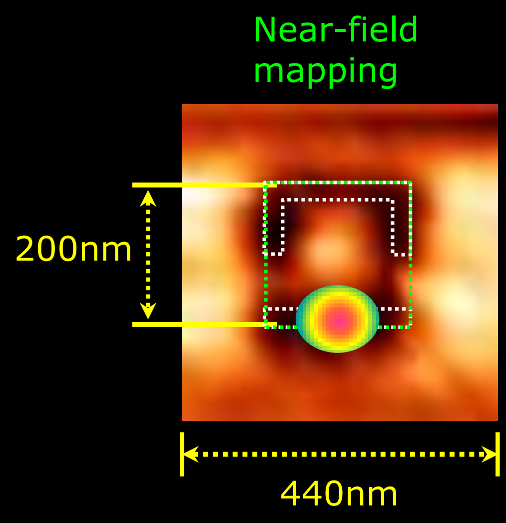
PRL 106, 085501 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

Coherent Control of Nanoscale Light Localization in Metamaterial: Creating and Positioning Isolated Subwavelength Energy Hot Spots

T. S. Kao,[1] S. D. Jenkins,[2] J. Ruostekoski,[2] and N. I. Zheludev[1,*]

“Digitally” addressable nanoscale light localization



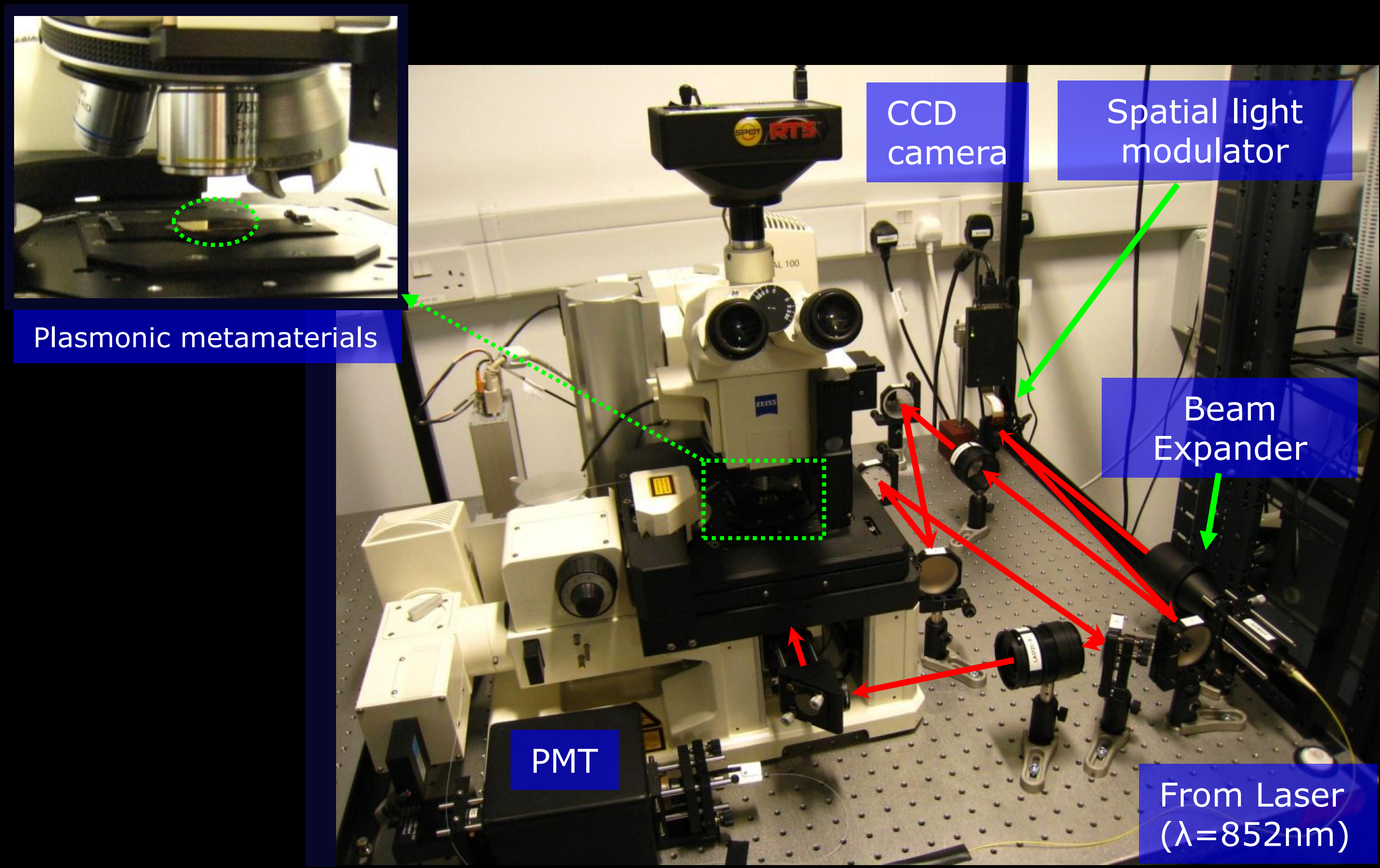


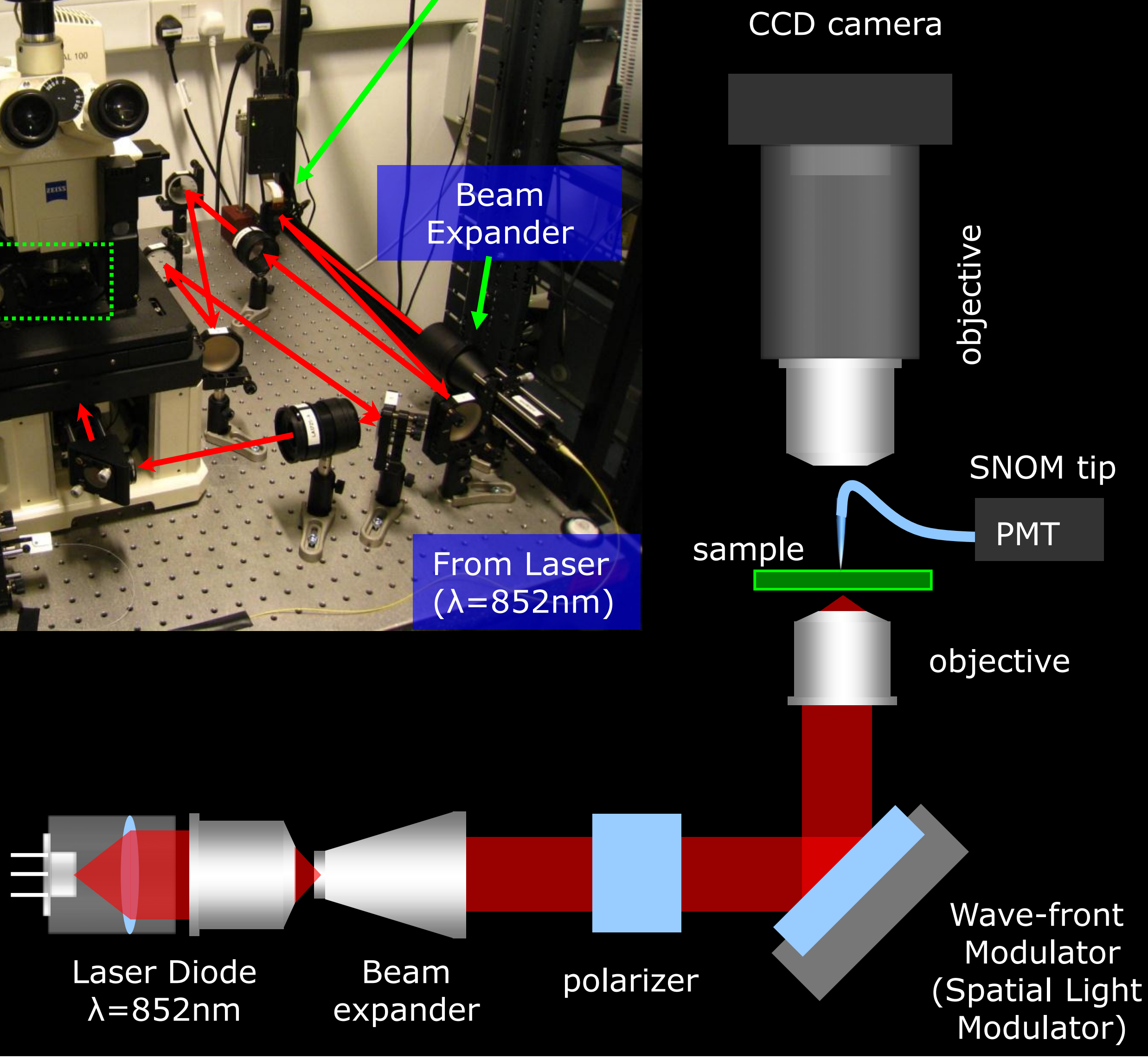
PRL 106, 085501 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

Coherent Control of Nanoscale Light Localization in Metamaterial: Creating and Positioning Isolated Subwavelength Energy Hot Spots

T. S. Kao,[1] S. D. Jenkins,[2] J. Ruostekoski,[2] and N. I. Zheludev[1,*]

Coherent control of nanospots: experiment

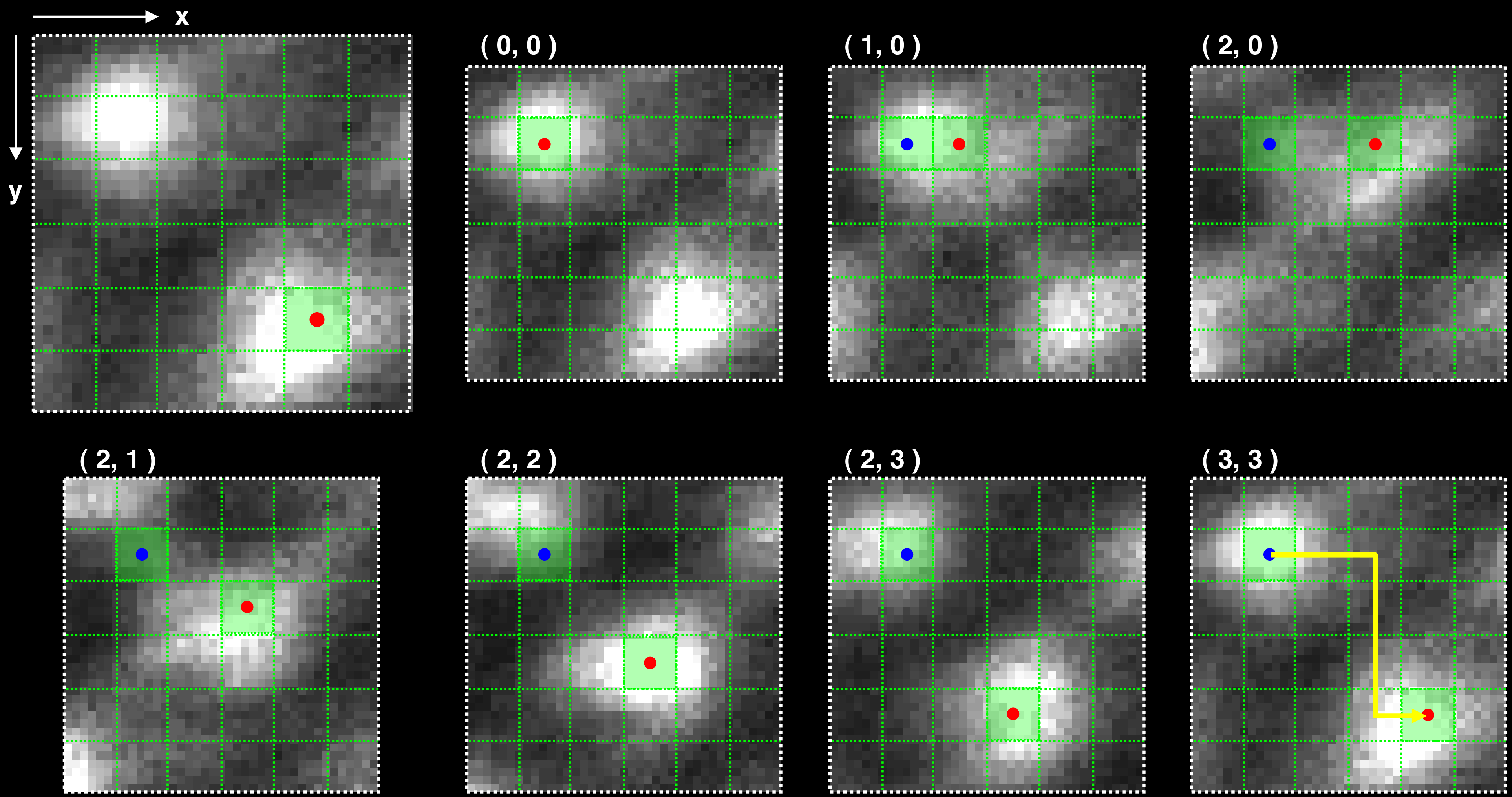




Digitally addressable placing of the hotspot

Metamaterials unit cell: 440nm, λ=852nm. Spatial wave-front profile: $\varphi(\vec{r}) = (\Delta\varphi / 2)\sin(kx)\sin(ky),\ k = 2\pi / a$

CCD images



Metamaterial
Light sources

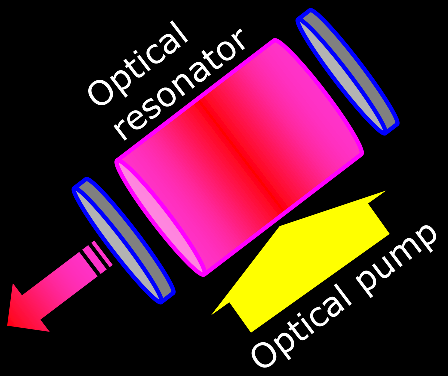
Goal:
Plasmonic & optical sources & lasers

Applications:
nanophotonics

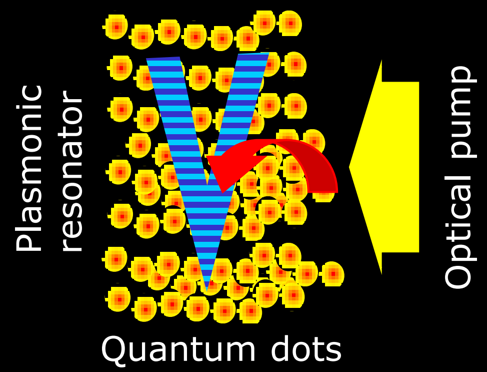
The Lasing Spaser (2008)

(a coherent source of optical radiation fuelled by plasmons)

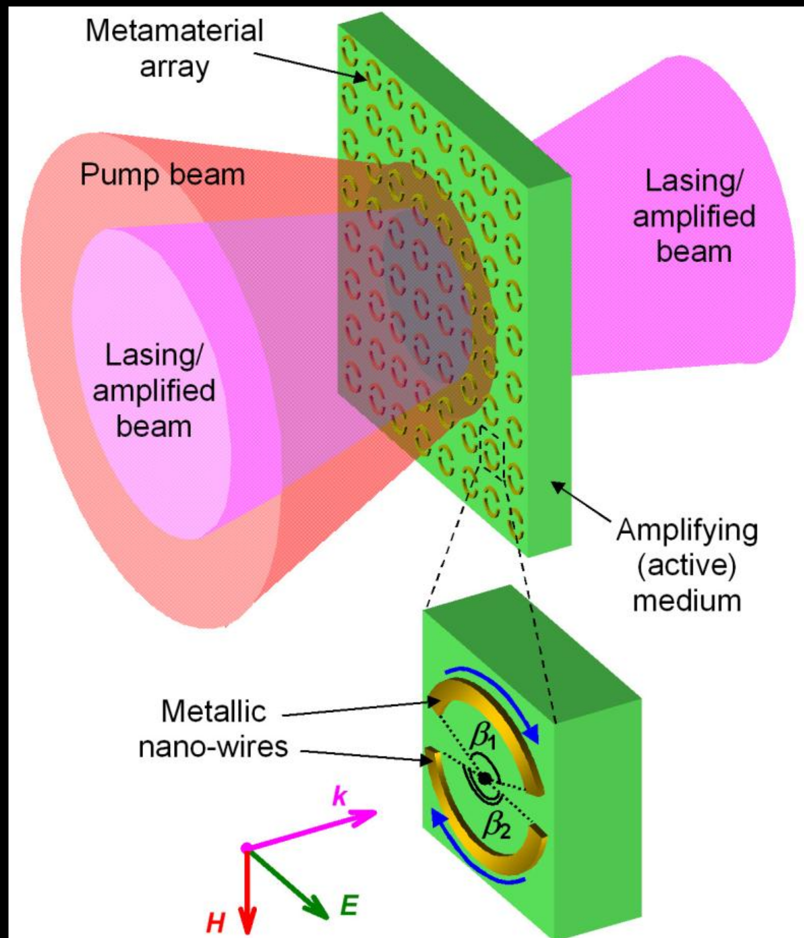
Laser 1953
Townes, Schawlow
Basov, Prokhorov



Spaser 2003
Bergman & Stockman



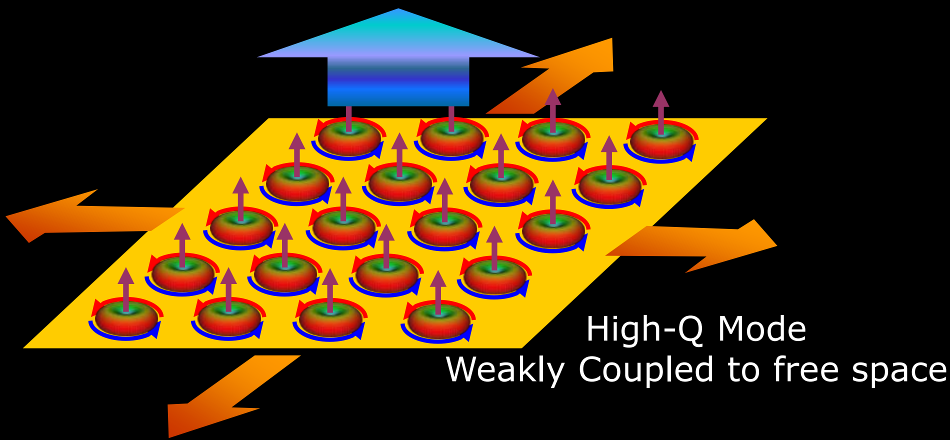
Lasing Spaser (2008)
Zheludev, Papasimakis, Prosvirnin, Fedotov



Lasing spaser

N. I. ZHELUDEV[1]*, S. L. PROSVIRNIN[2], N. PAPASIMAKIS[1] AND V. A. FEDOTOV[1]

nature photonics | VOL 2 | JUNE 2008 |

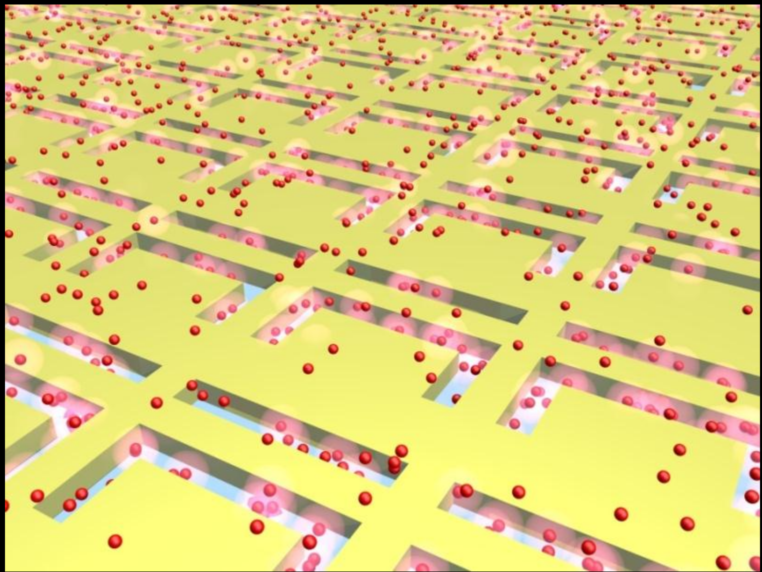


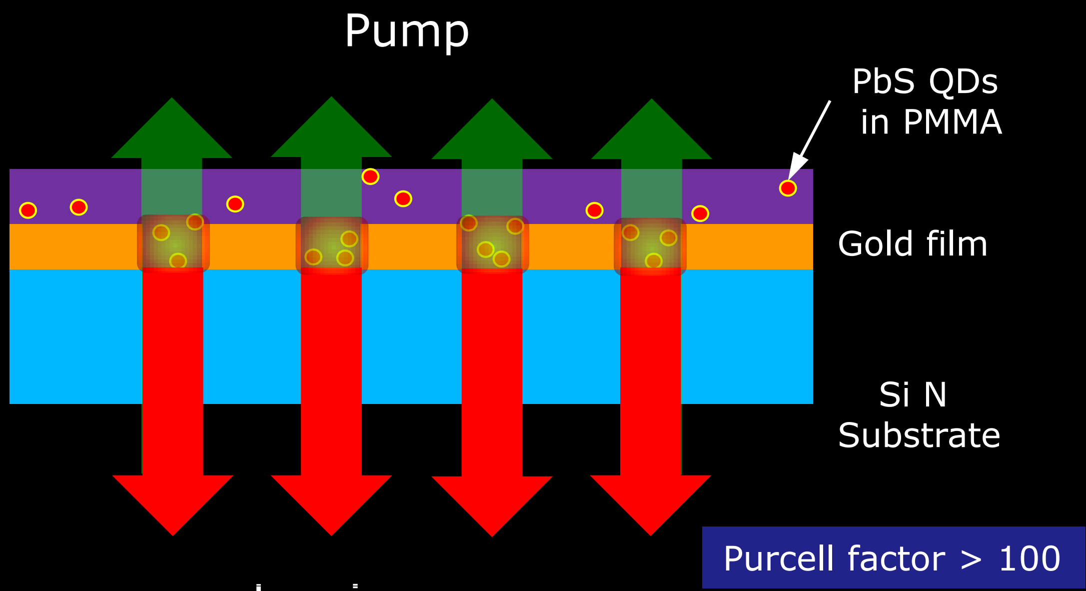
PRL **104,** 223901 (2010) PHYSICAL REVIEW LETTERS week ending 4 JUNE 2010

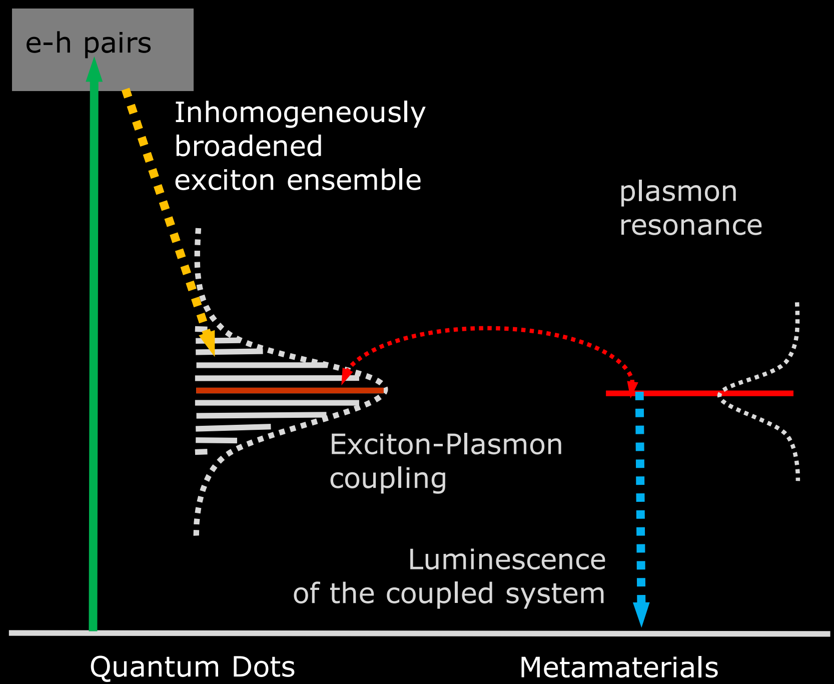
Spectral Collapse in Ensembles of Metamolecules

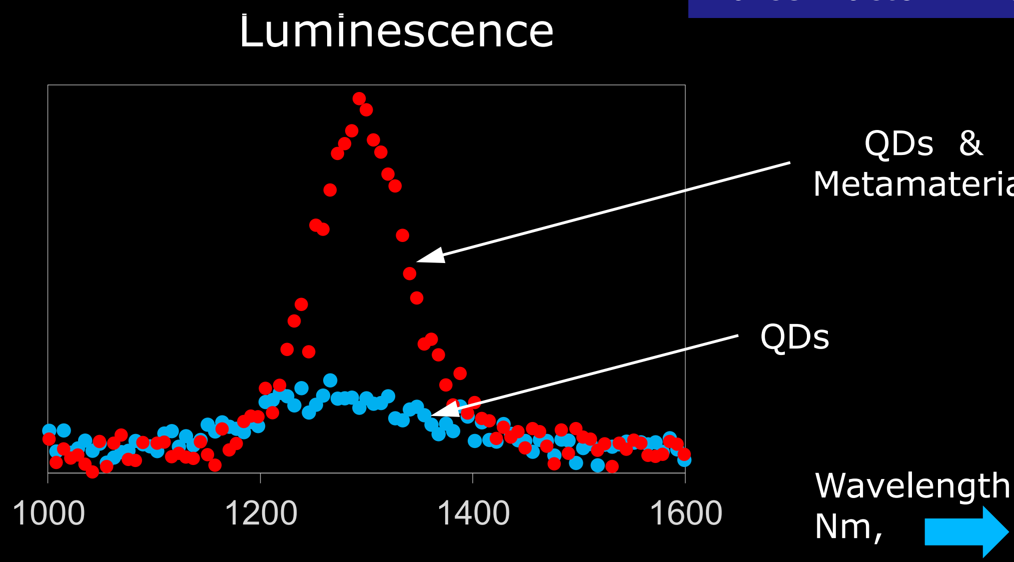
V. A. Fedotov,[1,*] N. Papasimakis,[1] E. Plum,[1] A. Bitzer,[2,3] M. Walther,[2] P. Kuo,[4] D. P. Tsai,[5] and N. I. Zheludev[1,†]

Quantum Dots in Plasmonic Metamaterial: Enhanced Luminescence









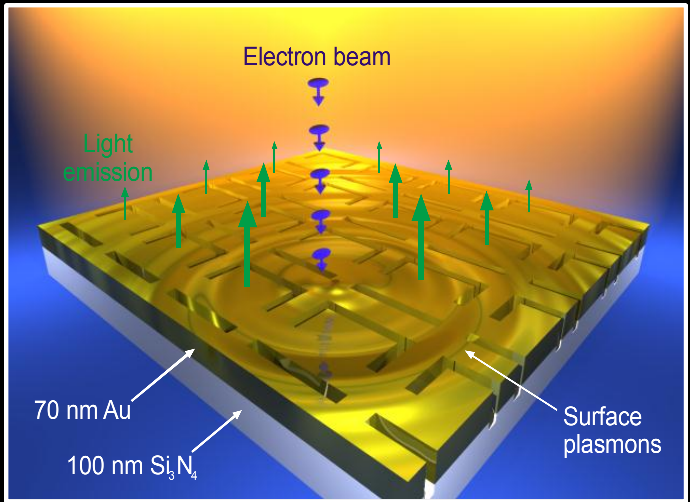
PHYSICAL REVIEW LETTERS October 2010

Multifold Enhancement of Quantum Dot Luminescence in a Plasmonic Metamaterial

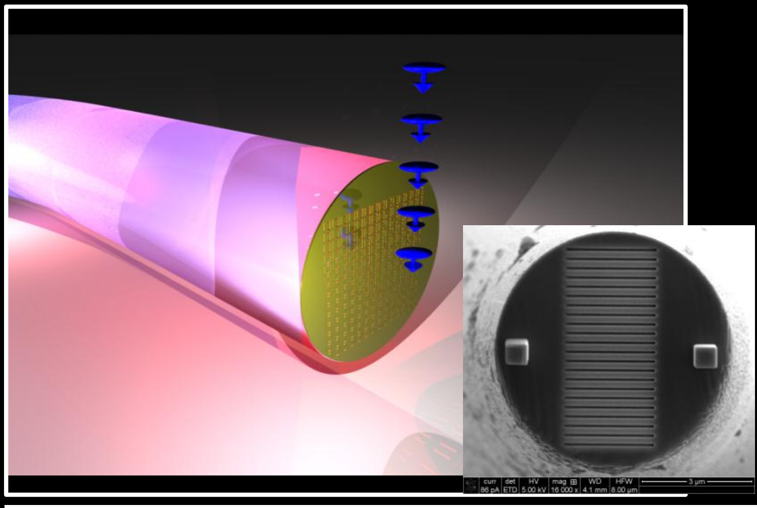
K. Tanaka,[1,2,*] E. Plum,[1,†] J. Y. Ou,[1] T. Uchino,[3] and N. I. Zheludev[1,‡]

Emission Linked to Plasmonic Resonance

Impact configuration



Fly by configuration

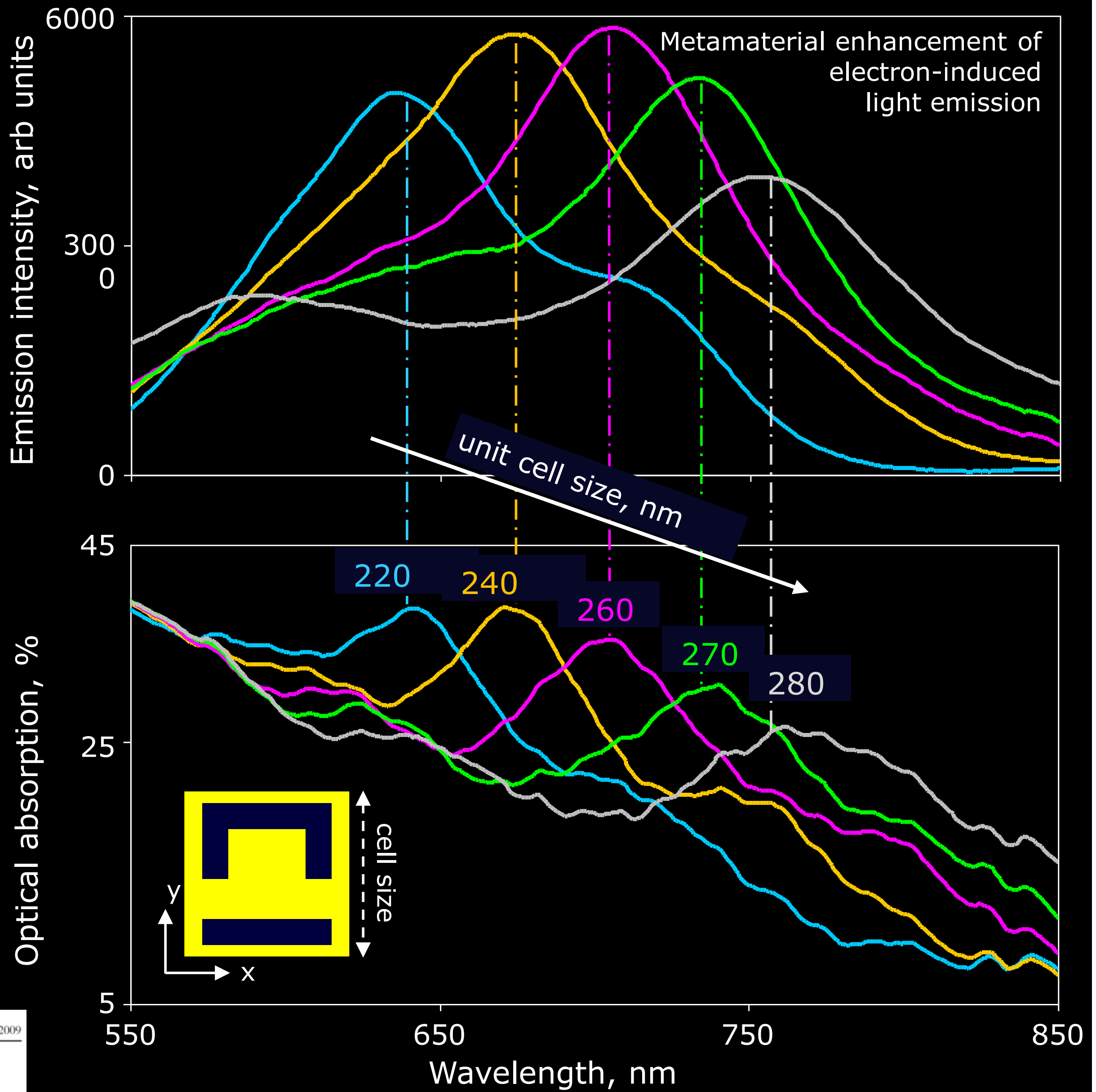


PRL 103, 113901 (2009) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2009

Light Well: A Tunable Free-Electron Light Source on a Chip

G. Adamo,[1] K. F. MacDonald,[1,*] Y. H. Fu,[2] C-M. Wang,[2] D. P. Tsai,[2] F. J. García de Abajo,[3] and N. I. Zheludev[1]

Electron-induced emission spectra Au/Si_3N_4 METAMATERIAL

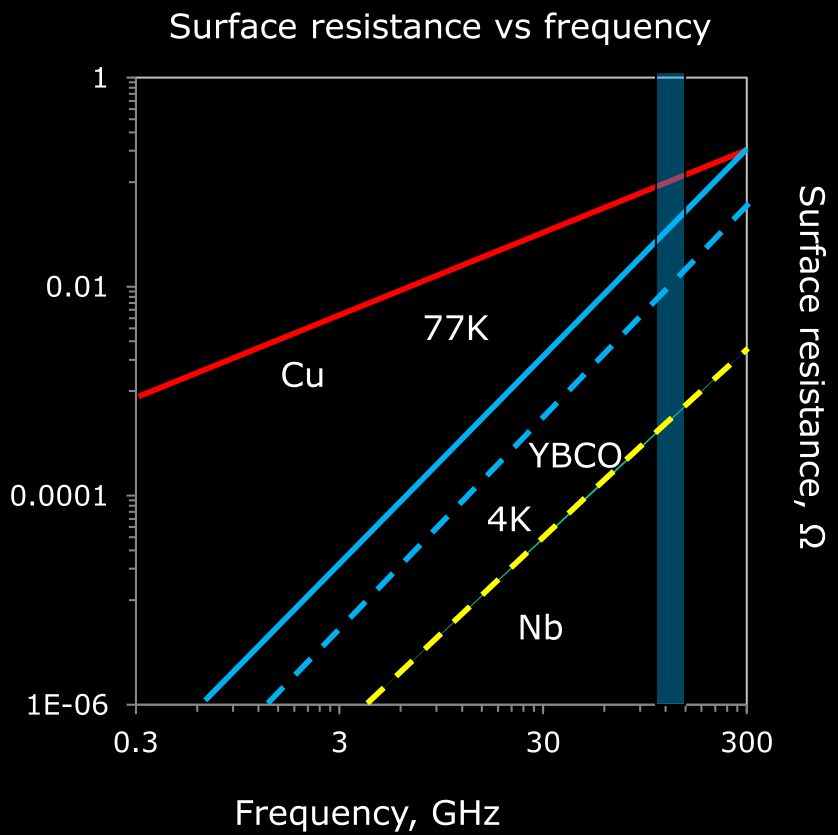


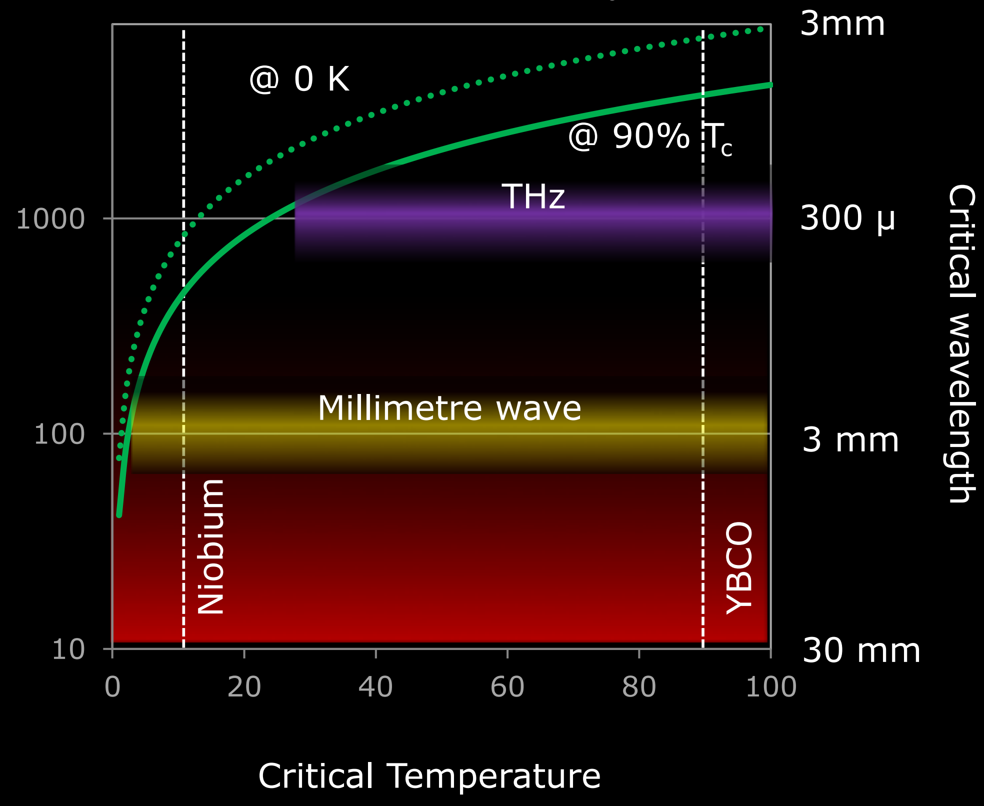
Quntum Superconducting Metamaterials

Goal:
High sensetivity

Applications:
New THz & Millimetre wave devices & quantum information platform

Low- *vs* high- temperature superconductors





Anlage Group - University of Maryland – Nb, waveguide microwave

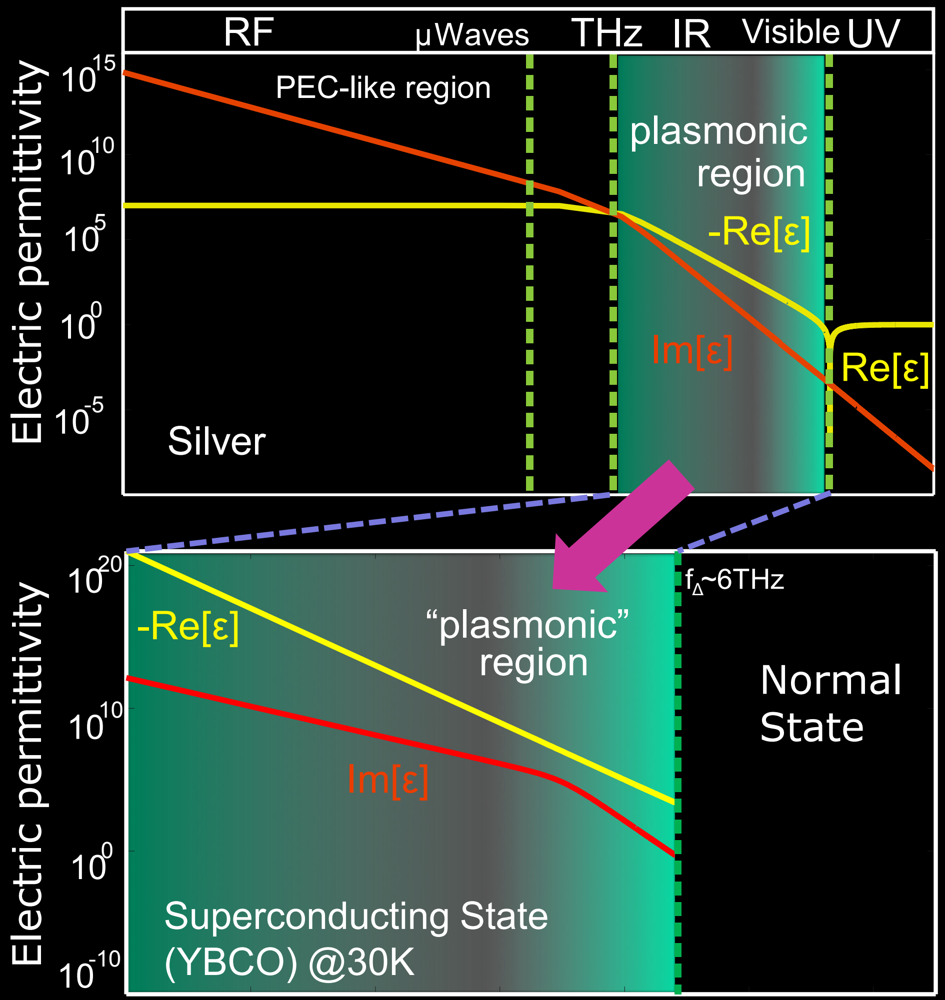
Los Alamos group – High-Tc, THz free space

Southampton group – High Tc and Nb, Millimetre wave free space

APL **97,** 111106 (2010)

OptExp **18**, 9015, (2010)

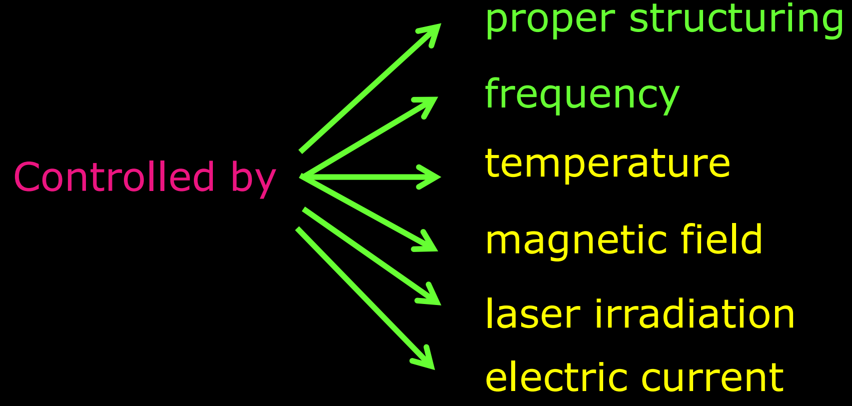
Case for Superconducting Plasmonics



When $T<T_c$ in superconductors :

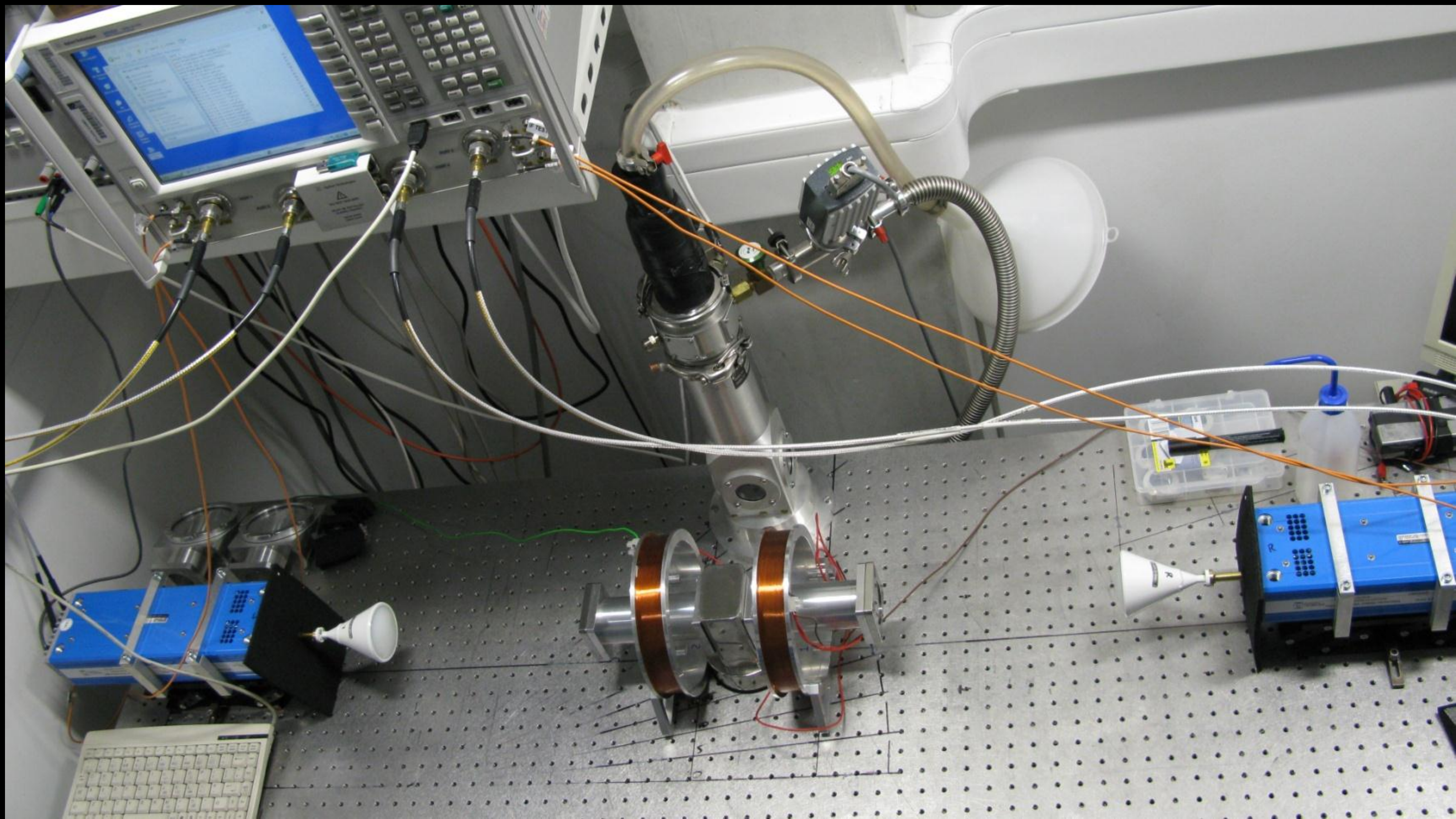
- losses are vanishing
- e^- inertia prevails

Superconductors are intrinsic plasmonic media



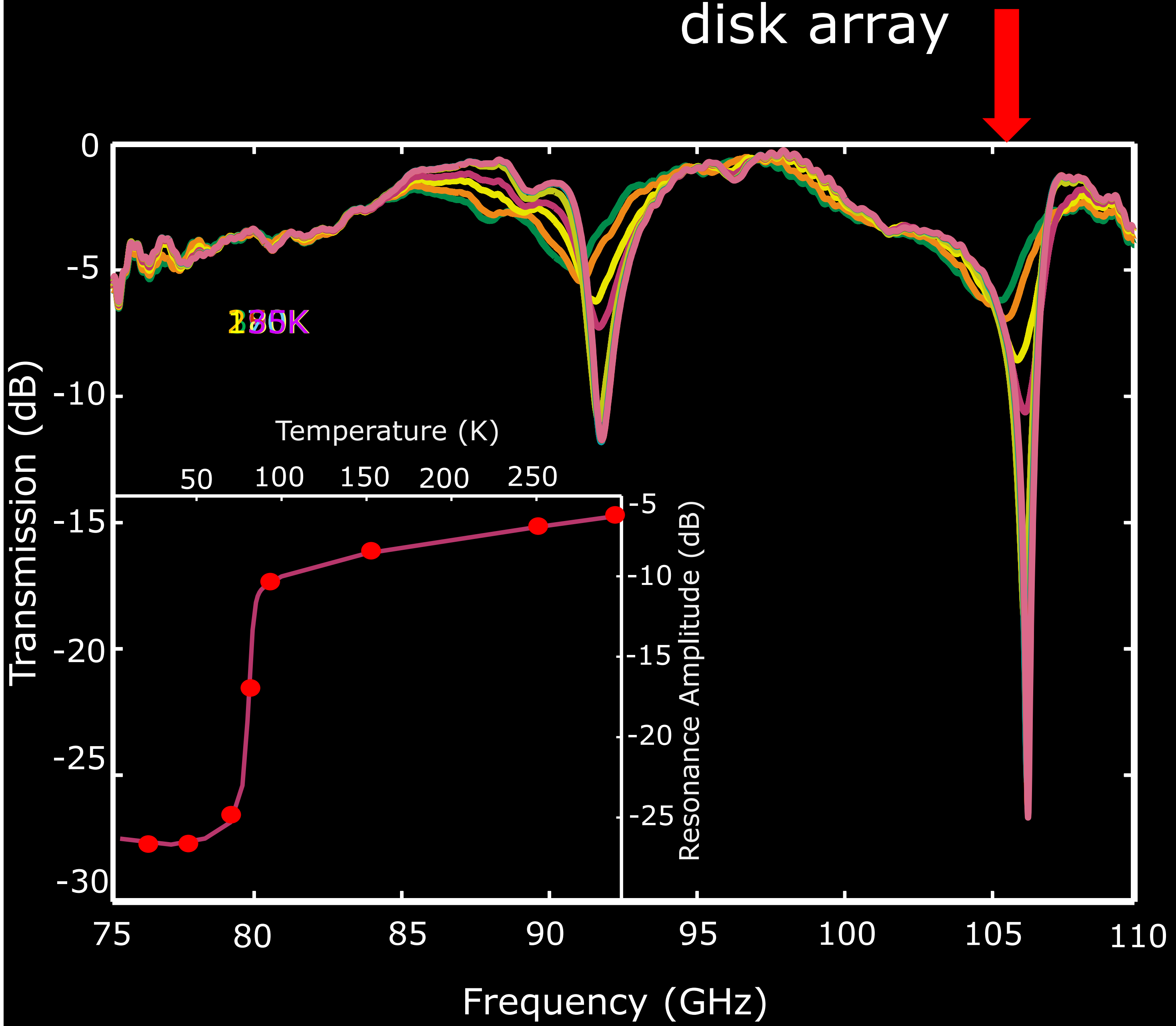
Low frequency plasmonics with easily integrated active control functionality

100GHz free-space (millimetre waves) spectrometer



Receiving/Transmitting Antenna | He Cryostat Coldfinger | Receiving/Transmitting Antenna

Sharp resonances in superconducting metamaterials
disk array



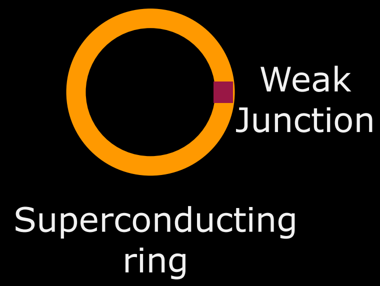
YBCO disks 0.5mm diameter
1.5mm period

Resonance becomes much sharper in Superconducting state
Q-factor>60

A. Tsiatmas N.I.Zheludev *et al.*, Appl. Phys. Lett. **97,** 111106 (2010)
Fedotov, Tsiatmas, Zheludev et.al. *Opt. Exp.* **18**, 9015 (2010)

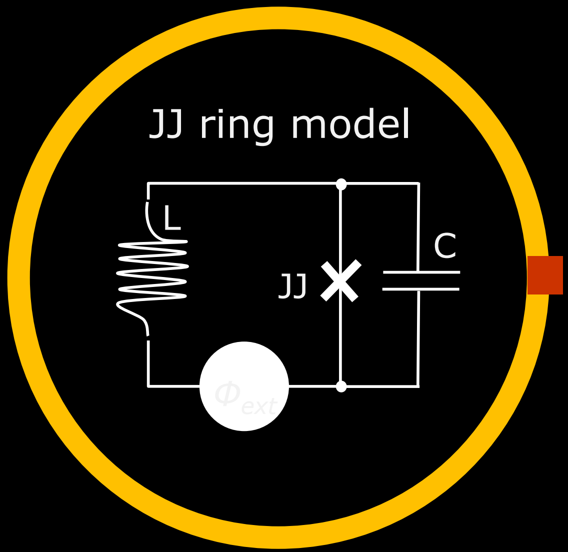
Towards digital / quantum metamaterials

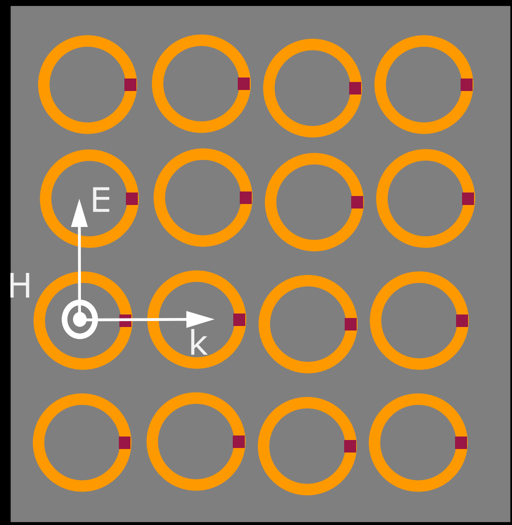
Conventional metamaterial	Quantum metamaterial
Classical plasmonic resonator	Quantum-interference circuit



Classical plasmonic resonator	**Quantum-interference circuit**
Excitation	
Plasmon	Quantum Qbit
Mode of Operation	
Analogue	Digital (Quantized flux)
Advantages	
Simple	Quantum level of operation, extremely high nonlinearities (100 000 times higher than p-n junction)

Superconducting metamaterial: Josephson Junctions



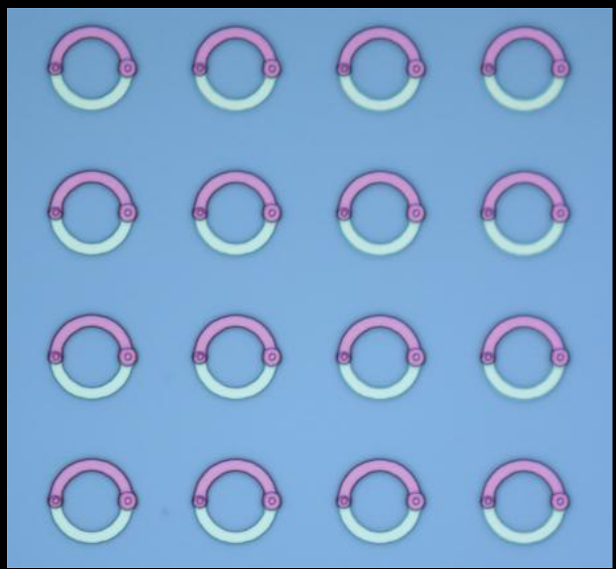


Flux dynamics

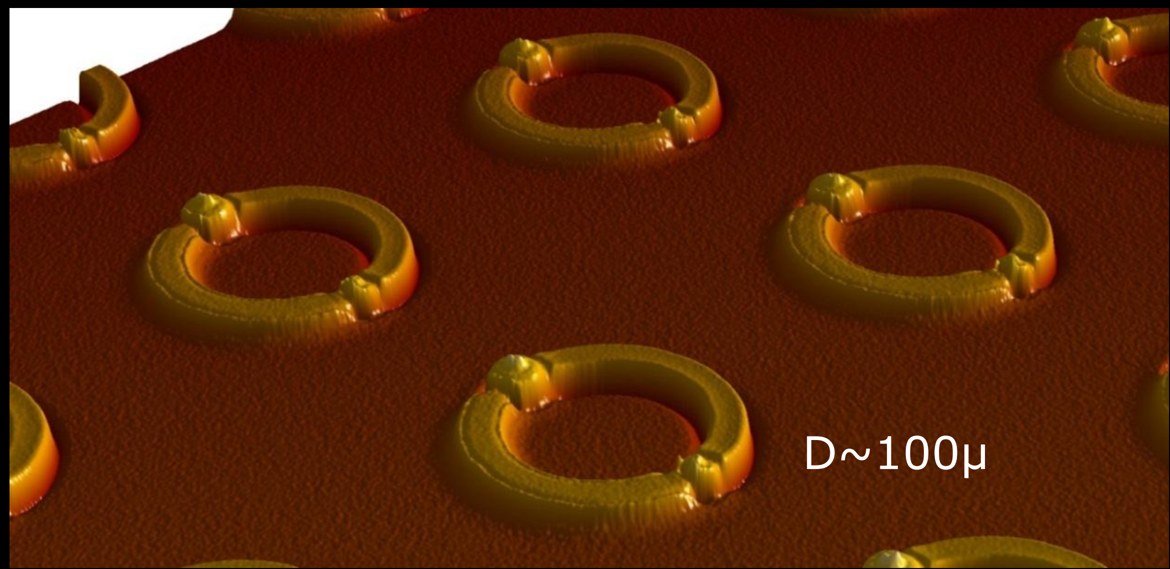
$$\ddot{\Phi}+\gamma\dot{\Phi}+\beta\sin(2\pi\Phi)+\Phi=\Phi_{ext}$$

Du, Chen, Li, 2006
Lazarides & Tsironis, 2007

Southampton Nb – Al_2O_3 – Nb Josephson Junction Arrays

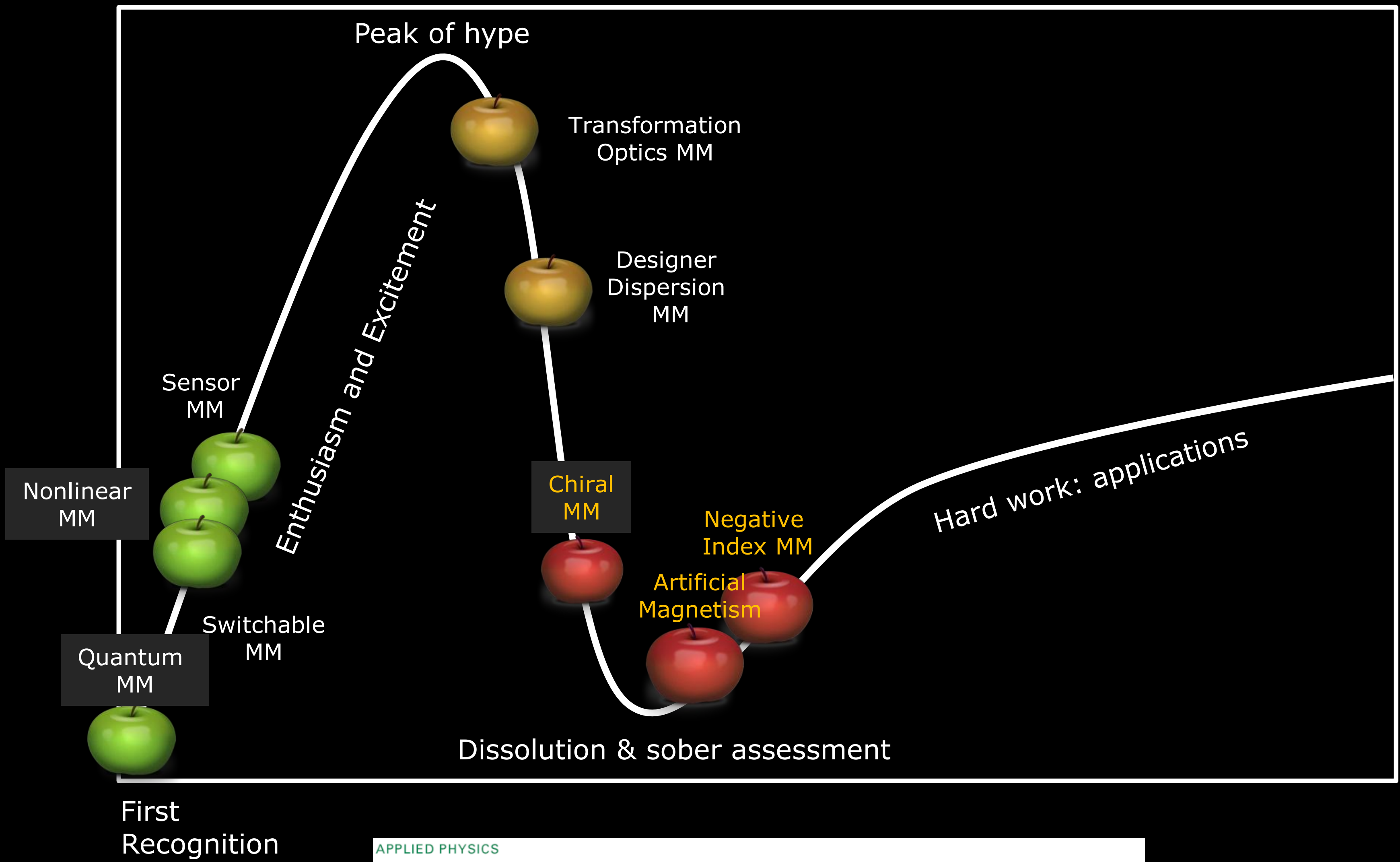


Optical micrograph



Profile

Metamaterials: the technology development curve



APPLIED PHYSICS

The Road Ahead for Metamaterials

Metamaterials enable us to design our own "atoms" and thus create materials with new properties and functions.

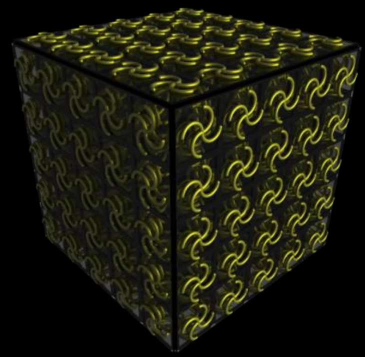
Nikolay I. Zheludev

30 APRIL 2010 VOL 328 SCIENCE www.sciencemag.org

In the Past:

Metamaterial is a **material**

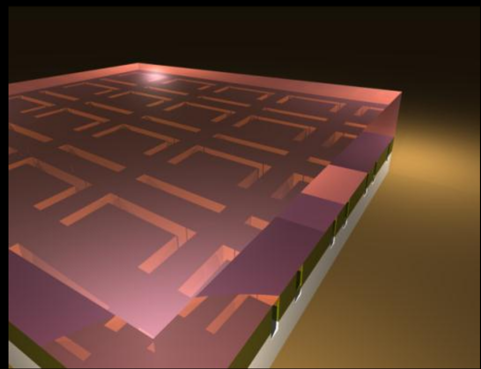
Structuring brings new properties



At Present:

Metamaterial is a **device**

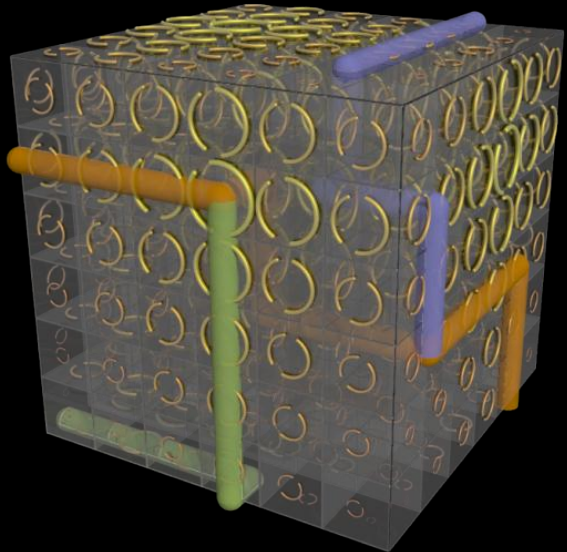
Structuring brings new functionality

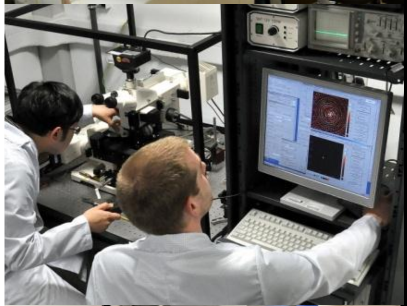
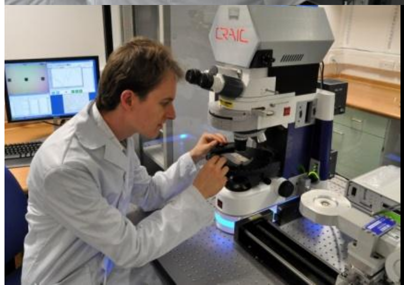


In the Future:

Metamaterial is a **system**

Structuring brings new functionalities & integration



Southampton Centre for Photonic Metamaterials

www.nanophotonics.org.uk