

Optical Functionalities on Demand: from metamaterials to metadevices

Nikolay Zheludev

10.50 - 11.35 9 June 2014. CIMTEC Plenary, Montecatini Terme, Italy



Centre for Photonic Metamaterial, ORC
University of Southampton, UK
www.nanophotonics.org.uk

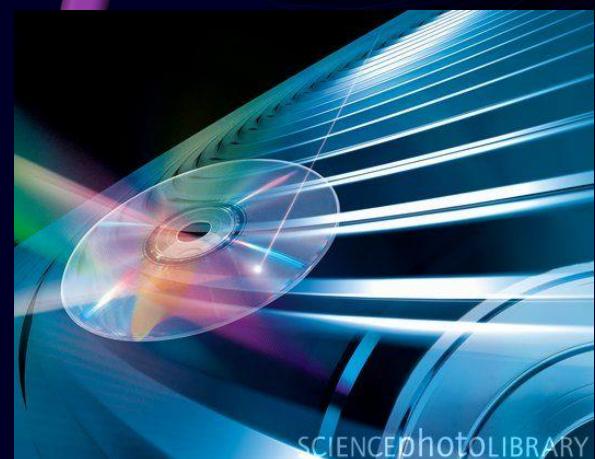
Centre for Disruptive Photonic Technologies
Nanyang Technological University, Singapore
www.nanophotonics.sg



The 1st Photonic Revolution



Global Telecommunications

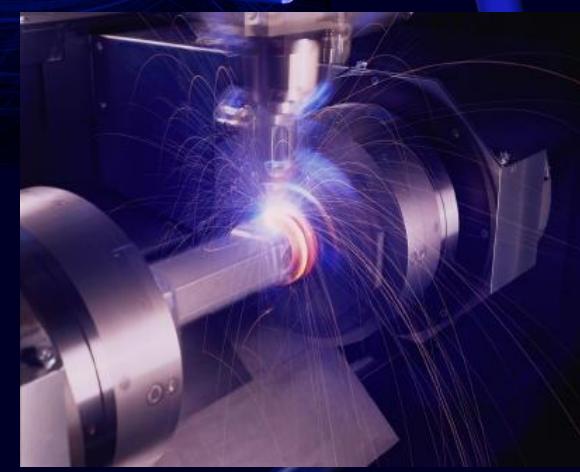


Optical Data Storage

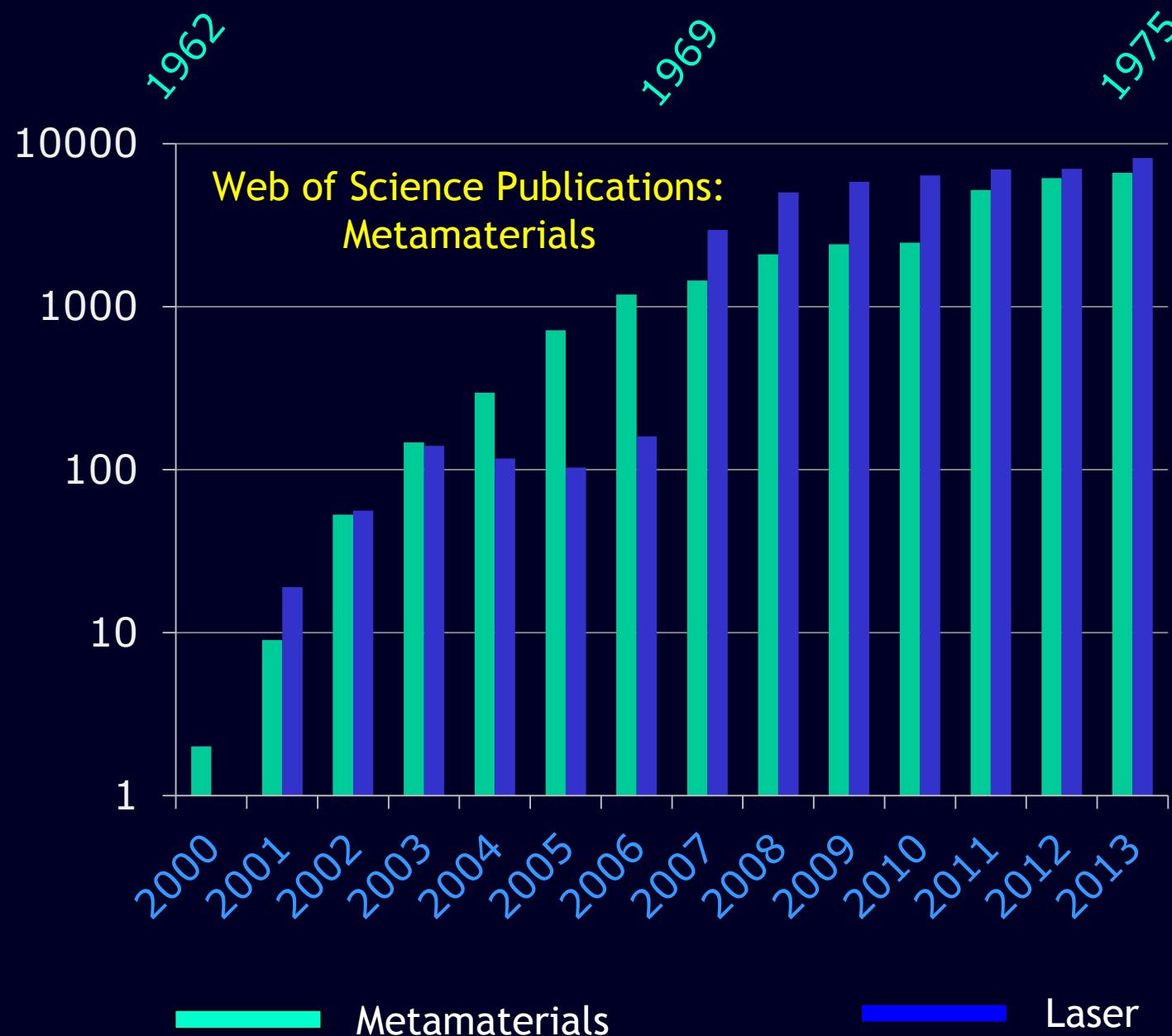
Laser medicine



Laser manufacturing



The Next Photonic Revolution: Metamaterials



Metamaterials =
Negative Index Media
& Superlens?



Metamaterials =
Invisibility
& Cloaking?

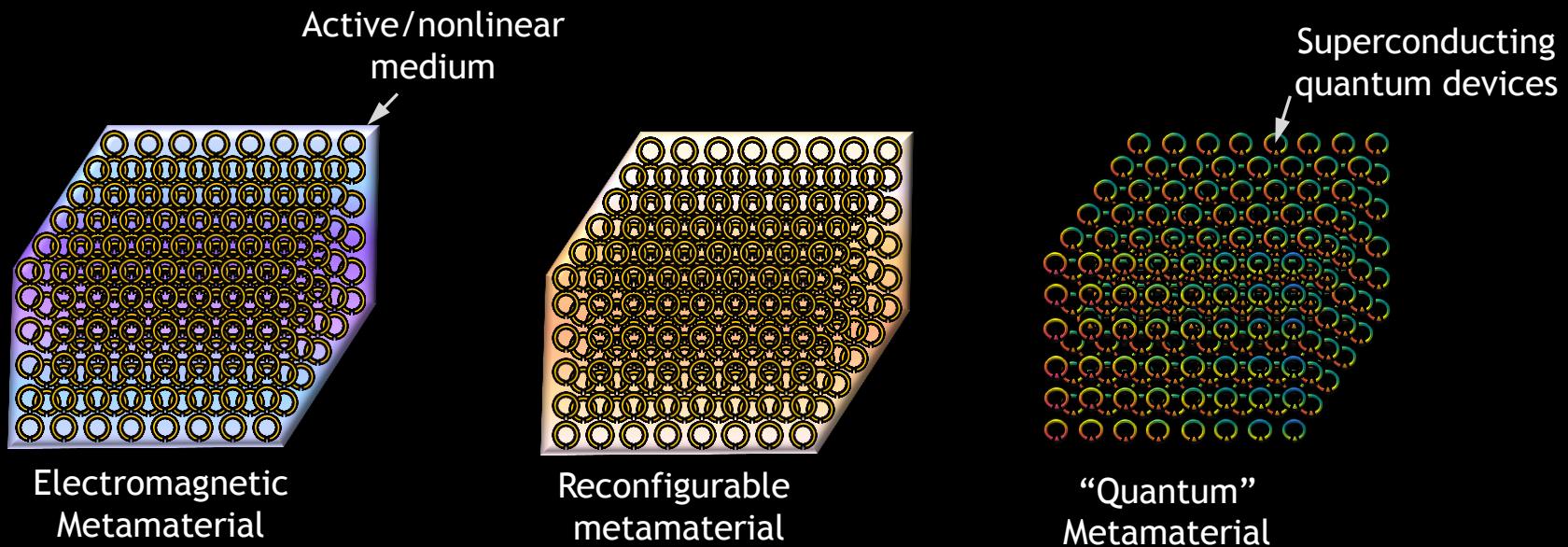
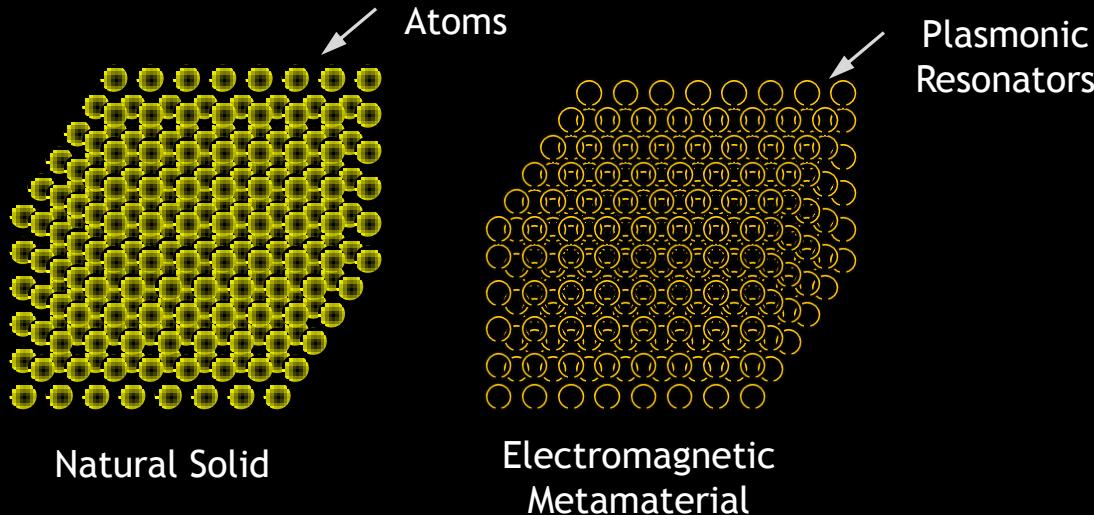


Metamaterial is a manmade media with all sorts of unusual functionalities that can be achieved by artificial structuring smaller than the length scale of the external stimulus.

N.I. Zheludev. Nature Materials 7, 420 (2008)

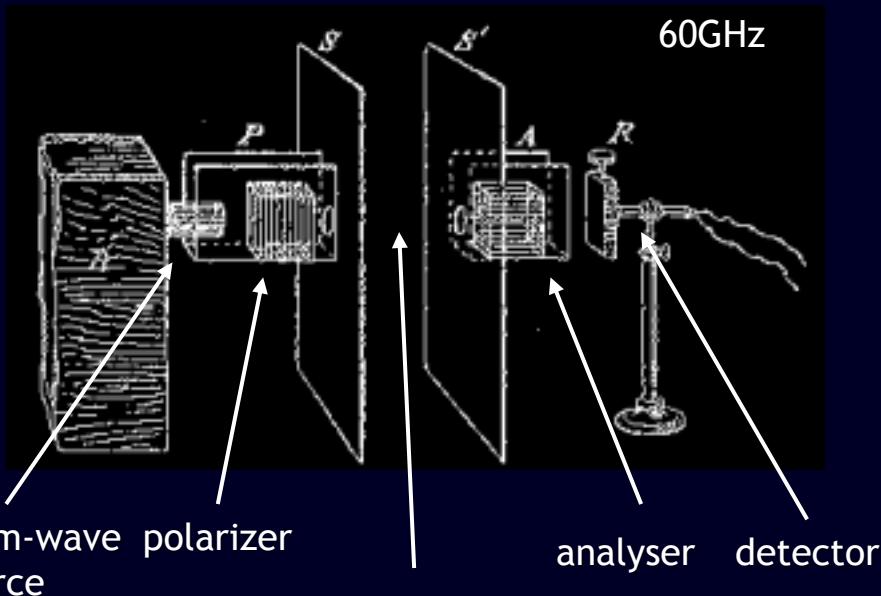
Metamaterials are manmade media with electromagnetic properties on demand

Metamaterials: electromagnetic properties on demand



1st Metamaterial (J.Bose, 1898)

"In order to imitate the rotation by liquids like sugar solutions, I made elements of molecules of twisted jute..."

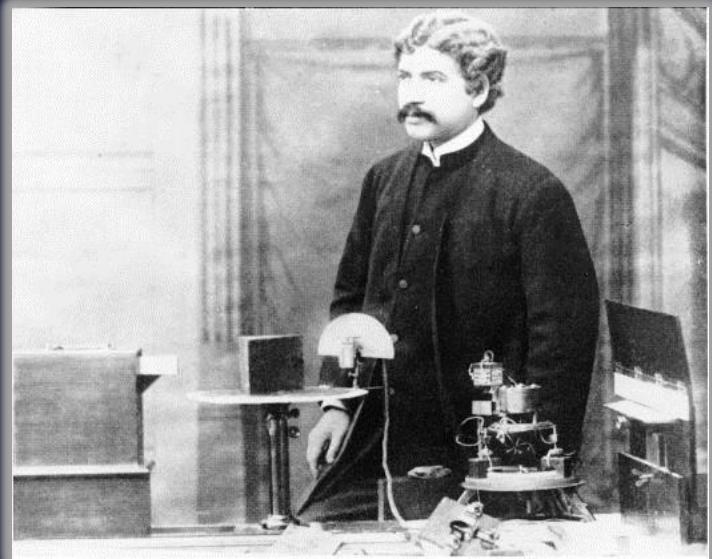


spark mm-wave source

polarizer

analyser

detector



J.Bose.
Proc. Royal Soc. of London (1898)



Chiral meta-Molecule
(twisted jute)



Anisotropic meta-Molecule
(metal sheets alternated with paper)

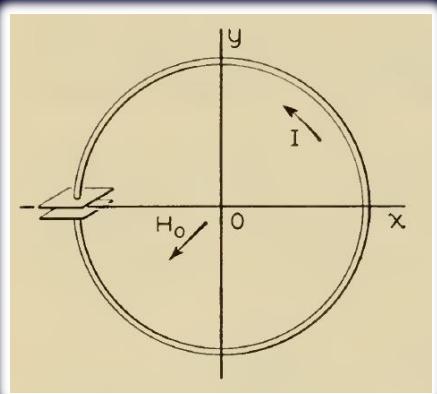
Hundreds of papers

Impact of Metamaterials on Fundamental Physics #1

Optical Magnetism & Negative Refraction

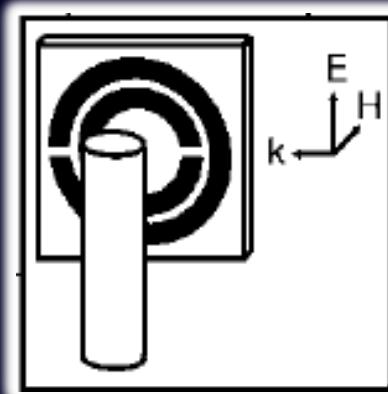
L. D. Landau, E. M. Lifshitz, and L. P. Pitaevskii (1962): "... there is certainly no meaning in using the magnetic susceptibility from optical frequencies onwards and ... we must put $\mu = 1$."

Method for increasing the permeability of artificial dielectrics



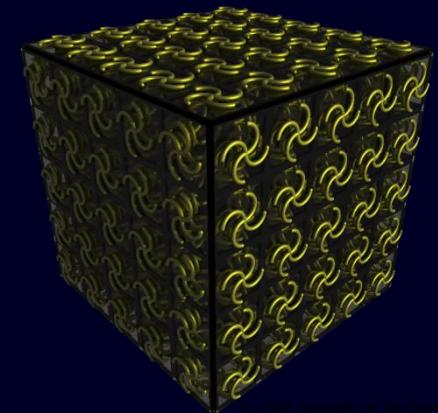
S.A.Schelkunoff & H.T.
Friis
Antennas Theory and
Practices. J.Wiley & Sons,
1952

Negative Permeability and Permittivity
("left-handed")



D. R. Smith, W. J.
Padilla ... S. Schultz,
PRL (2000)

Negative refraction due to
chirality $\sim \text{Im} \{ m_{kn} d_{nk} \}$



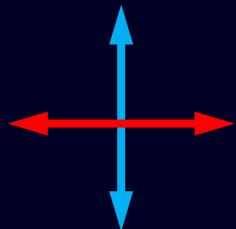
© 2009 University of Southampton

Tretyakov (2003)
Pendry (2004)
Rogacheva... Zheludev PRL. (2006)
Plum Zheludev, PR B (2009)

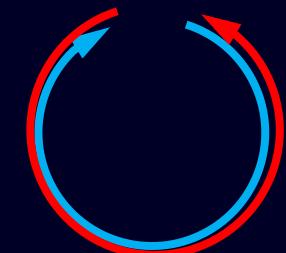
Impact of Metamaterials on Fundamental Physics #2

Reciprocal Asymmetric Transmission

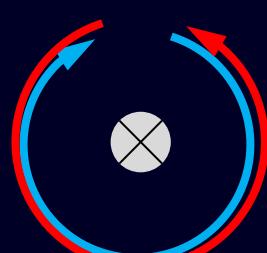
Birefringence



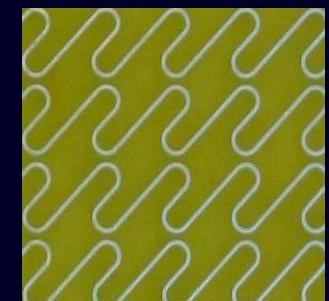
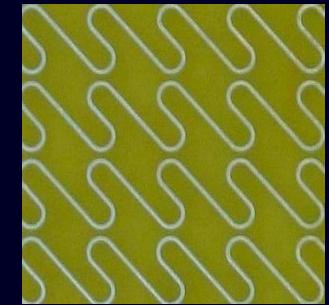
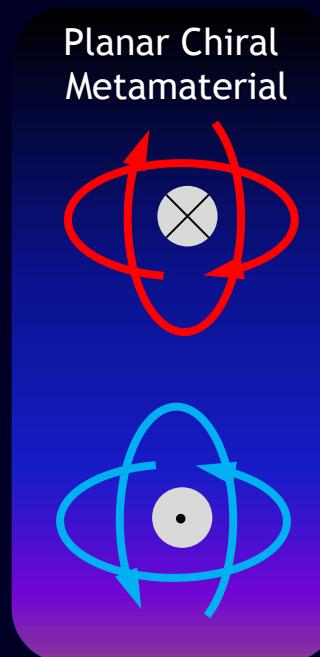
Optical Activity



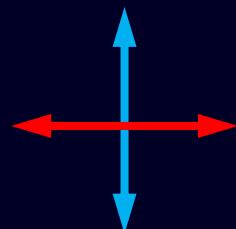
Faraday effect



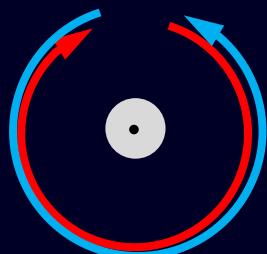
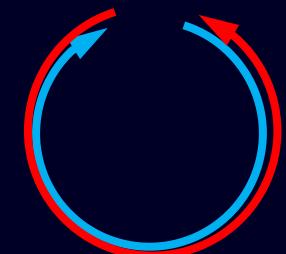
Planar Chiral Metamaterial



Forward



Reversed



Asymmetric transmission
Reciprocal effect!



Fedotov ...Zheludev. PRL (2006)

>30 papers

Impact of Metamaterials on Fundamental Physics #3

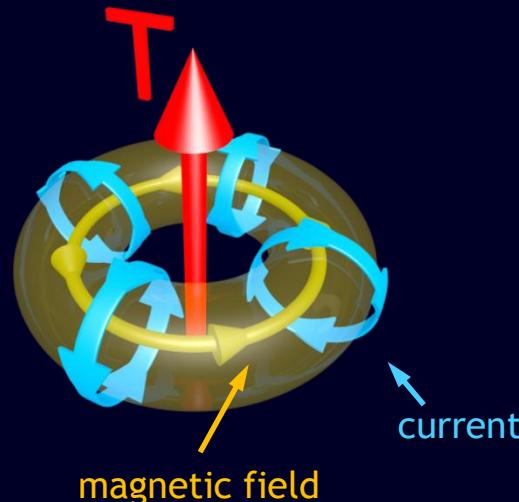
Toroidal Dipole

Magnetic
Multipoles
(transverse
currents)

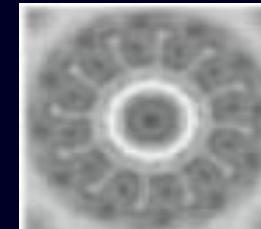
Zeldovich. Sov. Phys. JETP (1953)

Electric
Multipoles
(Charges)

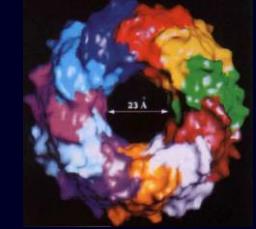
Toroidal
Multipoles
(Radial
Currents)



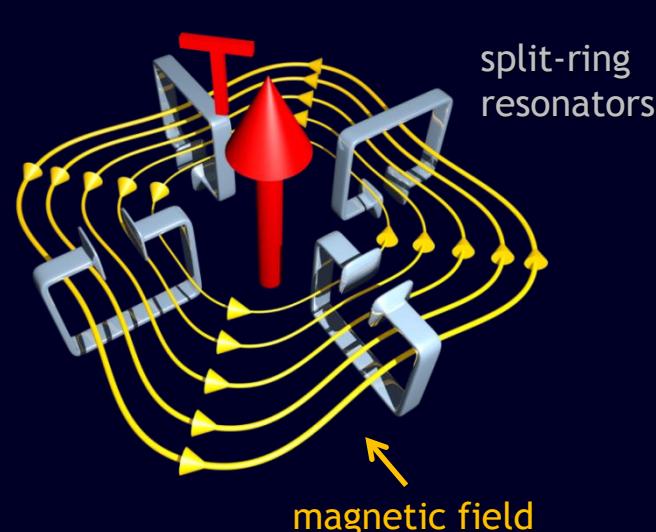
Bacteriophages



Proteins

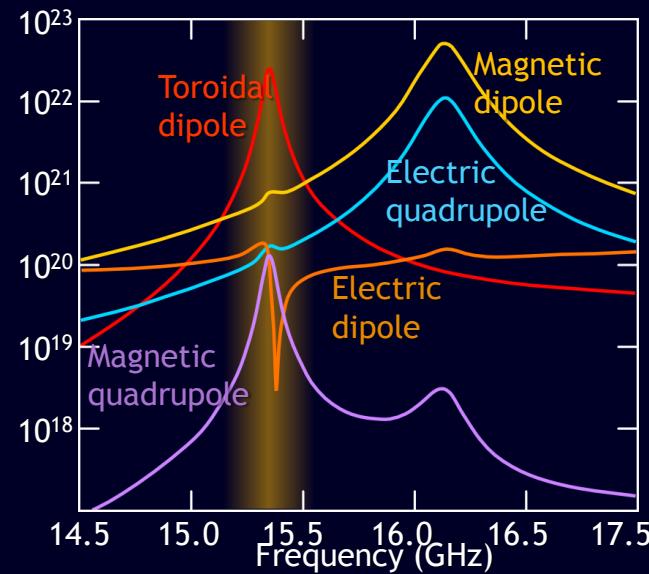


>25 papers
(and grows fast)



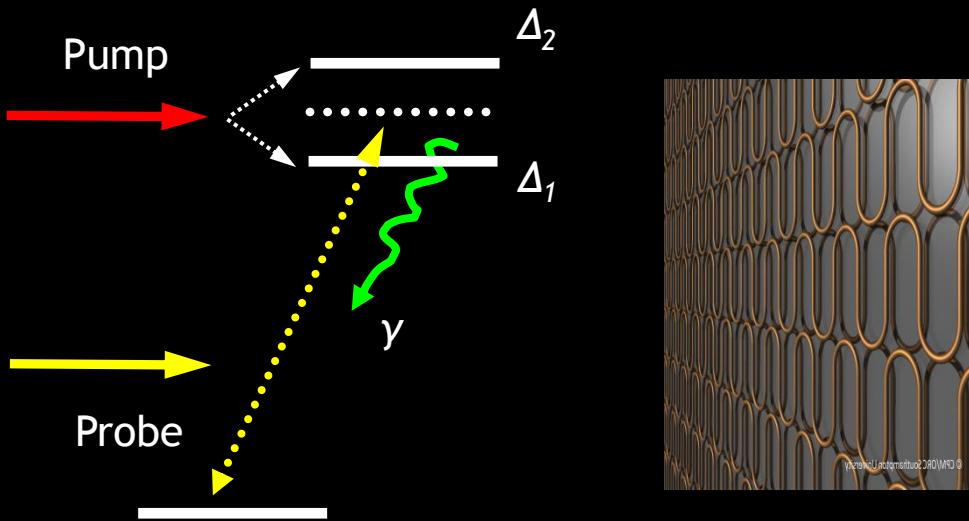
Kaelberer ... Zheludev
Science (2010)

Power Scattered

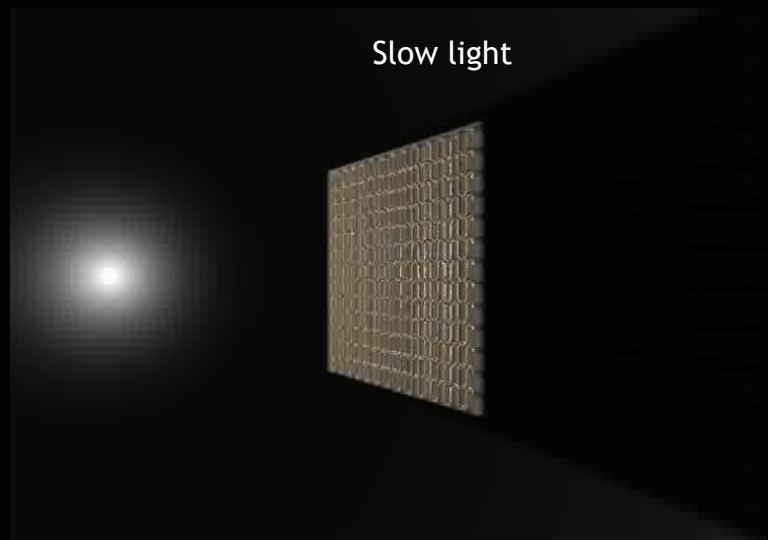


Designing Resonances: EIT & Fano resonances

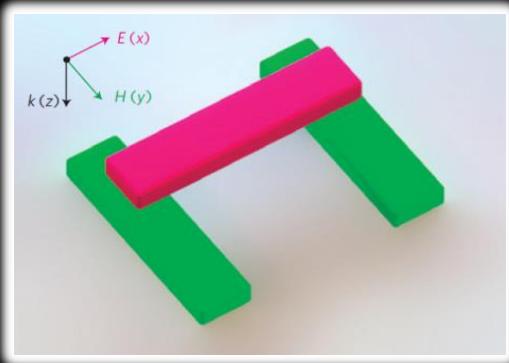
Electromagnetic Induced Transparency
& stopped light in Atoms



Electromagnetic Induced Transparency
& stopped light in Metamaterials

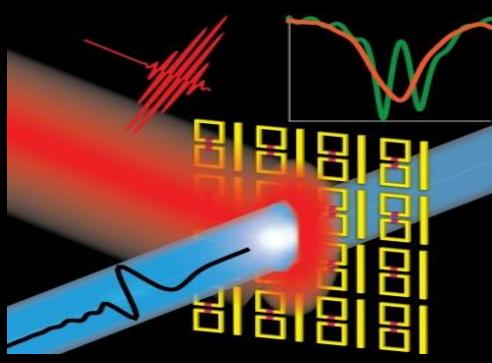


Plasmonic EIT



Zhang ... Zhang. PRL (2008)
Liu ... Giessen. Nat. Mat (2009)

Controlling EIT



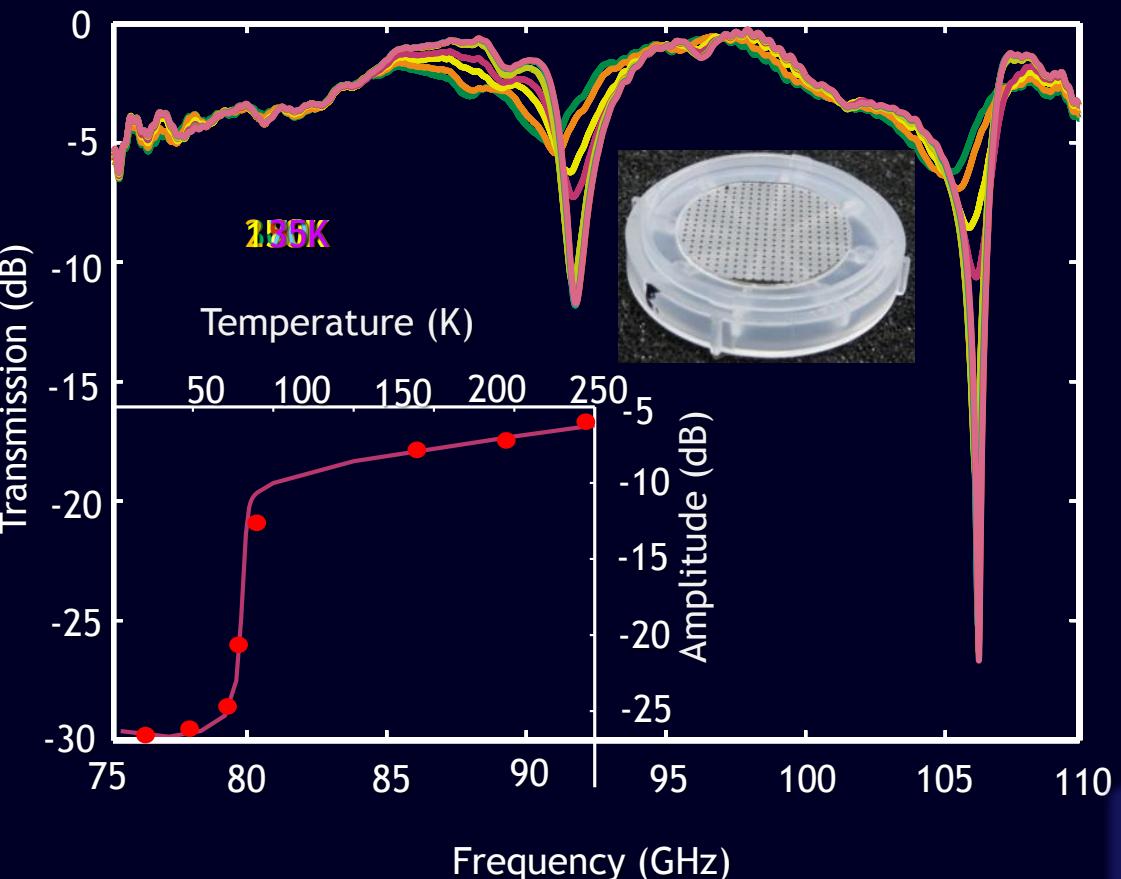
Gu ... Zhang.
Nat. Com. (2013)

Papamakos, Fedotov, ... Zheludev
PRL (2007 & 2008)
Luk'yanchuk, Zheludev Nat. Mat. (2010)

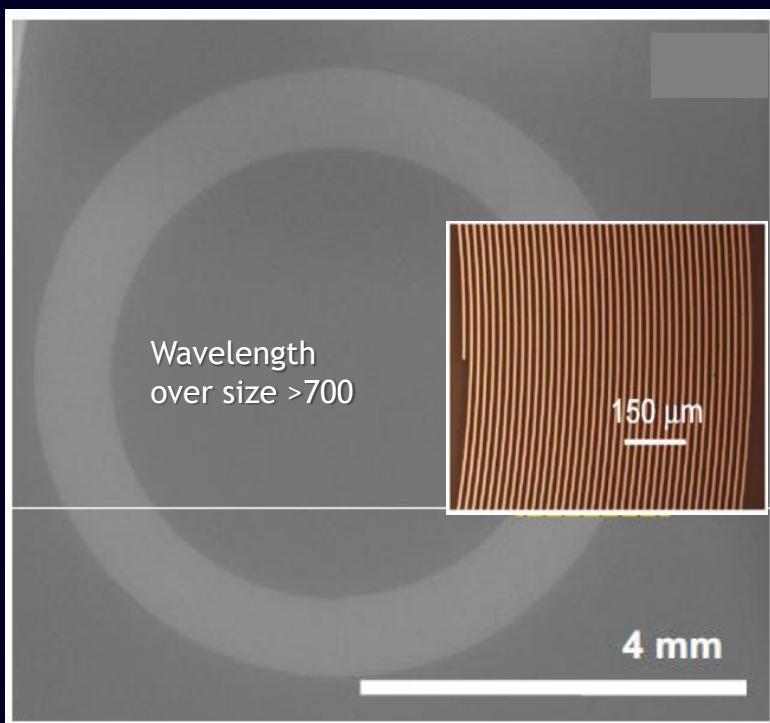
> 400 papers

Sharp resonances in superconducting metamaterials

Array of halls in high- T_c superconductor YBCO, $Q > 60$



Spiral meta-molecule in supercond. niobium



Kurter ... Anlage
IEEE Trans. Appl. Supercond. (2011)

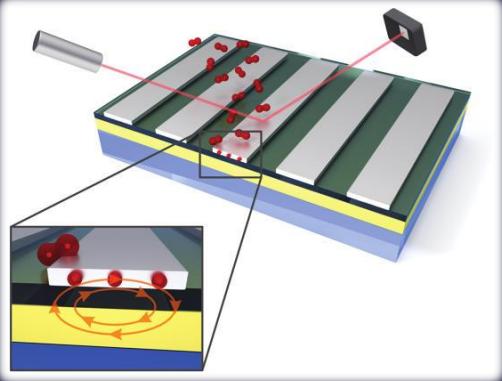
Tsiatmas ... Zheludev. APL (2010)
Fedotov ... Zheludev. Opt. Exp. (2010)

>30 papers

>400 papers

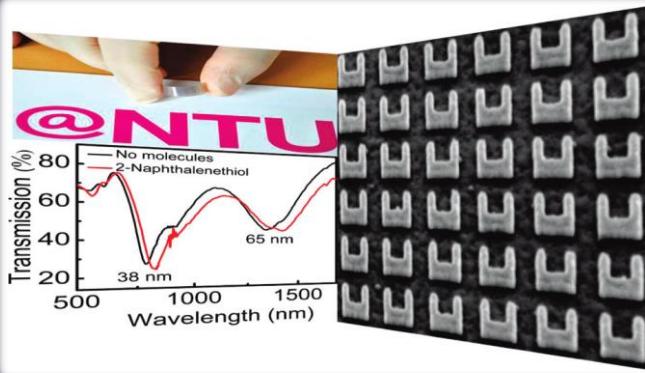
Sensor Metamaterials

Hydrogen Palladium Sensing



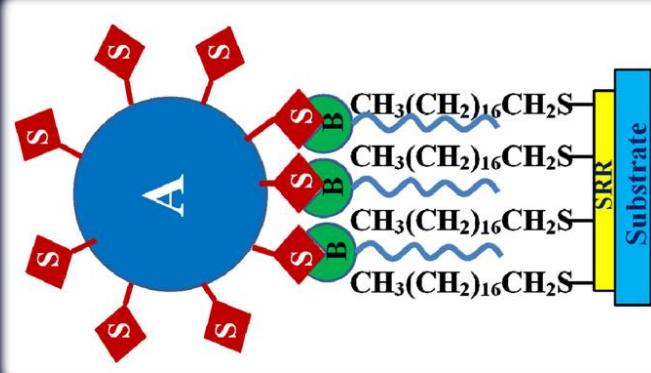
Tittl, ... Giessen
Nano Letters (2011)

Non-specific Protein Sensing



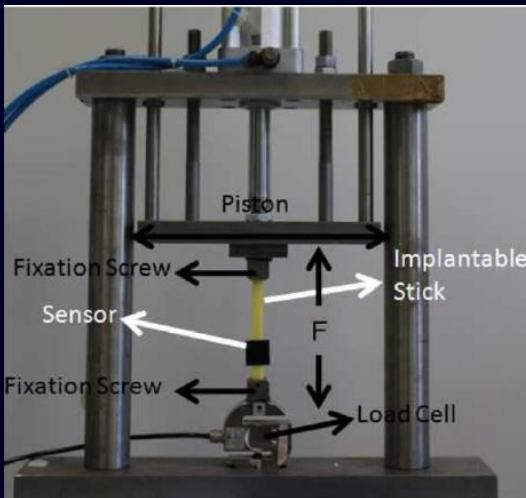
Xu, Xiong.
Nanoletters (2011)

Specific streptavidin prot. sensor



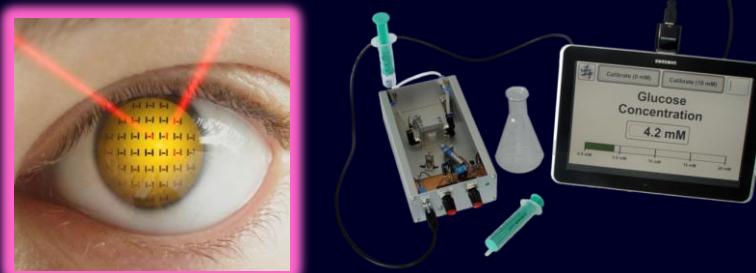
Xiaojun Wu, ... Li Wang
Biosensors and Bioelectronics (2013)

Strain sensors for orthopaedics



Melik, ... Demir.IEEE J. Sel. Top.
Quan. Electr. (2010)

Glucose sensor



Blood pressure monitoring with metamaterial antennas

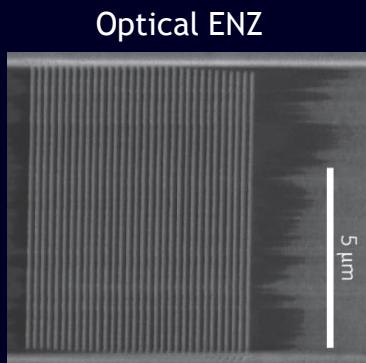
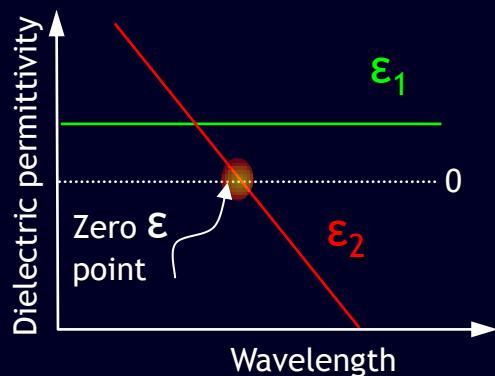


Noh ... Kim
Electr. Lett. (2014)

>180 papers

Designing Anisotropy & birefringence

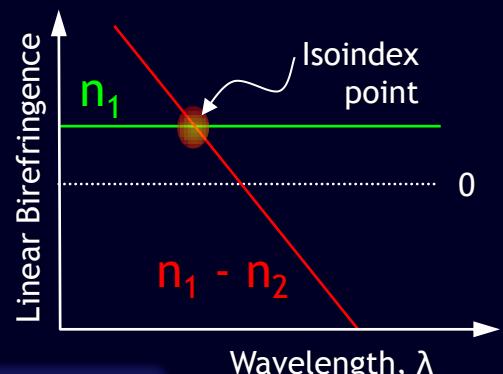
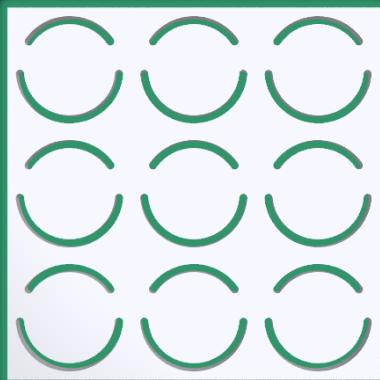
Epsilon zero metamaterials



Silveirinha ... Engheta. PRL (2006)
Elser, ... Narimanov. APL (2006)
Noginov, Narimanov. APL (2009)
PollardPodolskiy. PRL (2009)

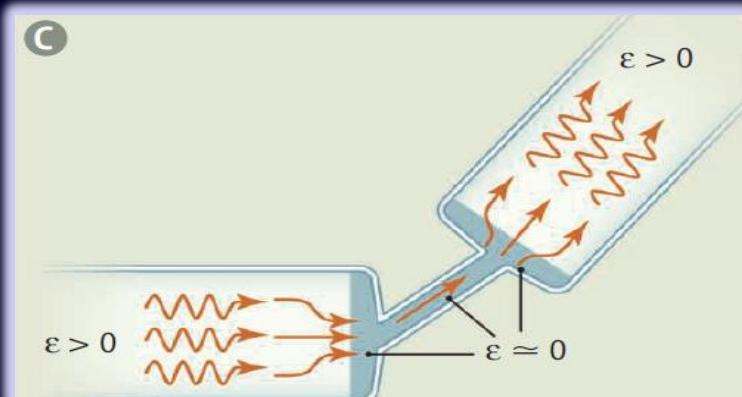
Mass ... Polman,
Nat.Phot. (2013)

Isoindex (index zero-crossing) metamaterials



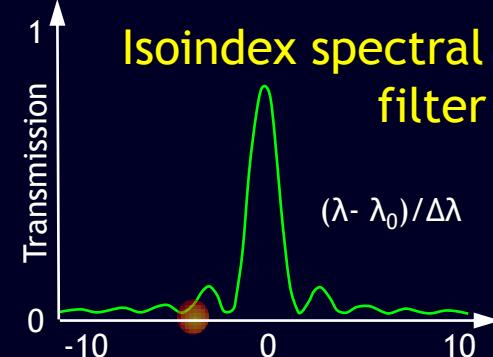
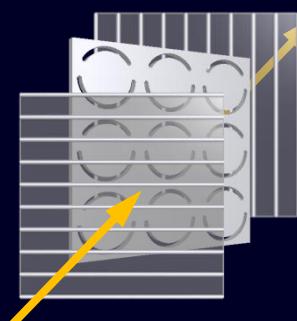
Zheludev, Plum, Fedotov. APL (2011)

Wave guiding in Epsilon zero MMs & Metatronics



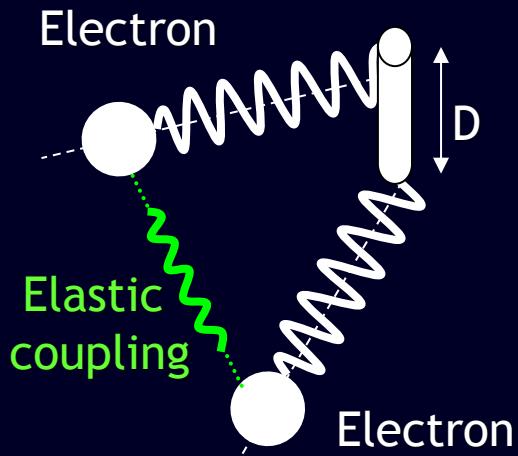
Negative-index in waveguides
Podolskiy & Narimanov. PR E (2005)

Zero-index waveguides
Silveirinha ... Engheta. PRL (2006)
Metatronics : Engheta . Science (2007)

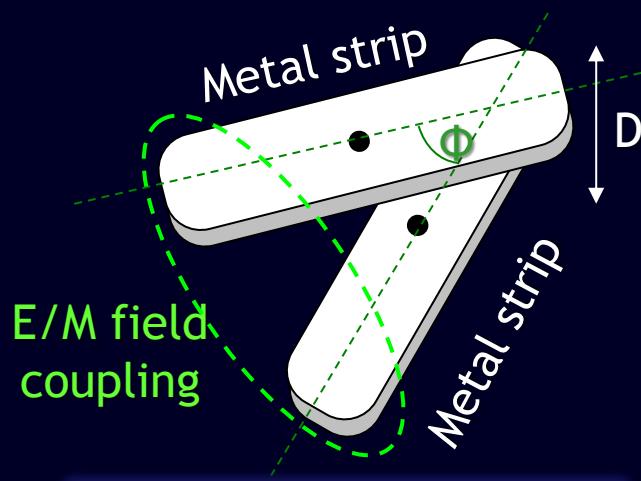


Controlling polarization: chirality

>300 papers

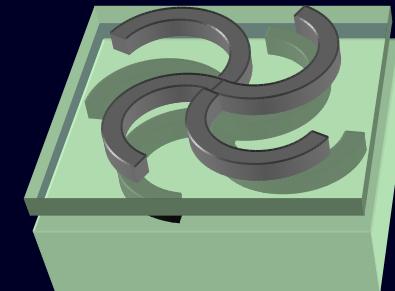


The Born-Kuhn
Molecular model (1915)



Meta-material.
Svirko-Zheludev-Osipov: APL (2000)

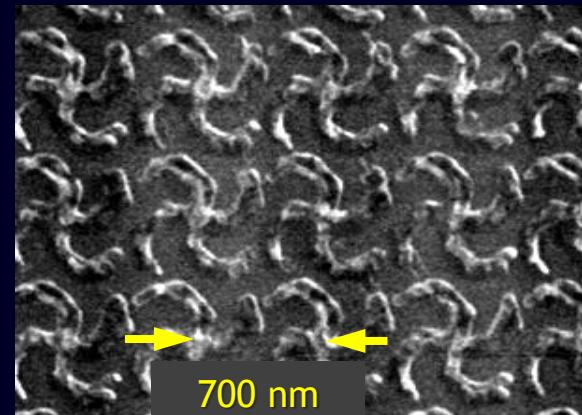
Chiral Metamaterials



Rogacheva ... Zheludev
PRL (2006)
Decker ... Wegener
(2007)

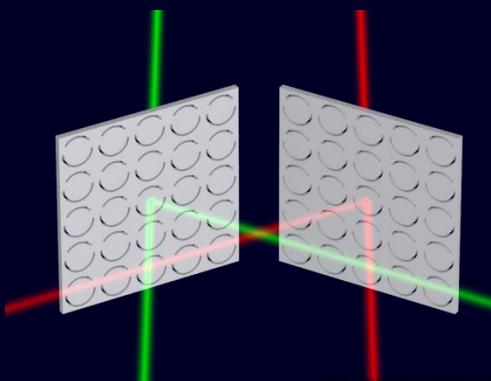
Rotatory power orders of magnitude stronger than in natural media!

Optical “Stereo” Metamaterials”



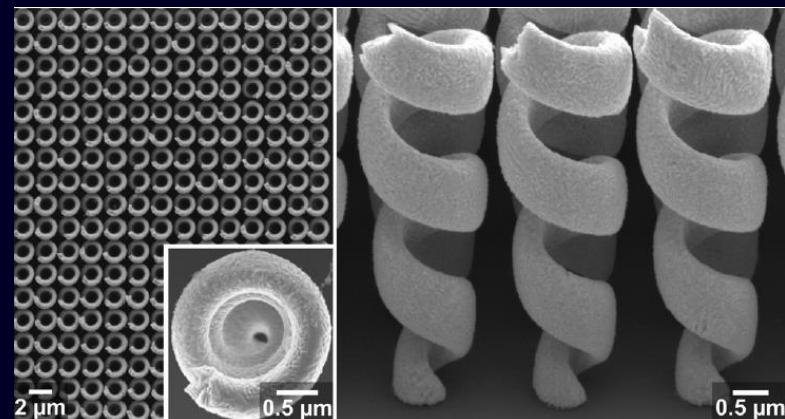
Plum ... Zheludev. APL (2007)

Extrinsic Chirality



Plum ... Zheludev
PRL (2009); APL (2008)

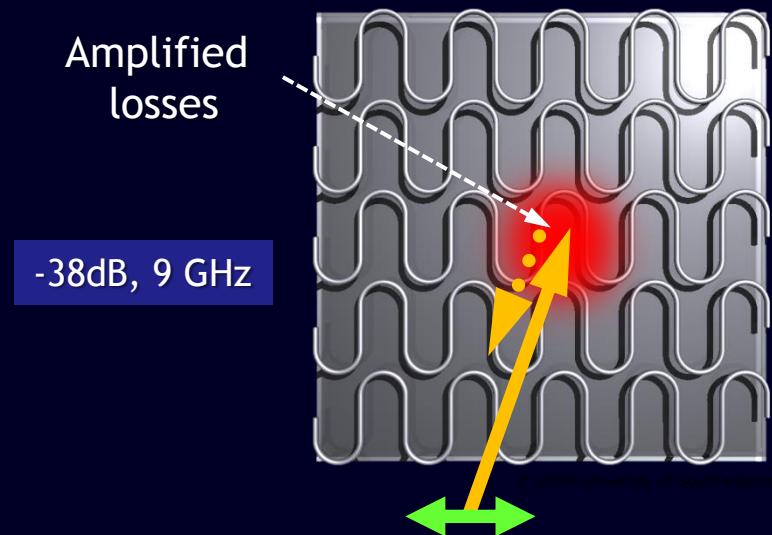
Metamaterials” Circular polarizers



Gansel ... Wegener. Science (2009); APL (2012)

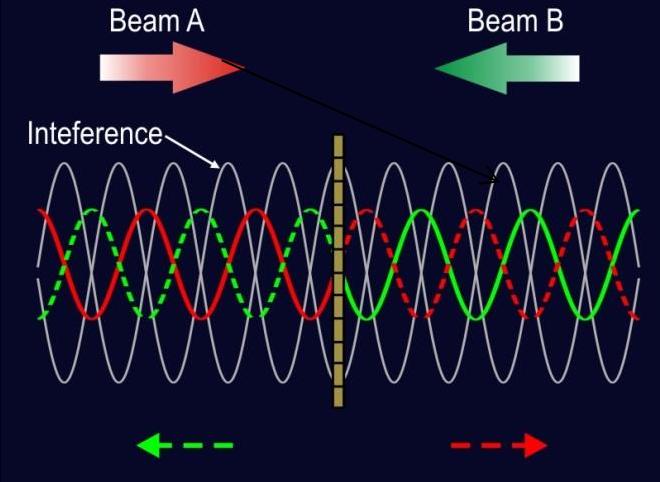
Controlling boundary conditions: Perfect absorber

“Amplification” of absorption with metamaterials

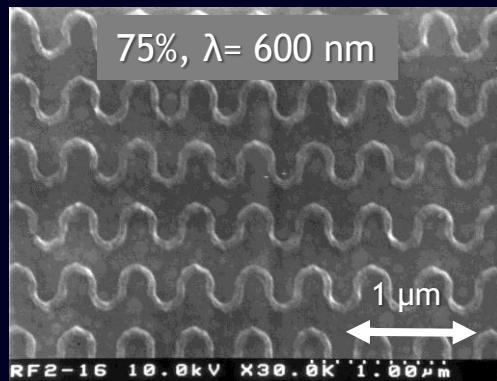


Fedotov Zheludev. PR-E (2005); APL (2006)

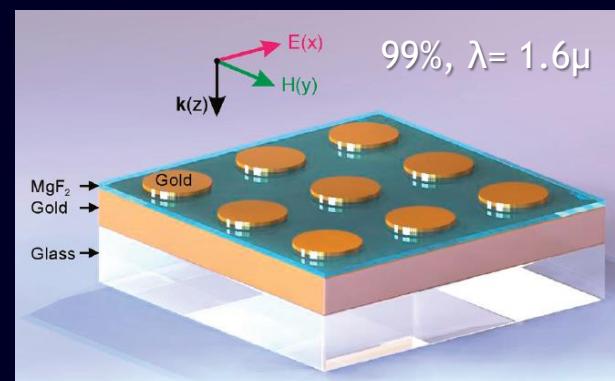
“Total” absorption with metamaterials



Zhang ... Zheludev
NPG Light (2012)



Schwanekeb... Zheludev
J. Opt. (2007)

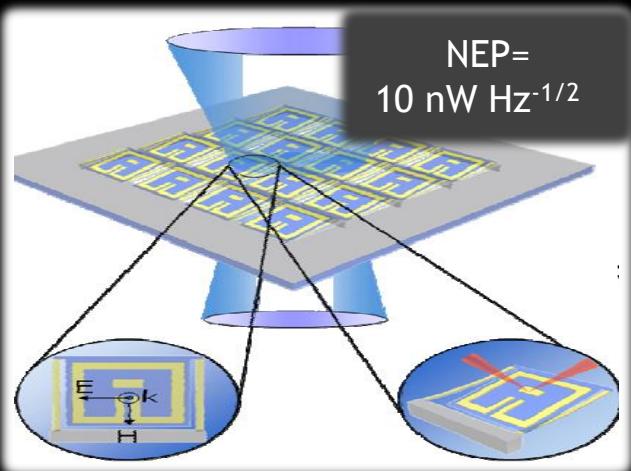


Liu... Giessen.
Nano Lett. (2010)



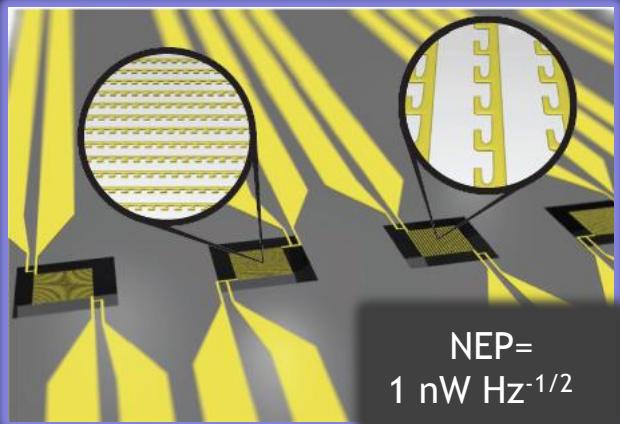
Light-Harvesting metamaterials: thermal detectors & bolometers

Infrared Detection with
cantilever pixels deflection



Tao, ... Padilla, Averitt. Opt.Exp. 2011

Enhanced optical Bolometer



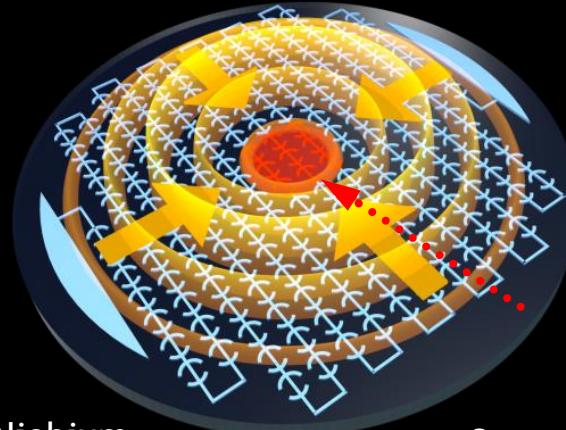
Niesler ... Wegener . APL (2012)



Incident
radiation

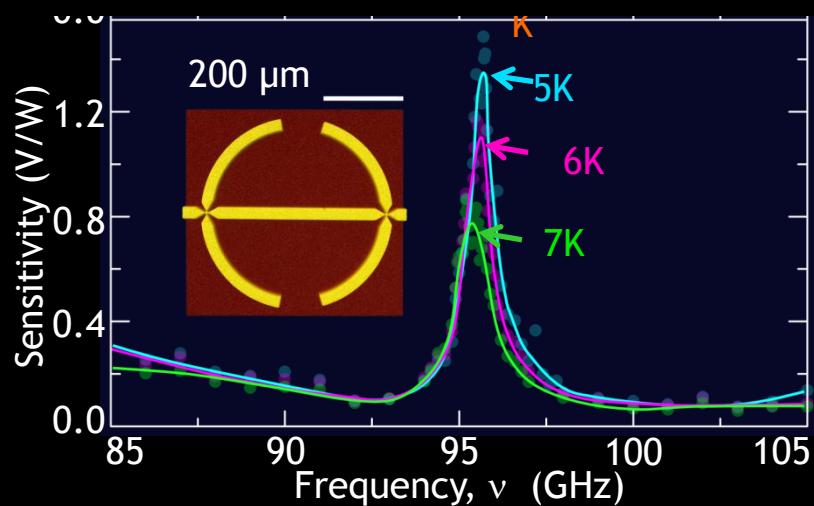
NEP =
 $0.3 \text{ nW Hz}^{-1/2}$

Savinov...
Zheludev
Super. Sci. &
Tech. (2013)



Niobium
on Sapphire

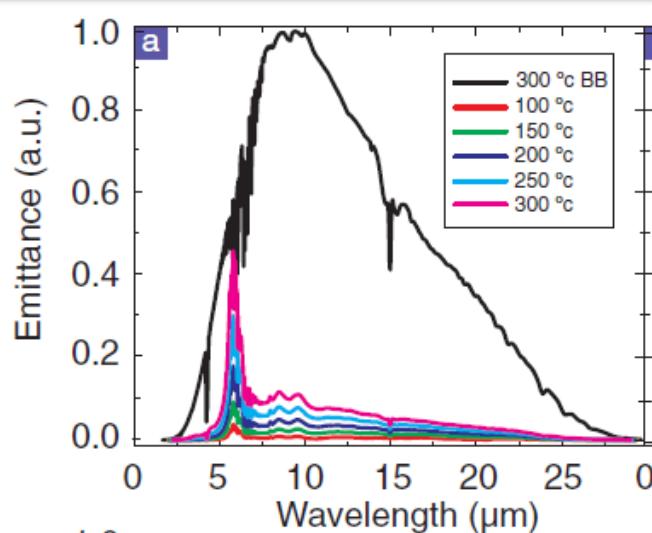
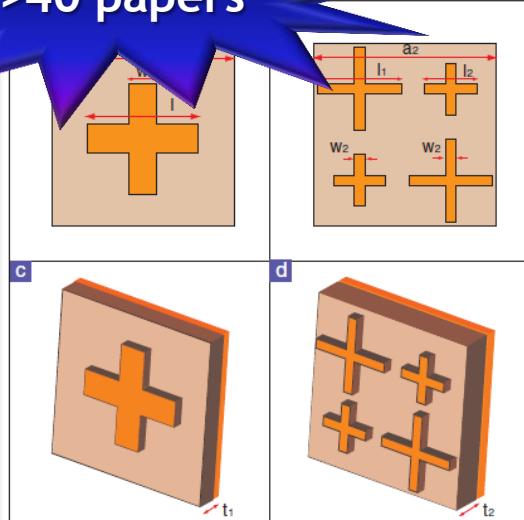
Superconducting
Meta- Bolometer



Tailoring emission lines with metamaterials

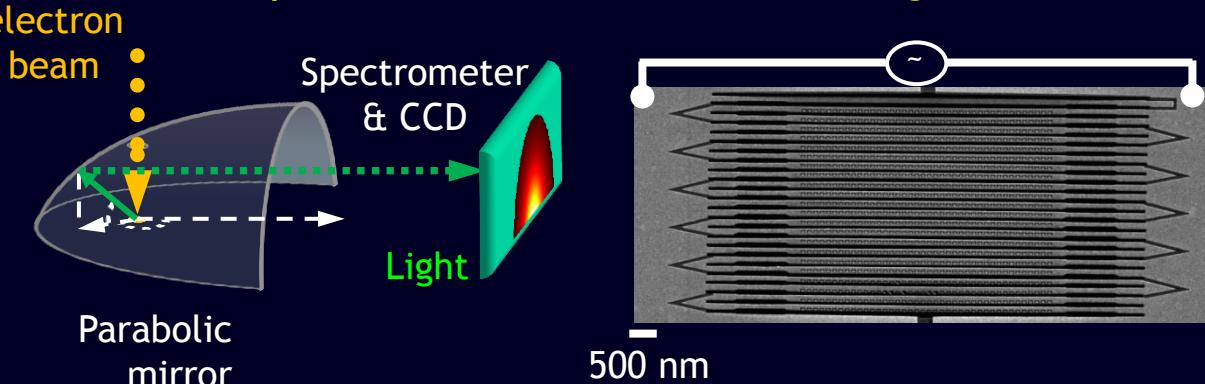
Control of thermal radiation with metamaterials

>40 papers

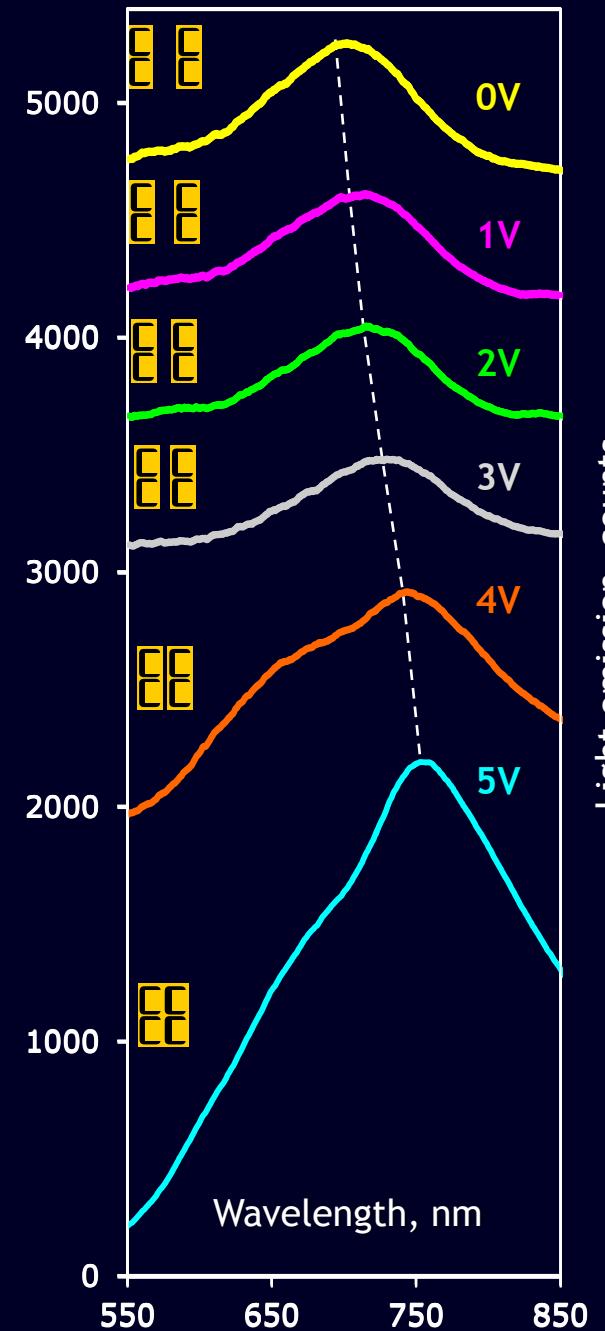


Liu ... Padilla. PRL (2011)

Tunable plasmonic emission in reconfigurable MM

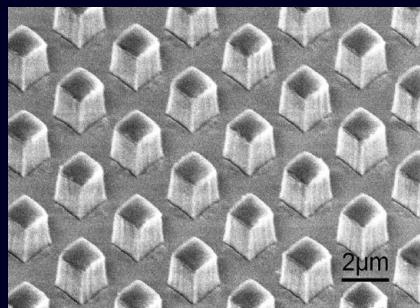


Adamo ... Zheludev. CLEO-Europe (2013)



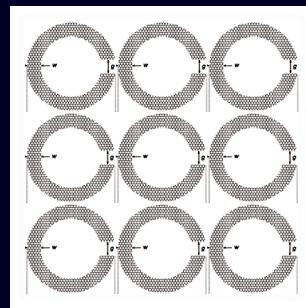
New Materials for metamaterials

IR magnetic response in Te metamaterial



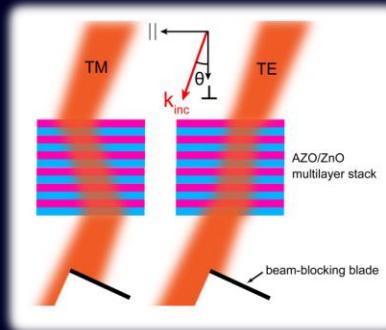
Ginn, Brener ... Sinclair.
PRL (2012)

Graphene metamaterial



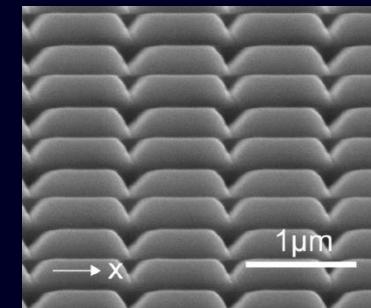
Papasimakis ...
Zheludev, de Abajo
. NPG Light (2013)

Negative refraction in conductive oxide metamaterial



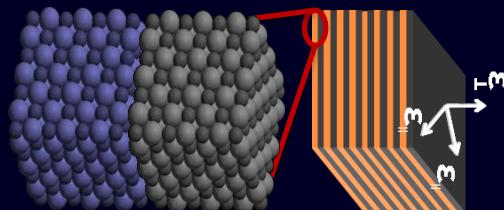
Naik ... Boltasseva.
Proc. Nat. Acad.
Sci. (2012)

Silicon metamaterial



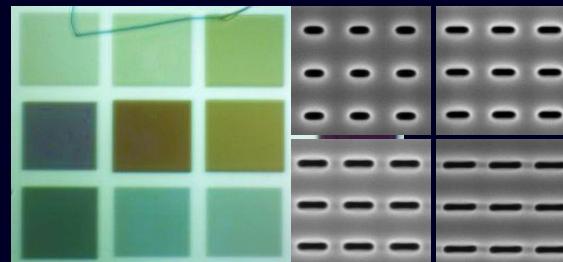
Zheng ... Zheludev.
OPT Exp. (2013)

TiN-based metamaterial:
enhanced emission



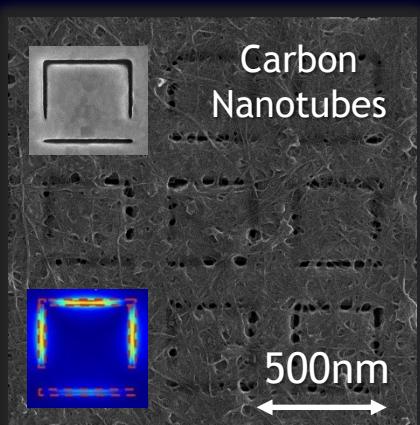
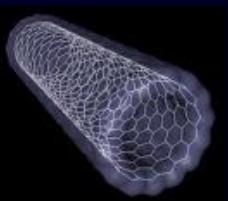
Naik ... Boltasseva.
TBP (2013)

Visible and UV metamaterials from topological insulator

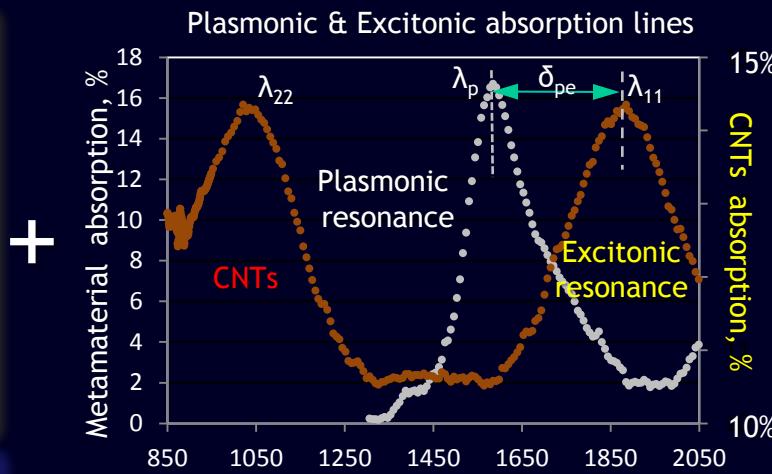


Ou, So, ... Zheludev
Arxive (2013)

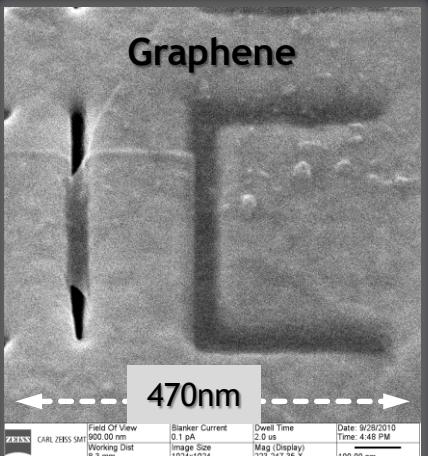
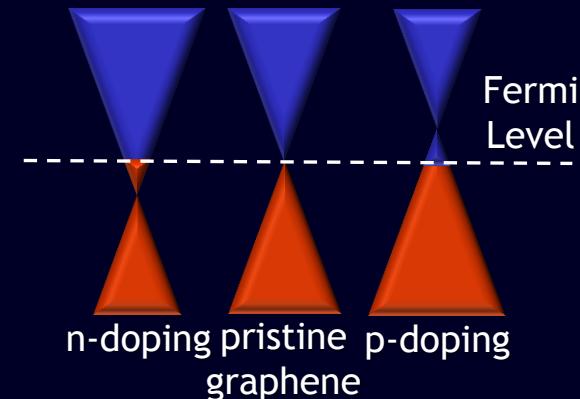
CTNs & Graphene in metamaterials



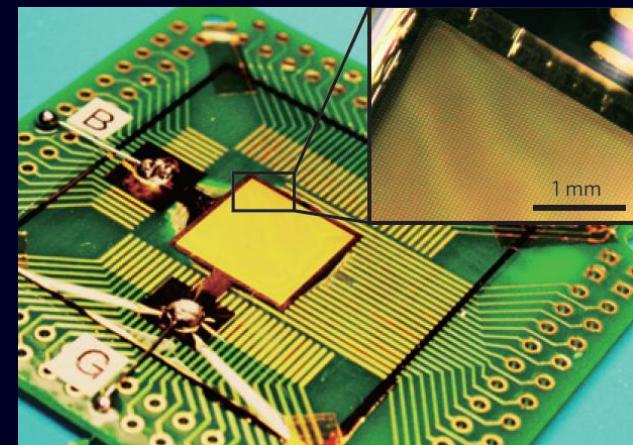
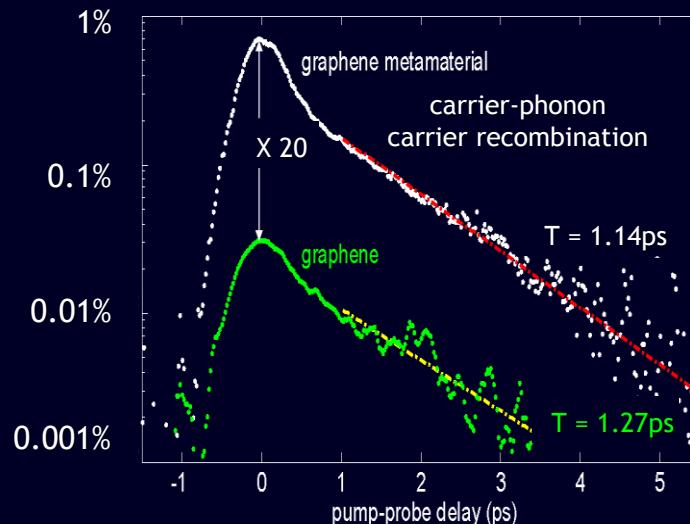
Nikolayenko... Zheludev
PRL (2010)



Modulating graphene properties by carrier injection

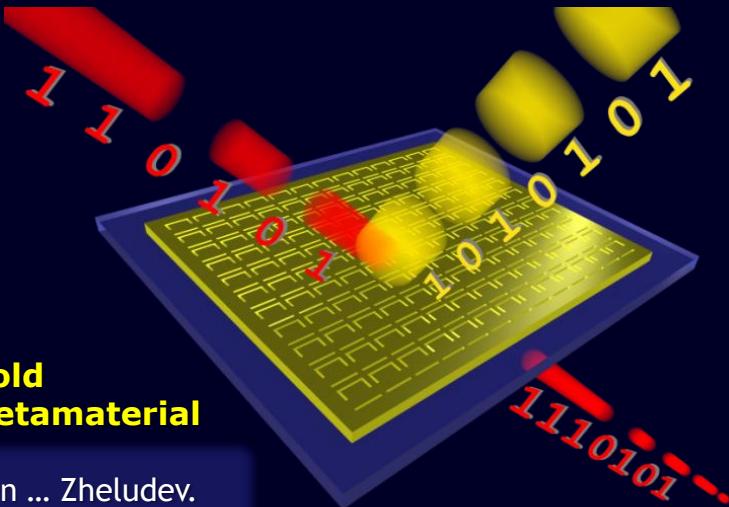


Nikolayenko... Zheludev
APL (2012)

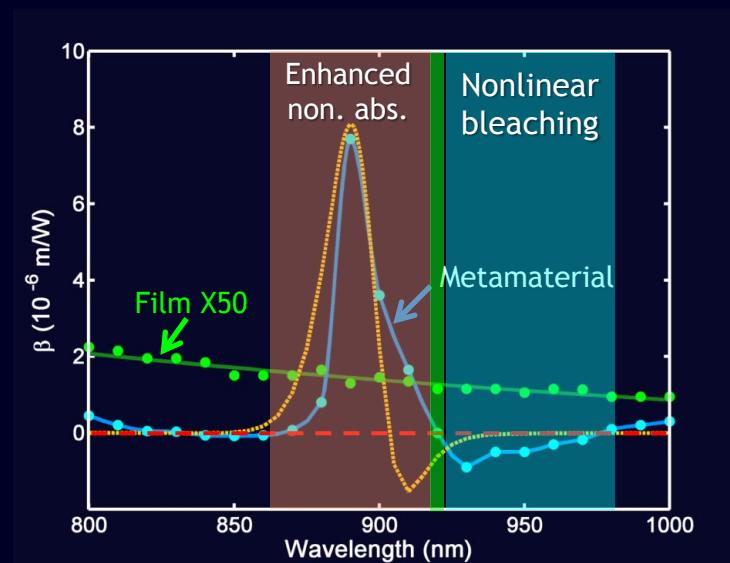


Lee, ... Min. Nat. Mat. (2012)

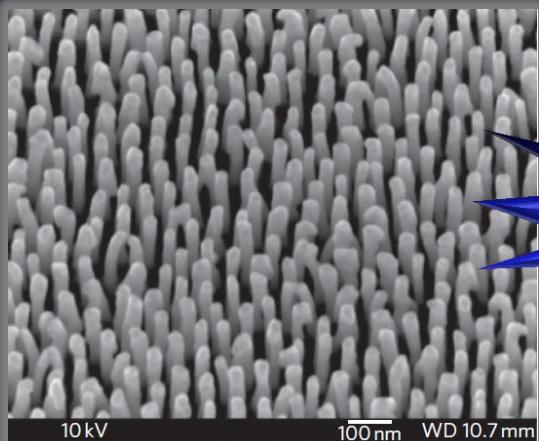
Ultrafast switching with metamaterials



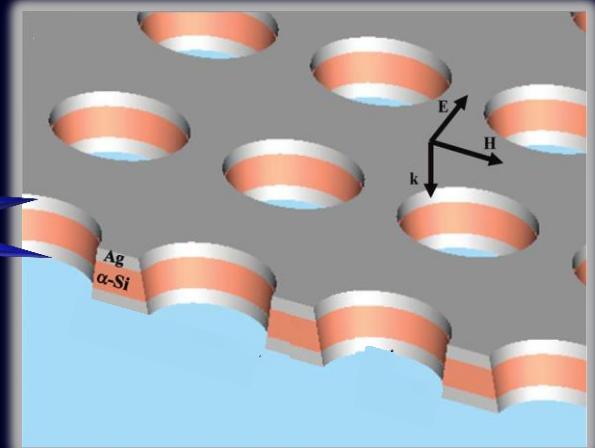
Ren ... Zheludev.
Adv. Mater. (2011)



Fluence [J/cm²] x Relax.time [s] = 10⁻¹⁸ J x sec / cm²



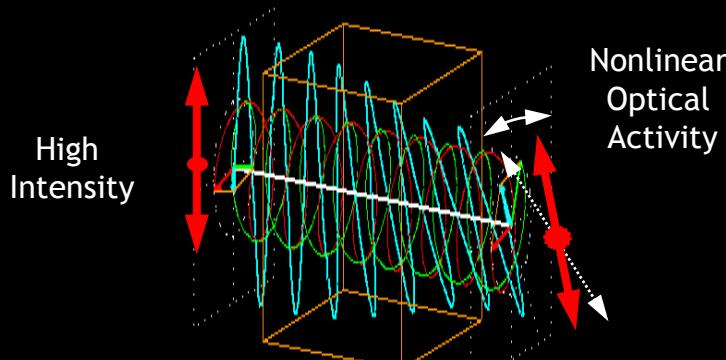
>40 papers



Wurtz ... Zayats . Nature
Nanotech. (2011)

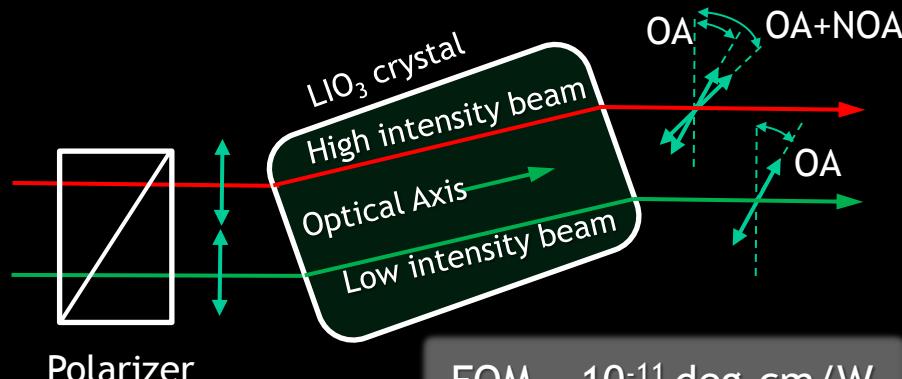
Padilla ... PRL (2006)
Chen ... Opt. Lett. (2007)
Dani... Nano Lett. (2009)

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

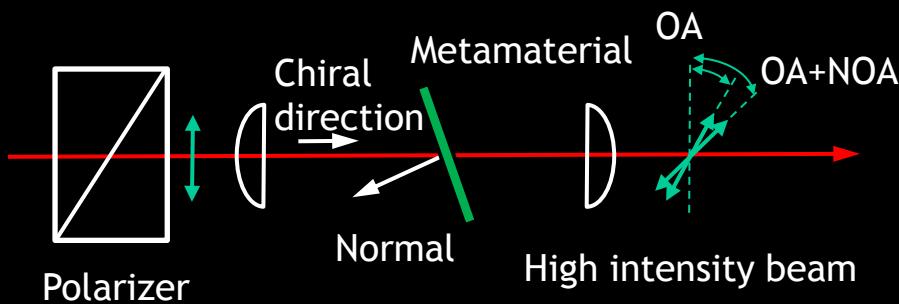


NONLINEAR OPTICAL ACTIVITY, 1972

1979: Nonlinear optical activity in crystals.
Ahmanov, Zheludev et.al, JETP Lett, 29, 5 (1979)

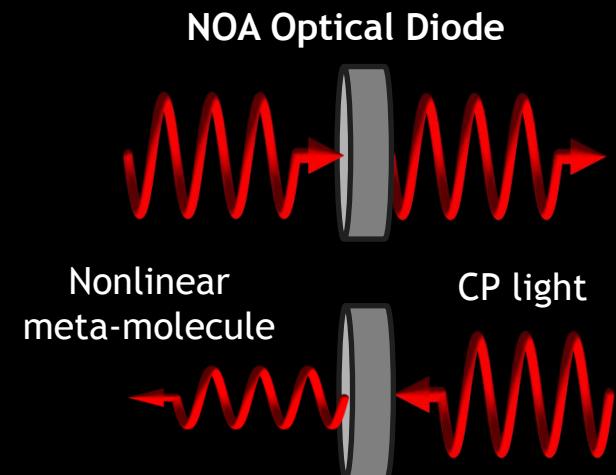


FOM $\sim 10^{-11} \text{ deg}\cdot\text{cm}/\text{W}$



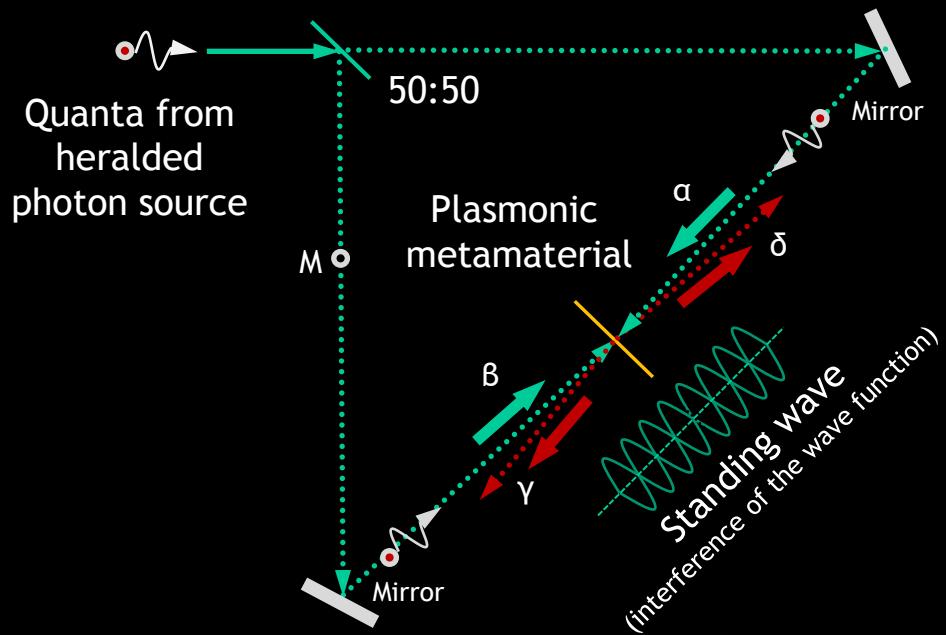
FOM $\sim 10^{-4} \text{ deg}\cdot\text{cm}/\text{W}$

2012: Giant nonlinear optical activity in a plasmonic metamaterial
Ren, Plum, Xu and Zheludev. *Nat. Commun.* 3, 833 (2012)



Shadrivov .. Kivshar, Zheludev
NJP (2011)

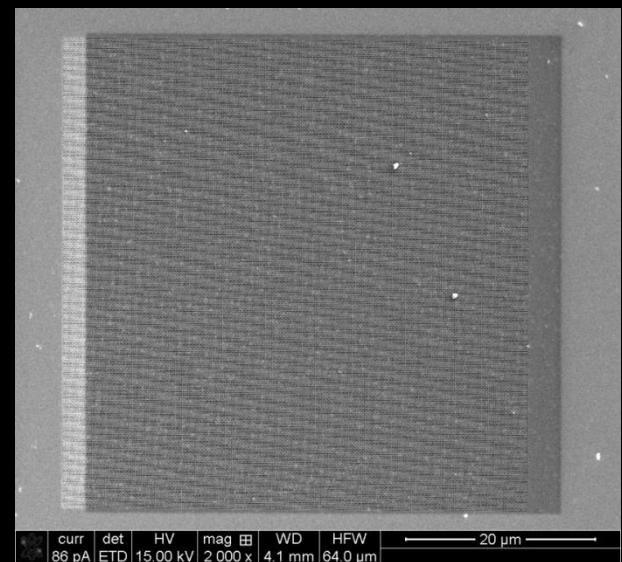
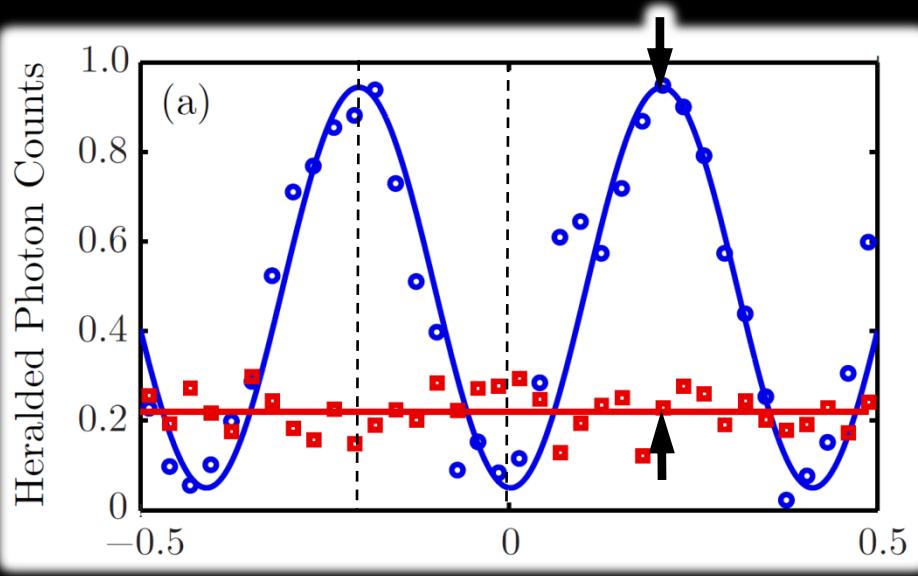
Quantum Optics of Metamaterials: Single Photon gate, multi-THz bandwidth



Quantum:
META-14, Singapore
Roger, Heitz, ... Zheludev, Faccio

Ultrafast:
Fang, Tseng, Ou, MacDonald, Tsai & Zheludev
APL 104, 141102 (2014)

Ultrathin 50nm free-standing plasmonic
metamaterial absorber

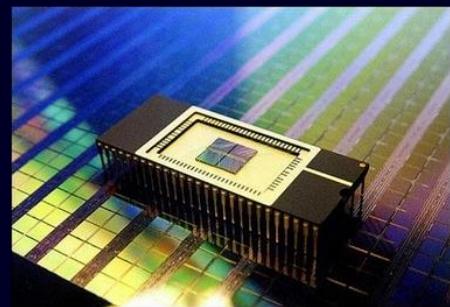


Phase Change Metamaterials & Optical memory

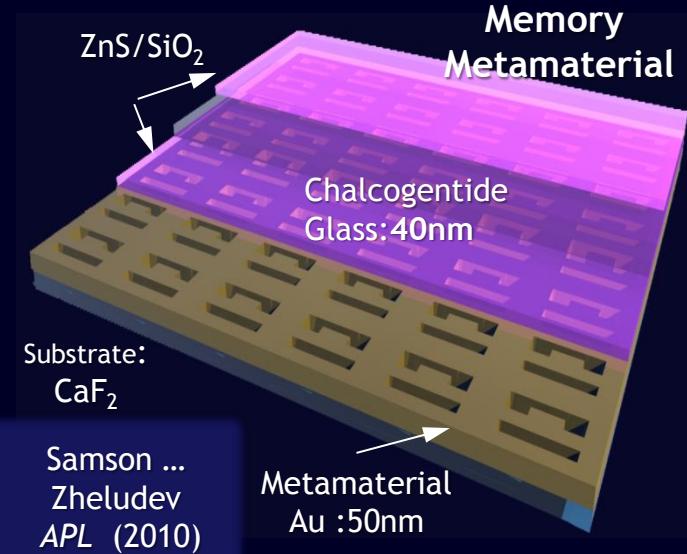
Chalcogenide Glass Technology



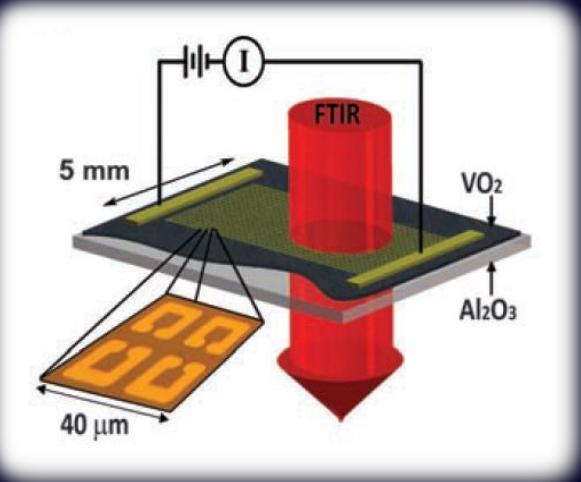
Re-Writable CD



Samsung PCh Memory

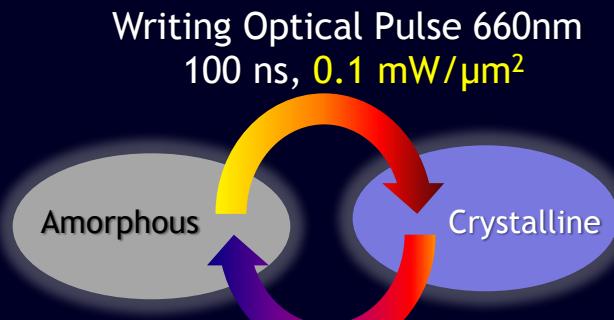


Electrical THz frequency tuning

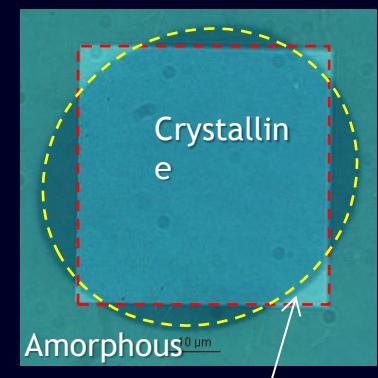


Driscoll. Basov. *Science* (2009)

All-optical, non-volatile, bidirectional switching



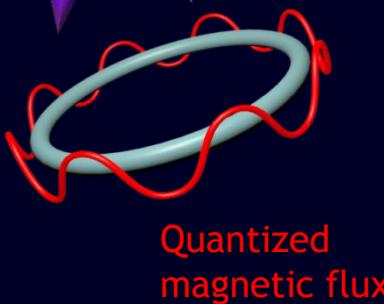
Arasing Optical pulse 660nm
50 ns, 0.25 mW/ μm^2



Gholipour.... Zheludev. *Adv. Mater.* (2013)

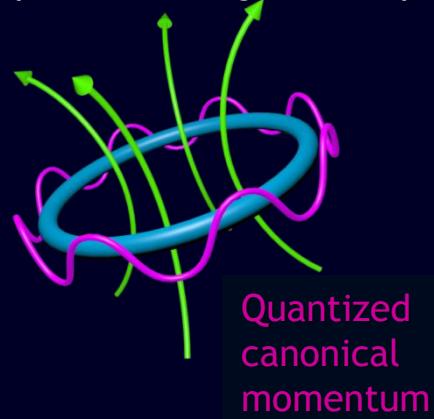
Quantum effects
in MM >300 pps

Light in a fibre loop

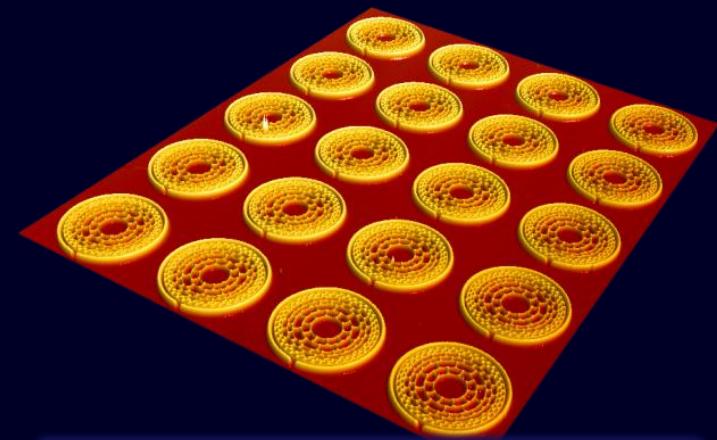


Quantum Metamaterials

Superconducting wire loop

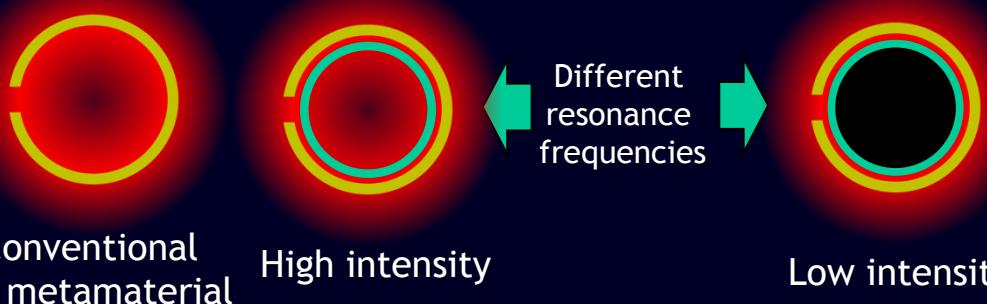
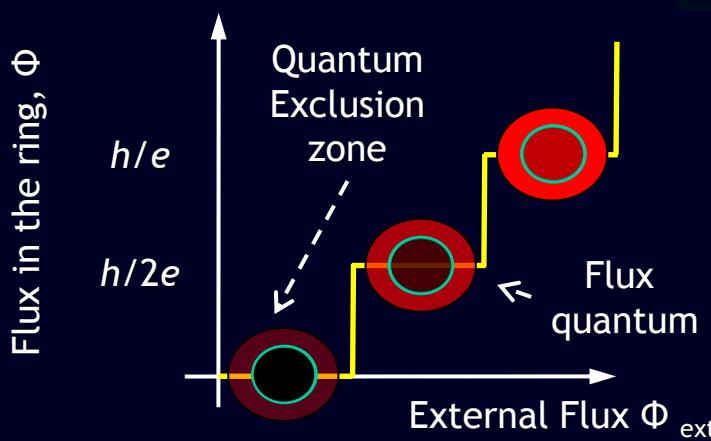
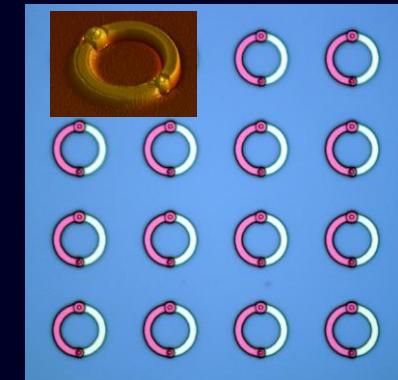


YBCO metamaterial



Savinov ... Zheludev et. Al. Sc. Rep. (2012)

Quantum SCQID Metamaterial

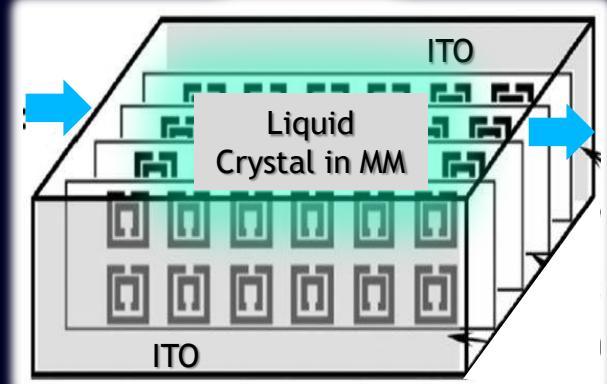


Trepanier ... Anlage, 2013
Du, Chen, Li, 2006
Lazarides & Tsironis, 2007

Metamaterials and LC devices

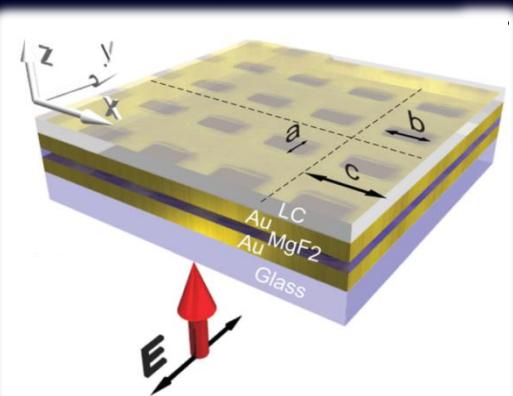
>50 papers

Microwave



Zhao... Zhang. *APL* (2007).

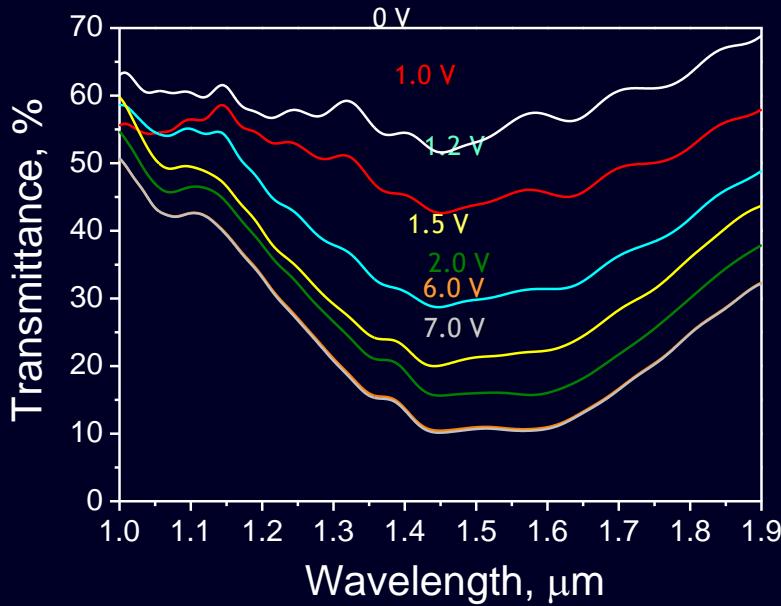
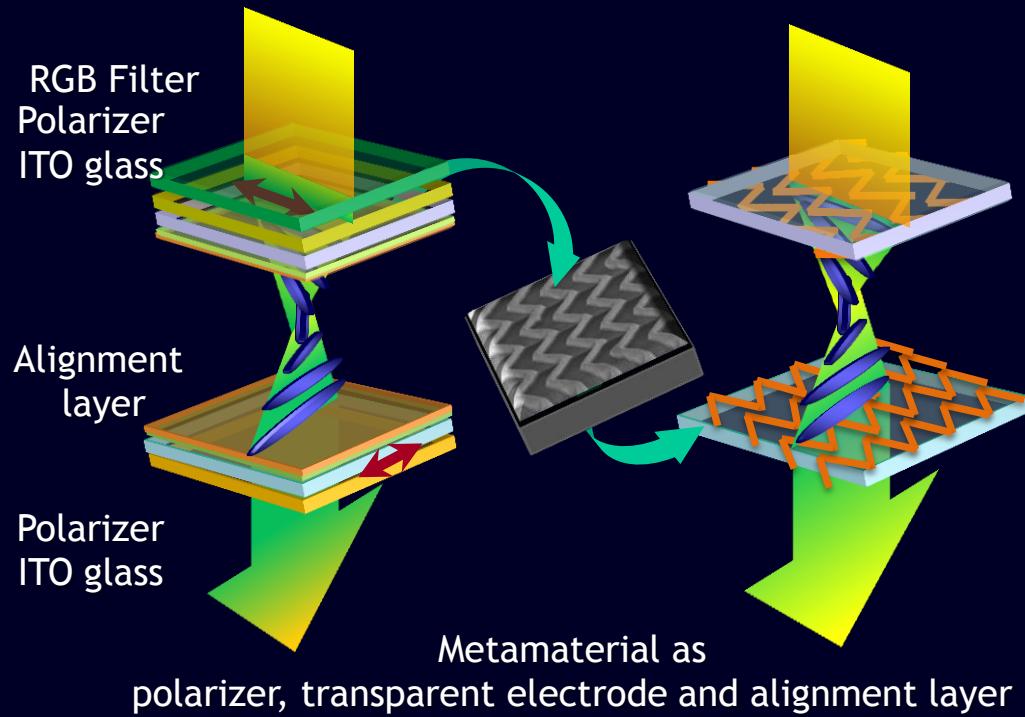
Optical



Minovich ... Kivshar *APL* (2012)



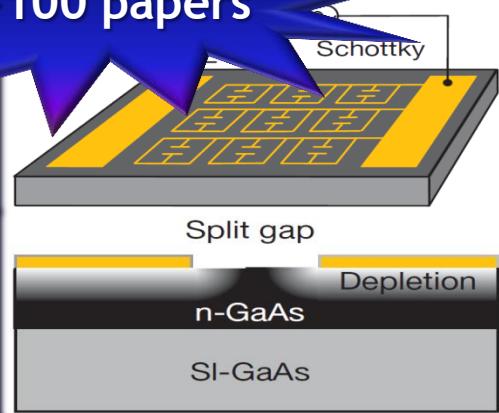
Buchnev ... Zheludev, Fedotov
Opt. Exp. (2013)



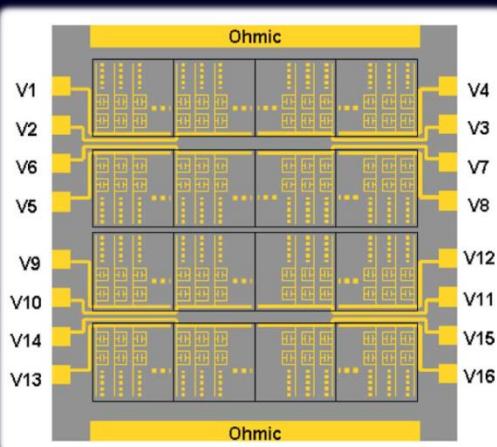
EO & MO modulation with metamaterials

THz modulation in metamaterial: carrier injection

>100 papers

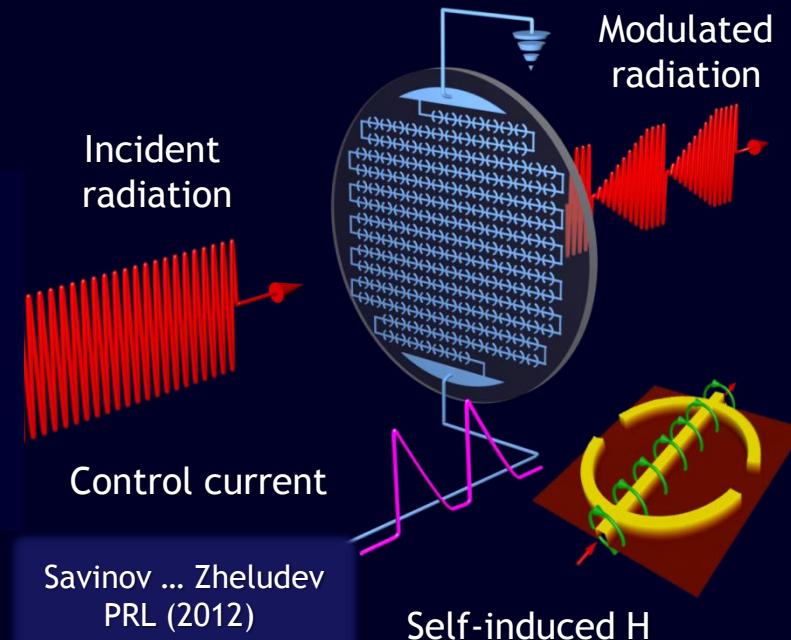


Chen... Averitt
Nature (2006)



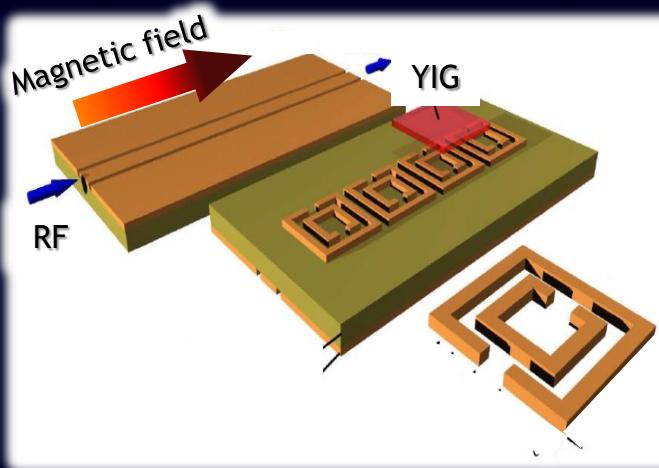
Chan... Mittleman
APL (2009)

EO Superconducting Metamaterial



Savinov ... Zheludev
PRL (2012)

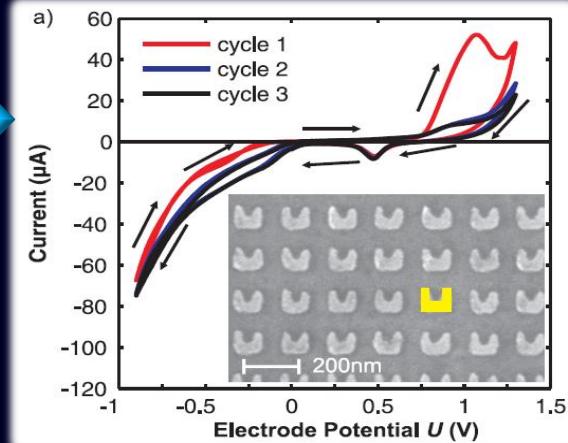
Magnonic Metamaterial Waveguide



Shao ... Wegener.
Adv. Mat. (2010)

Stenning... Zheludev
Opt. Exp. (2013)

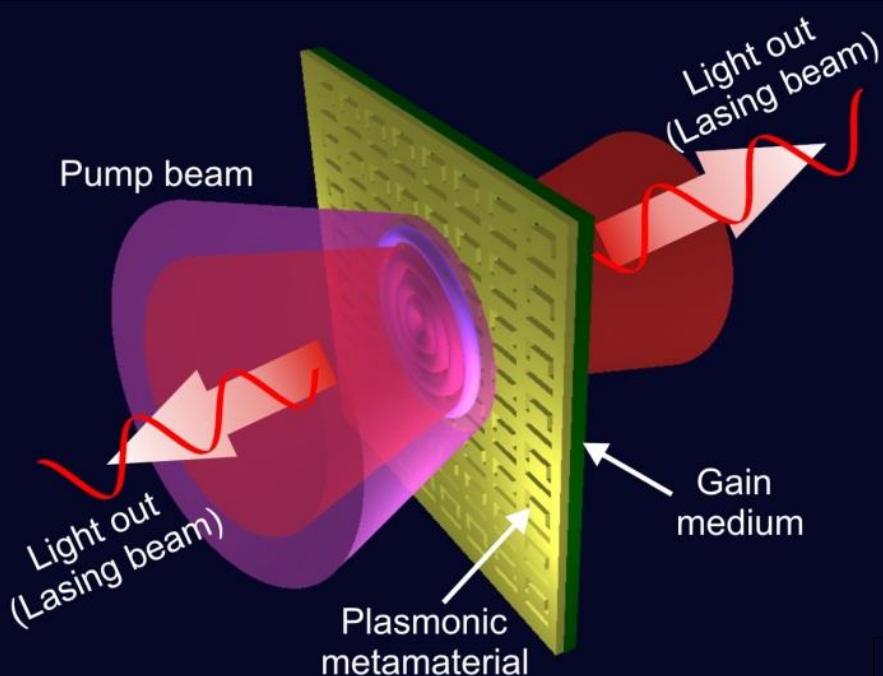
Electrochemical Modulation MM



Control of Spontaneous Emission with MMs & “Lasing Spaser”

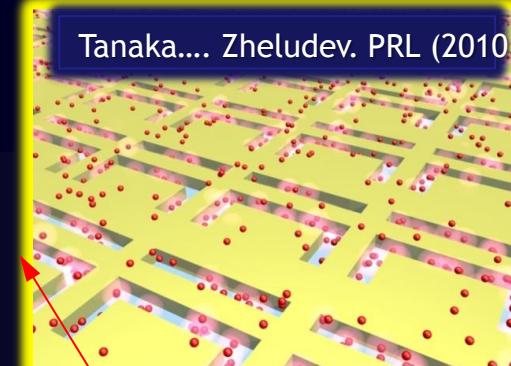
>50 papers

The Lasing Spaser

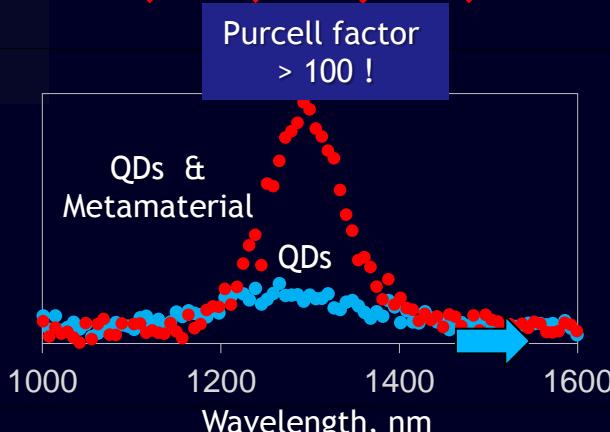
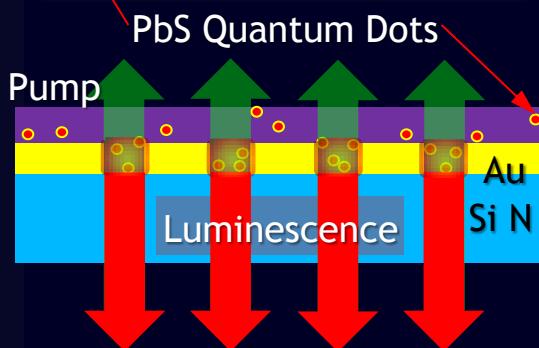


Zheludev ... Fedotov.
Nat.Phot. (2008)

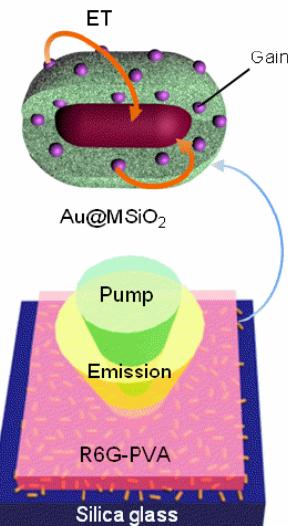
Enhanced Emission



Tanaka.... Zheludev. PRL (2010)



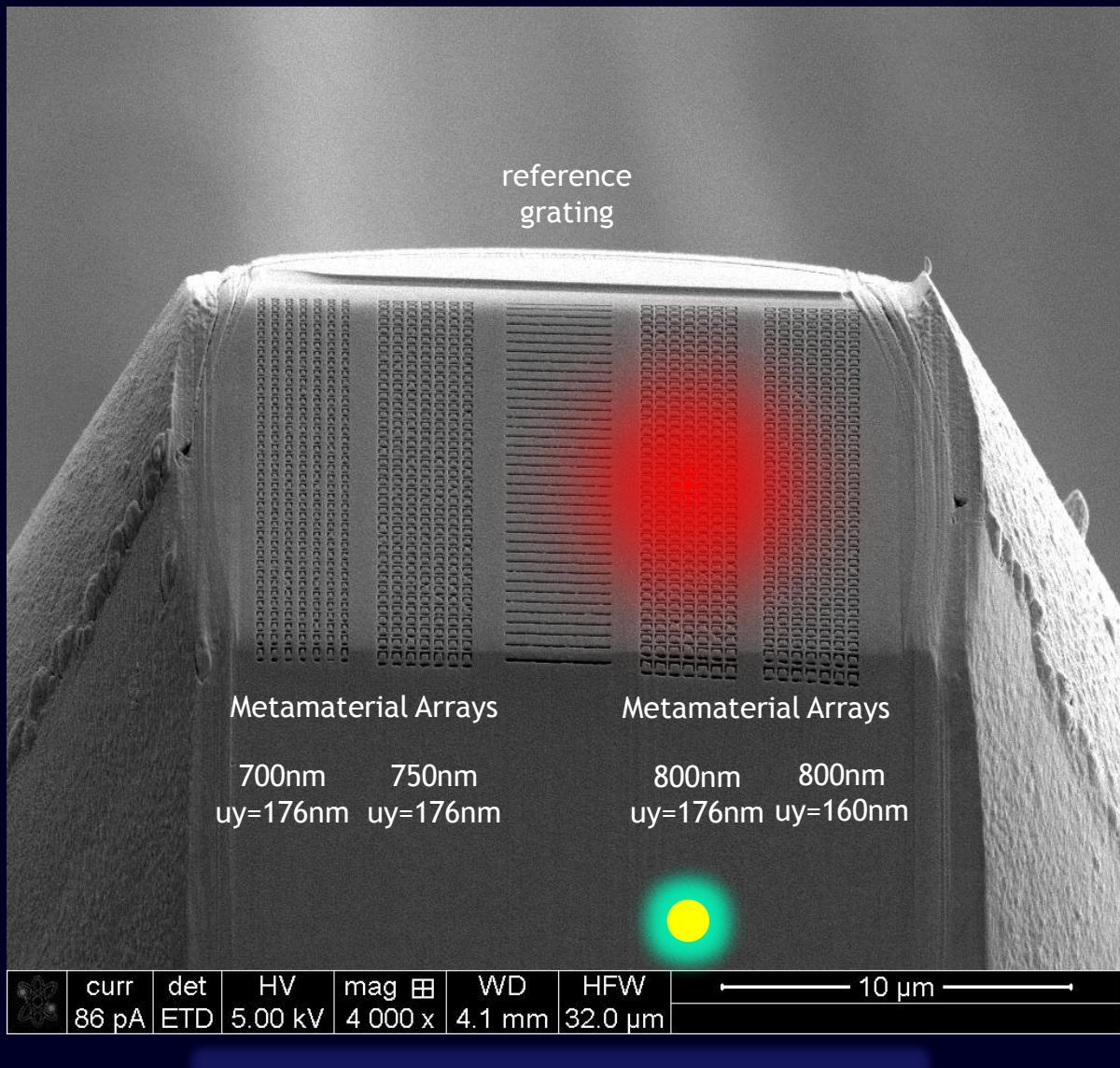
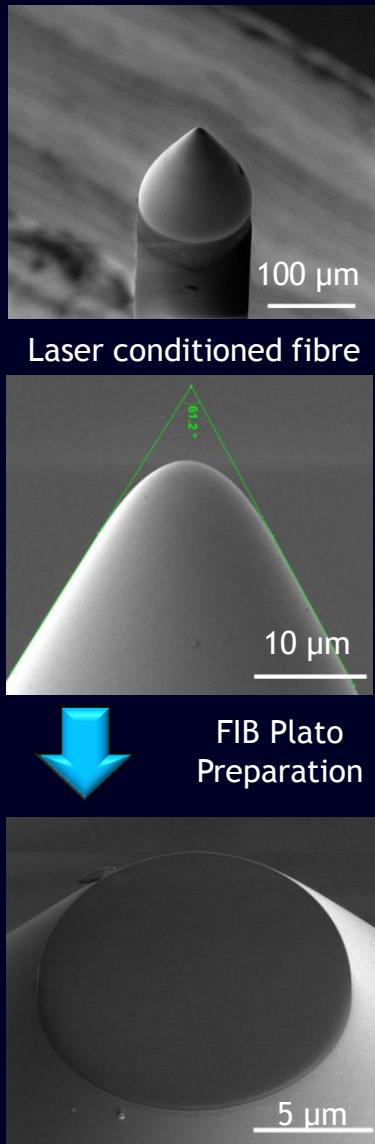
Lu ... Liu. Nat.
Nano (2014)



Meng ... Shalaev
Nano.Let (2013)

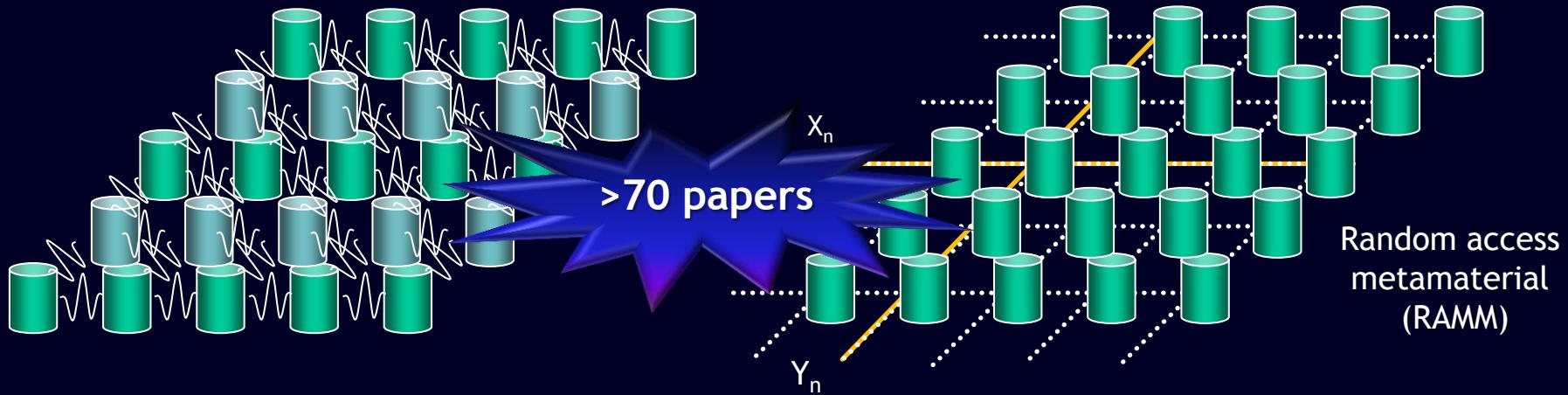


Free-electron driven metamaterial light sources



Adamo ... Zheludev PRL (2012)
So ... Zheludev TBP(2014)

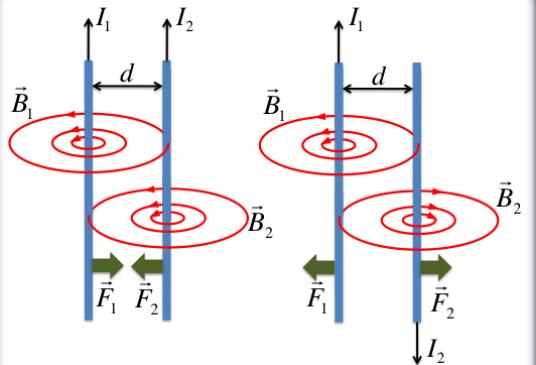
Reconfigurable metamaterials: nanoscale forces



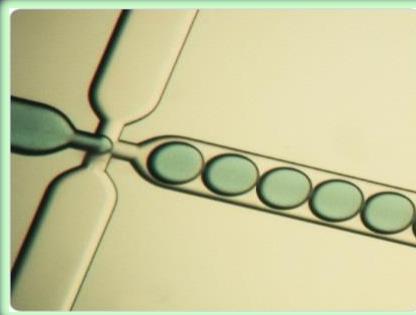
Differential thermal expansion



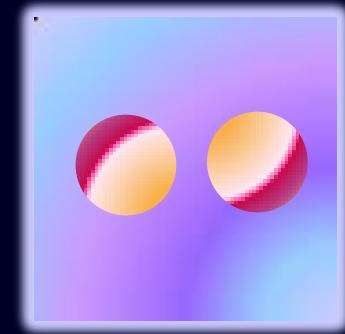
Ampere Force



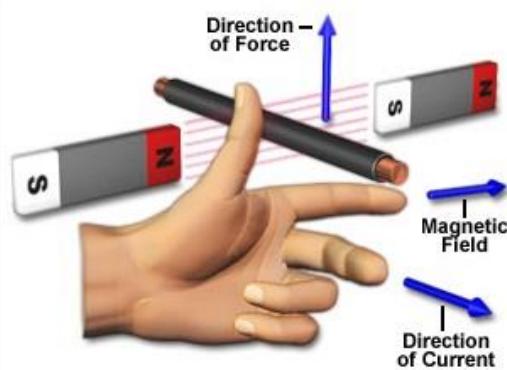
Micro/nano fluidics



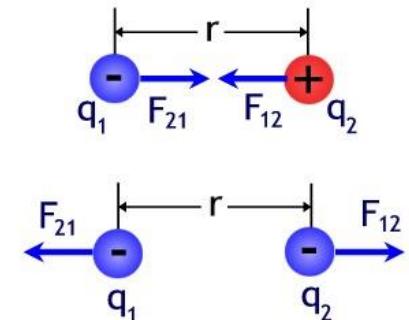
Optical Forces



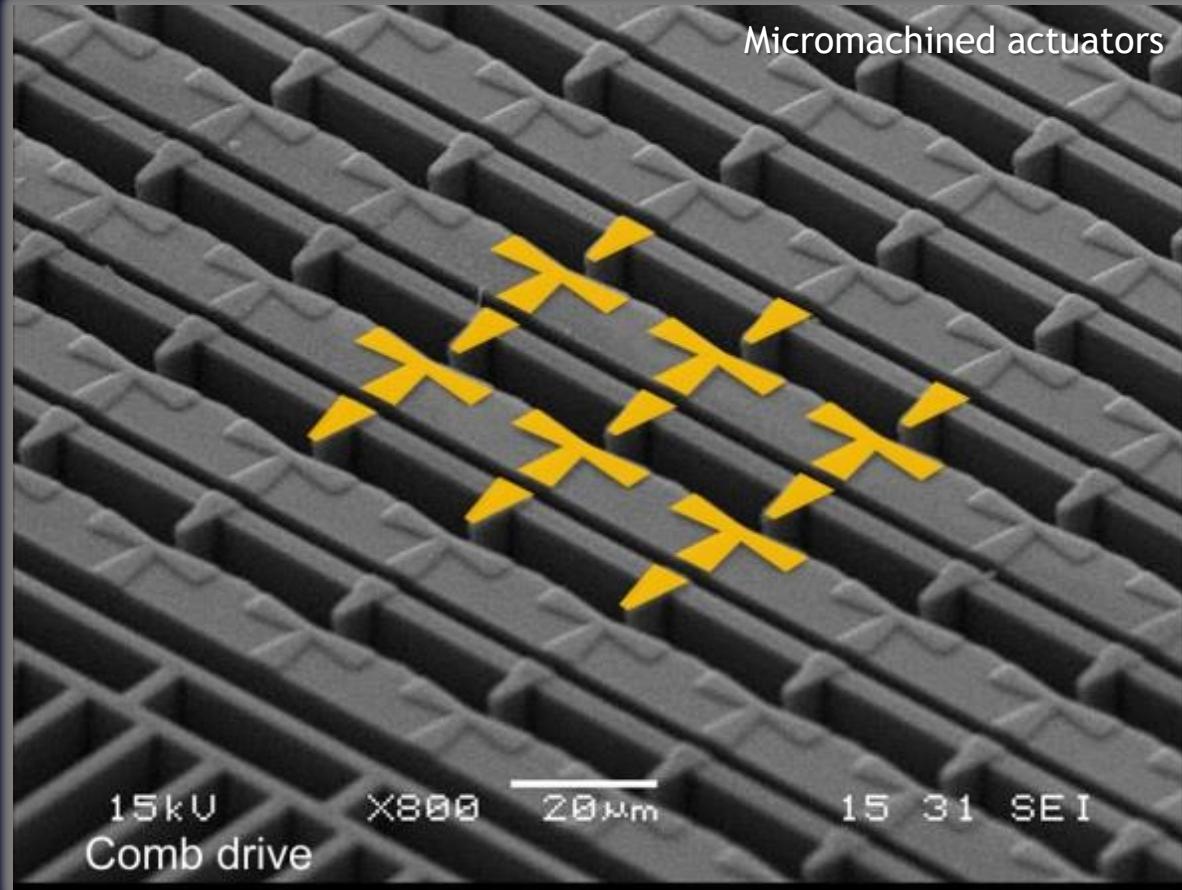
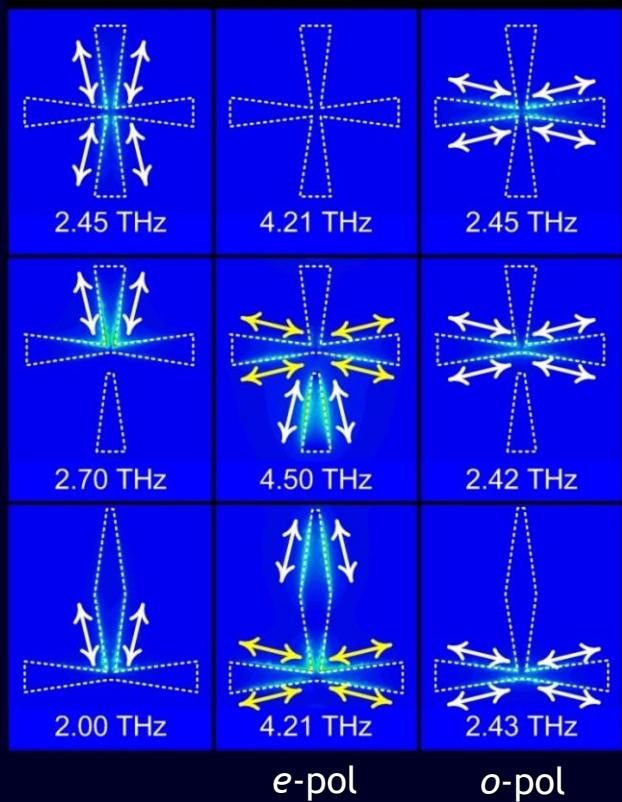
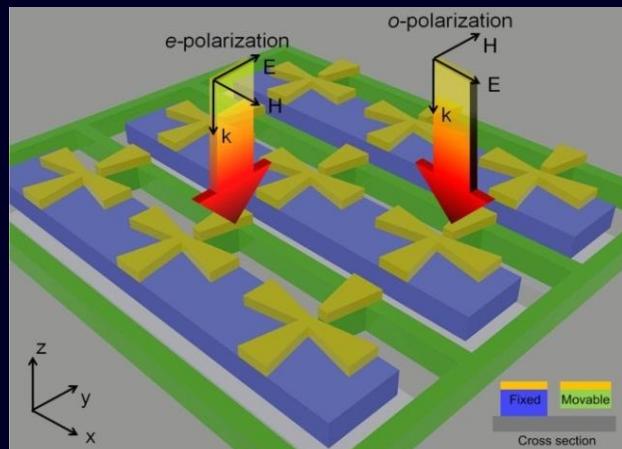
Lorentz-Laplace force Force



Coulomb Force Force



THz MEMS reconfigurable Metamaterials

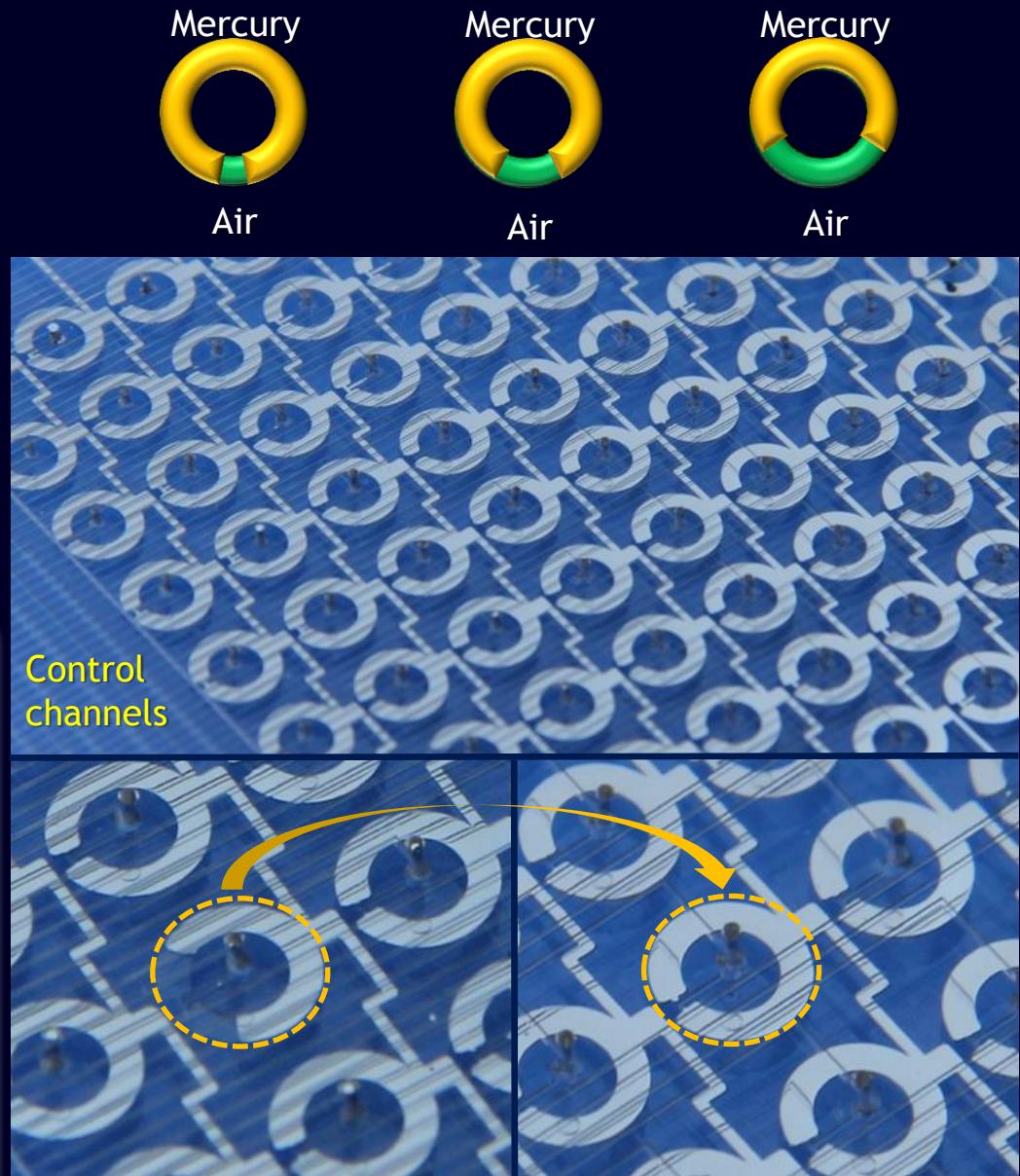
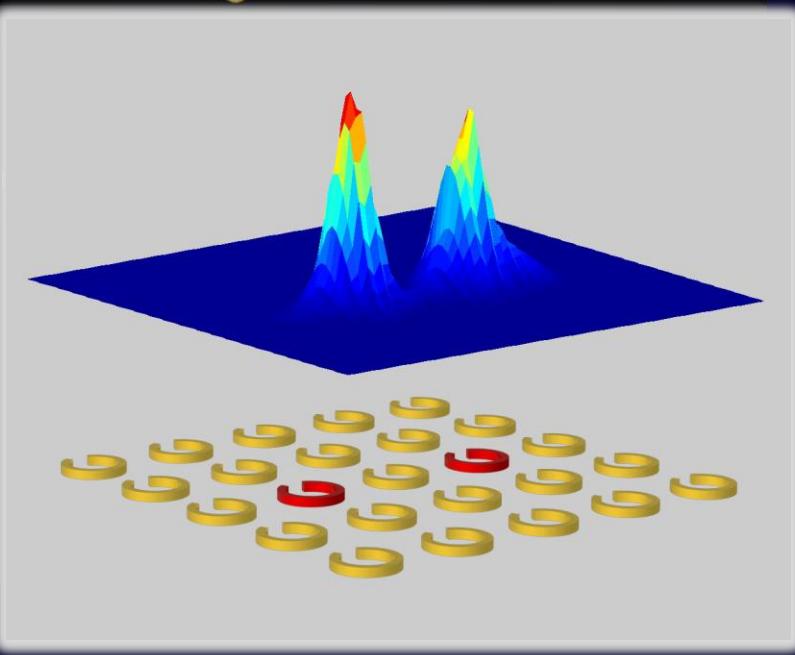
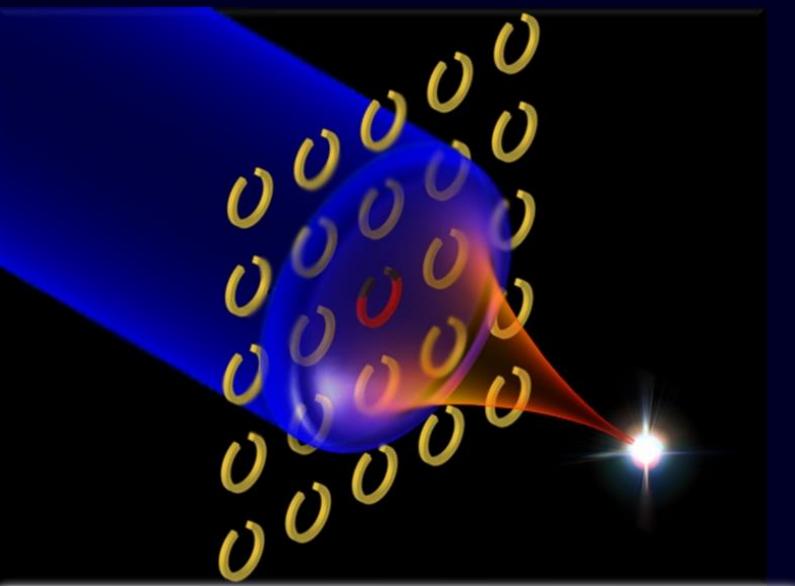


- Tunable anisotropy
- Terahertz var. waveplates
- Tunable filters
- Polarimetry

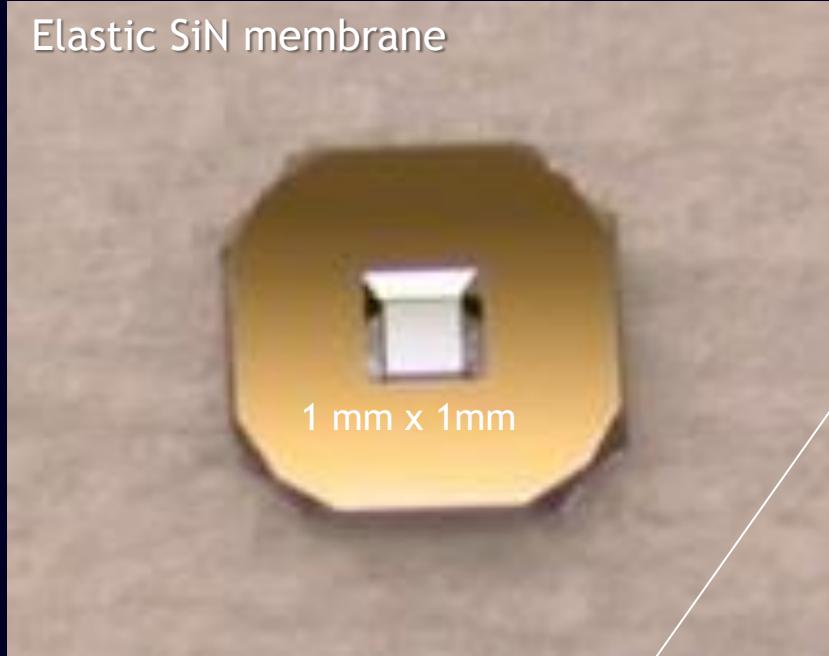
Zhu, W. M. & Liu, A.Q. Zheludev N.I. et al.,
Nature Communication (2012)

Y. H. Fu, A. Q. Liu, N. I. Zheludev, et.al.
Advanced Functional Materials (2011)

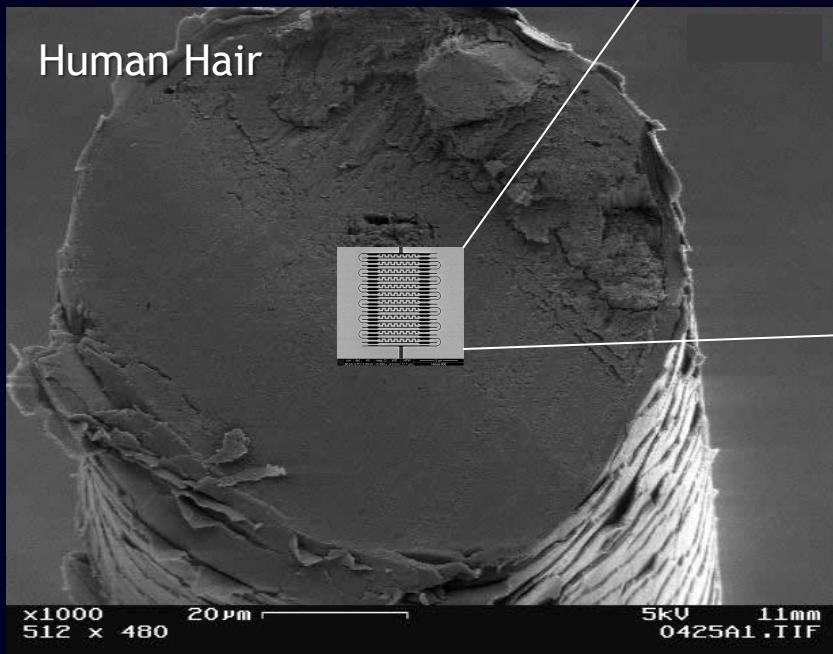
Liquid Metal (Hydraulic) Random Access Metamaterial



Elastic SiN membrane



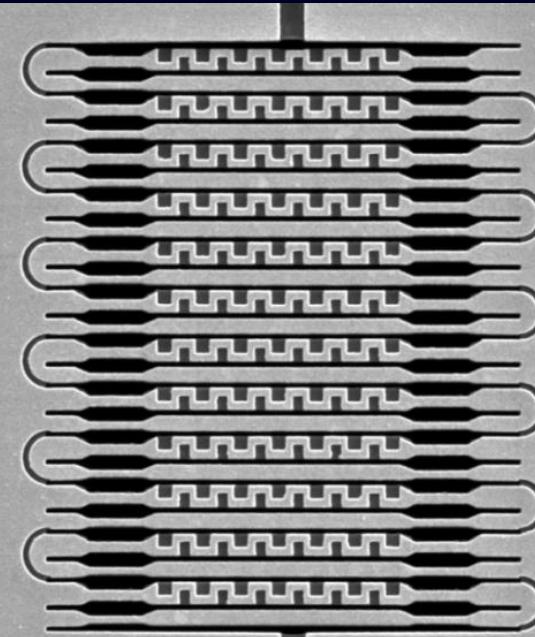
Human Hair



$\times 1000$
512 x 480 20 μm

5kV 11mm
0425A1.TIF

Reconfigurable metamaterials

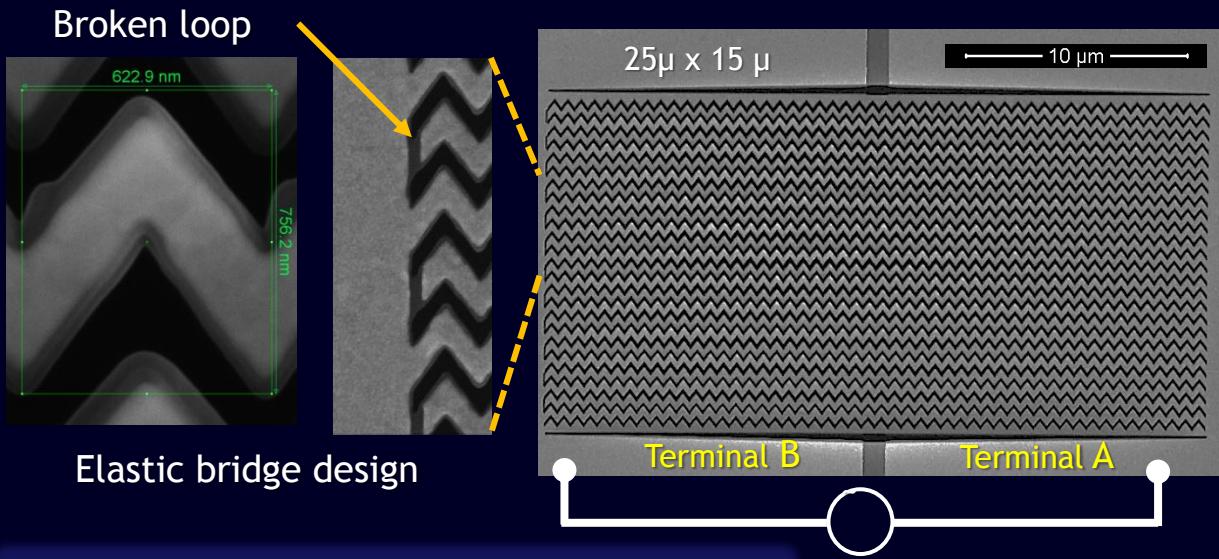
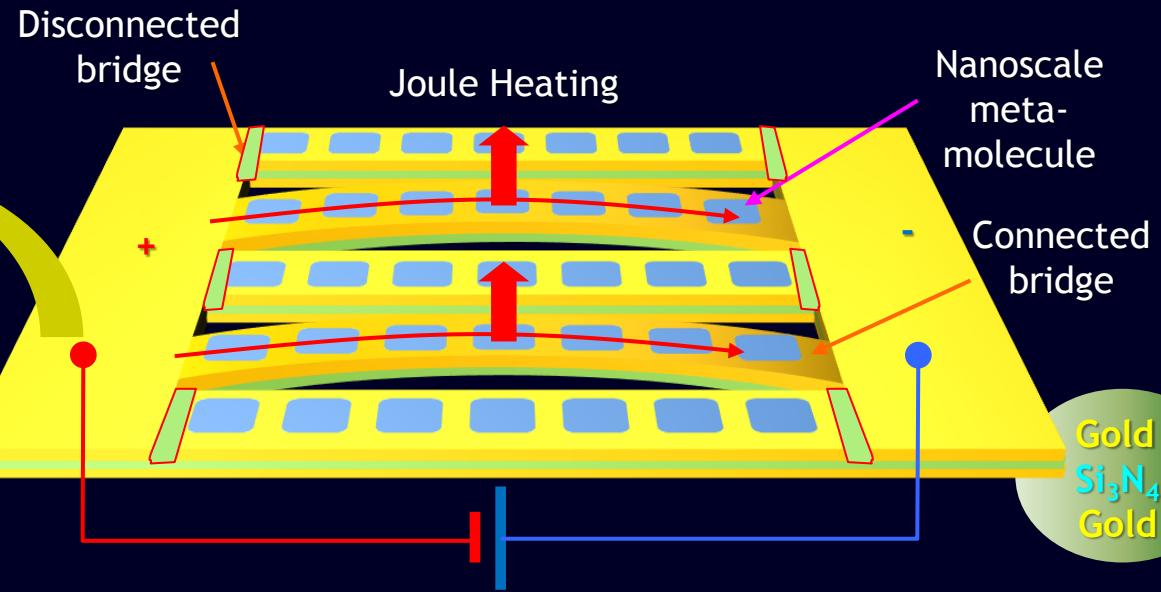
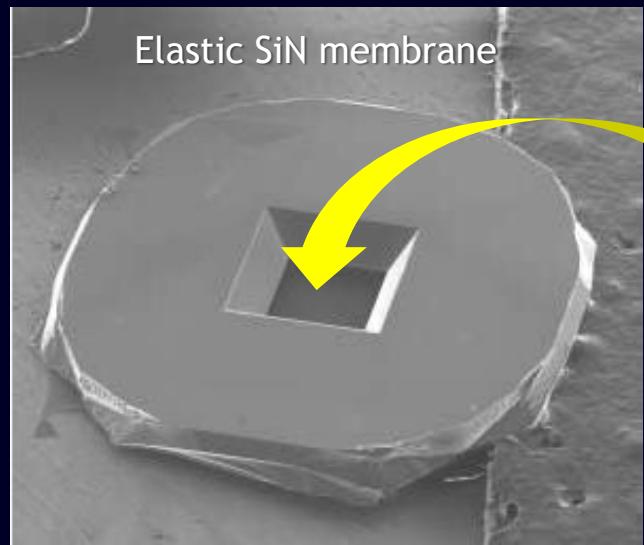


curr det HV mag WD HFW — 5 μm —
86 pA ETD 5.00 kV 15 000 x 4.0 mm 17.1 μm Helios 600

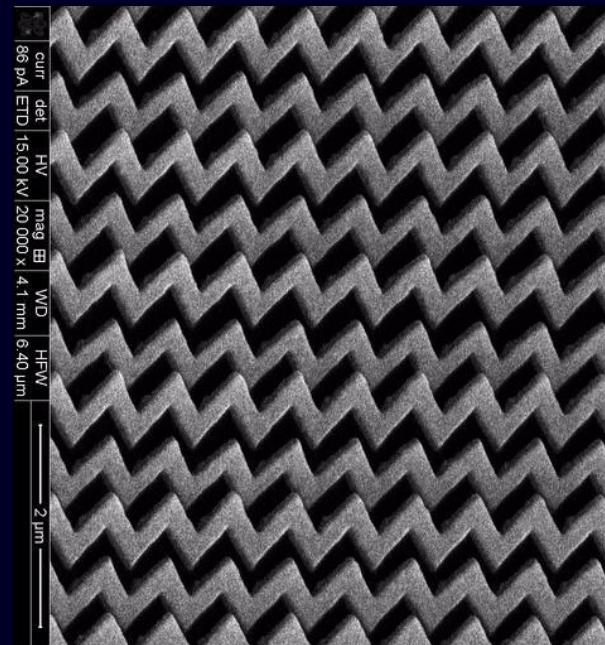
Giant Electro-optic Effect:
Ou, Plum ...Zheludev. Nat. Nanotech (2013)

Giant Optical Nonlinearity
Zhang, Macdonald, Zheludev. Nature/ Light (2013)

Joule reconfigurable metamaterial

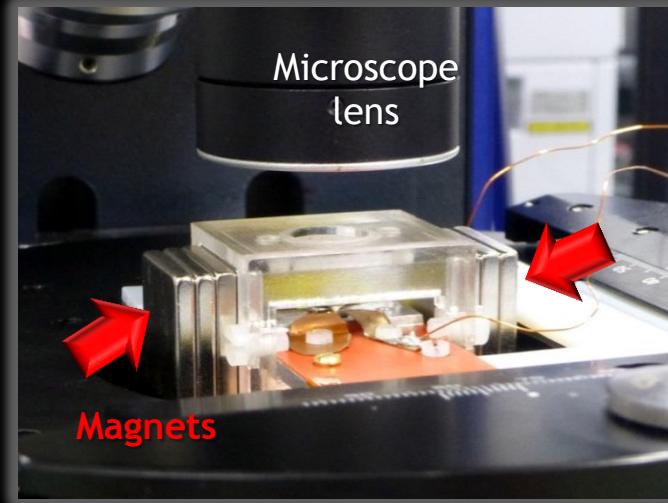
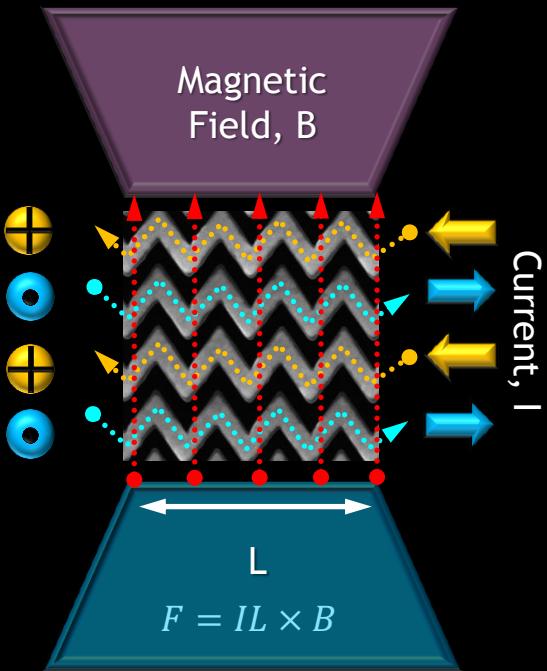


Ou.... Plum, Zheludev. Nano Lett. (2011)
Ou, Valente, Plum ... Zheludev. CLEO-Europe (2013)

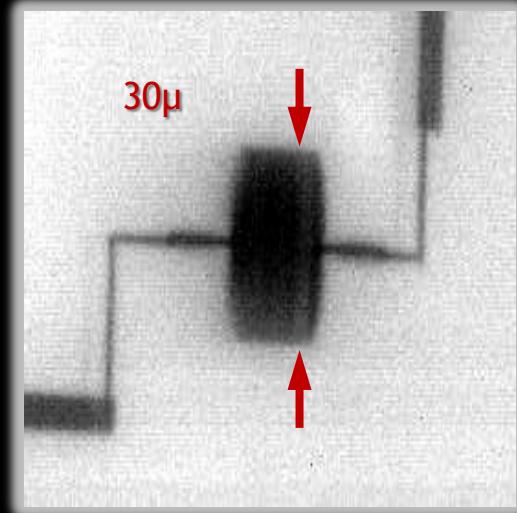
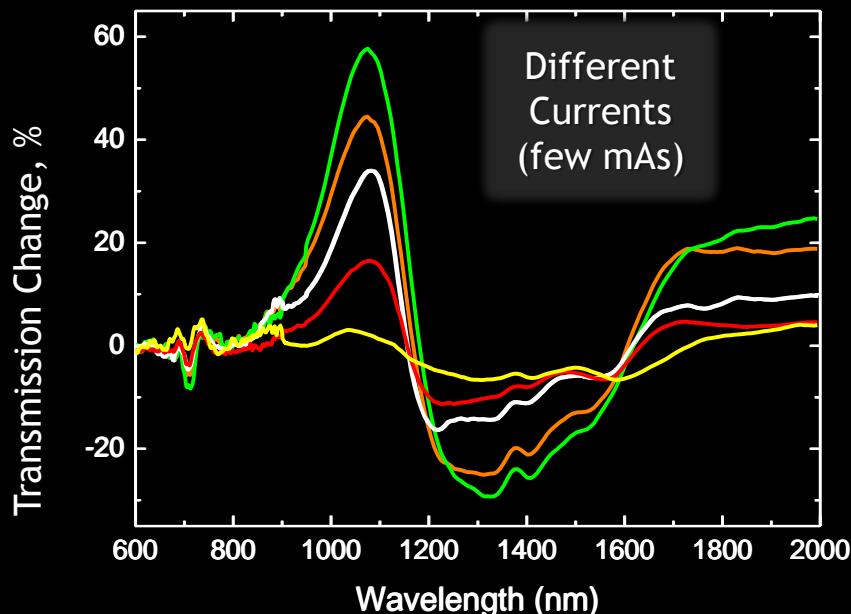


Lorentz-Laplace reconfigurable metamaterials

Ou, Valente, Plum ... Zheludev. CLEO-Europe (2013)



RPM in micro spectrometer

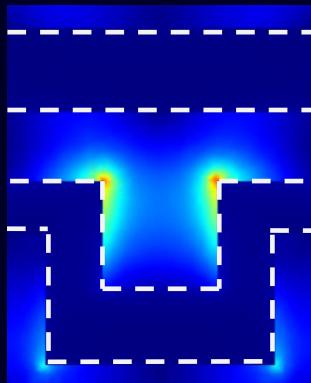
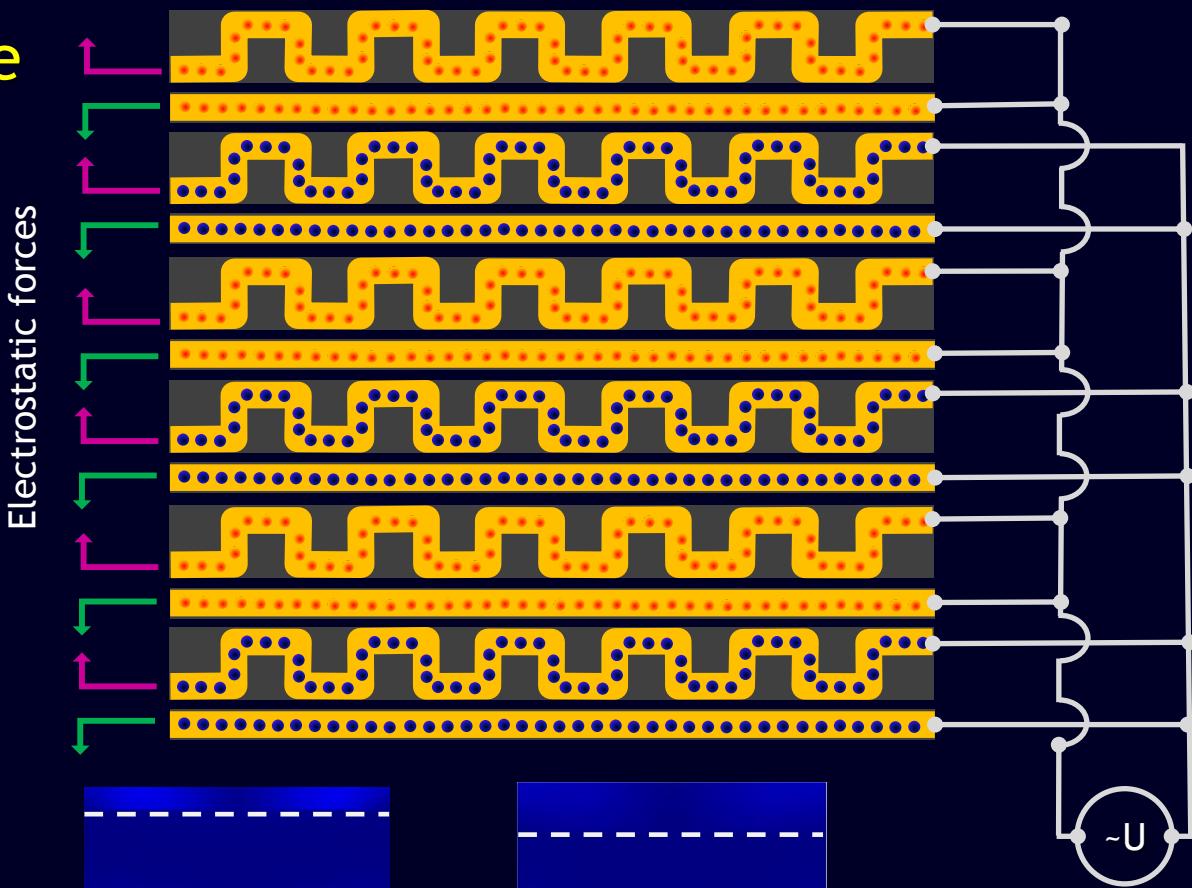
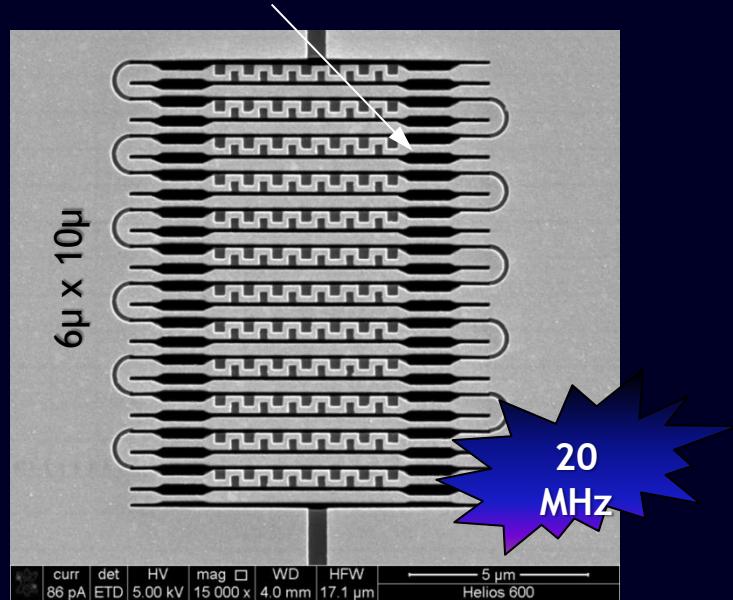


RPM with contact wires on wafer

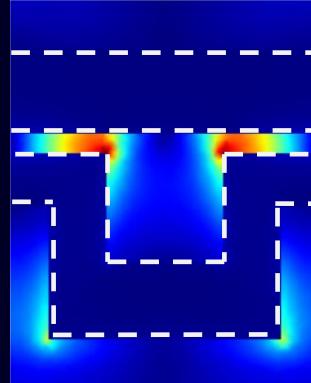
Coulomb reconfigurable metamaterials



Mass ~ 0.5 pg (pico-gram)



Off
> 70% change in transmission/reflection

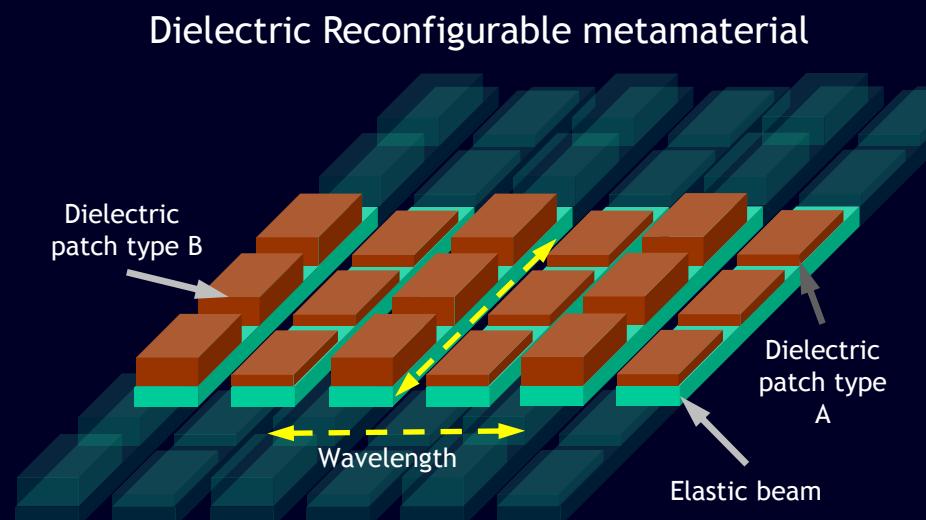
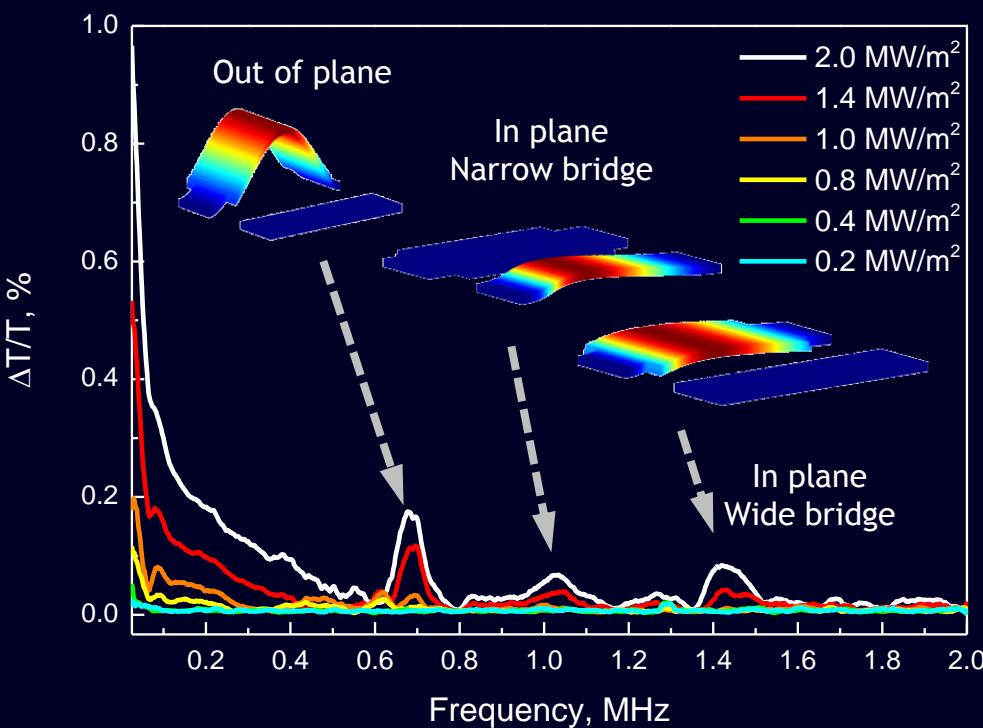
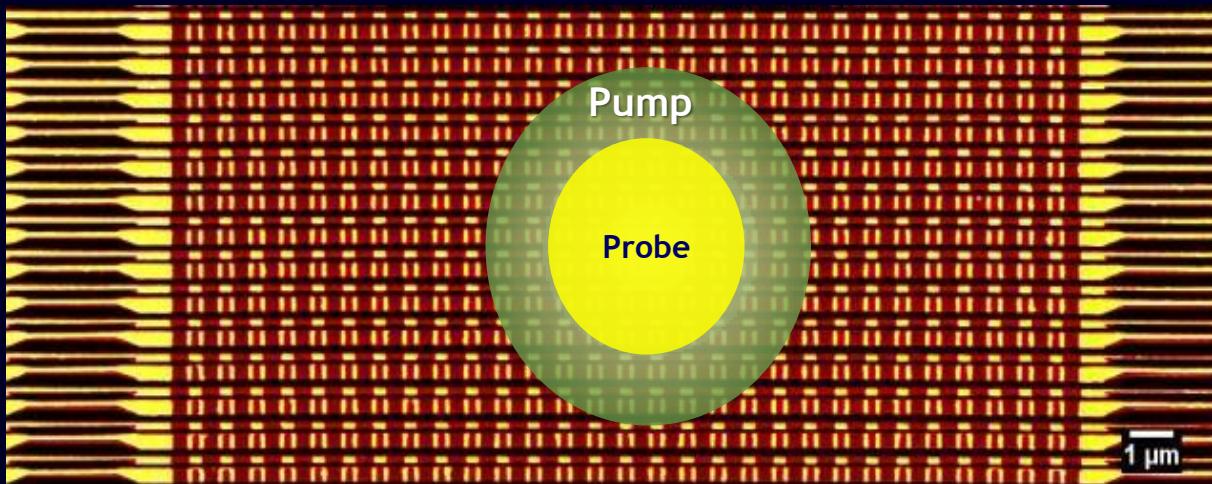


EO coefficient
5 orders of
magnitude stronger
than in LiNbO₃

Ou, Plum ...Zheludev
Nat. Nanotech (2013)

Reconfiguring metamaterials with light

Plasmonic Reconfigurable metamaterial



Zhang, Macdonald, Zheludev
NPG Light:
Science and Applications (2013)

Size matters



Weak elastic force at the nanoscale

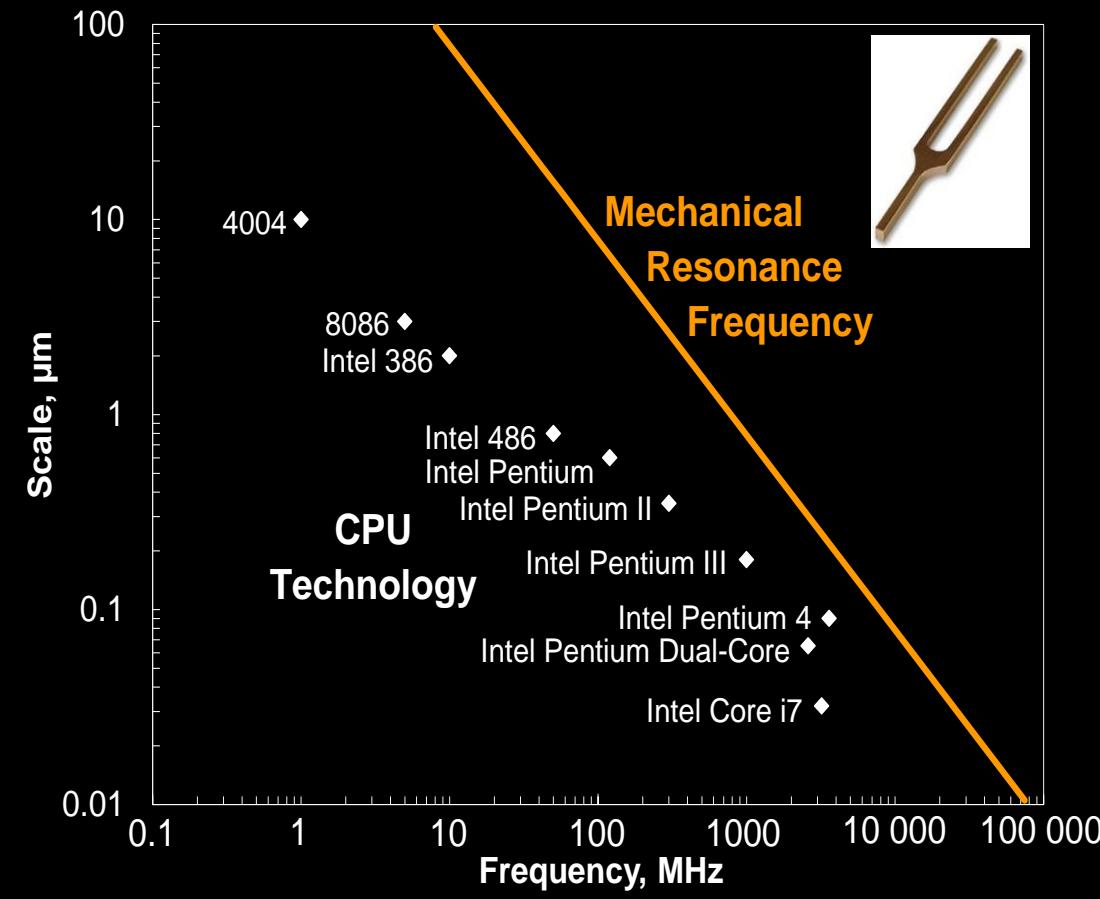


Hooke's force
 $F \sim k \Delta x \sim r^2$

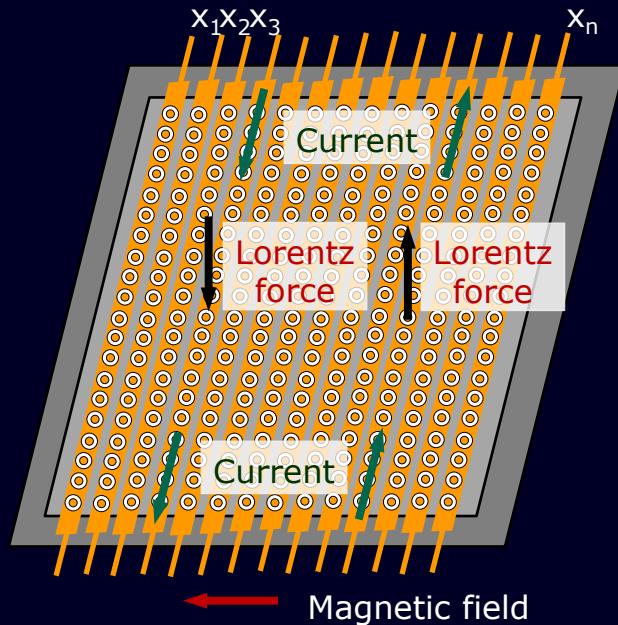


High natural frequencies at the nanoscale

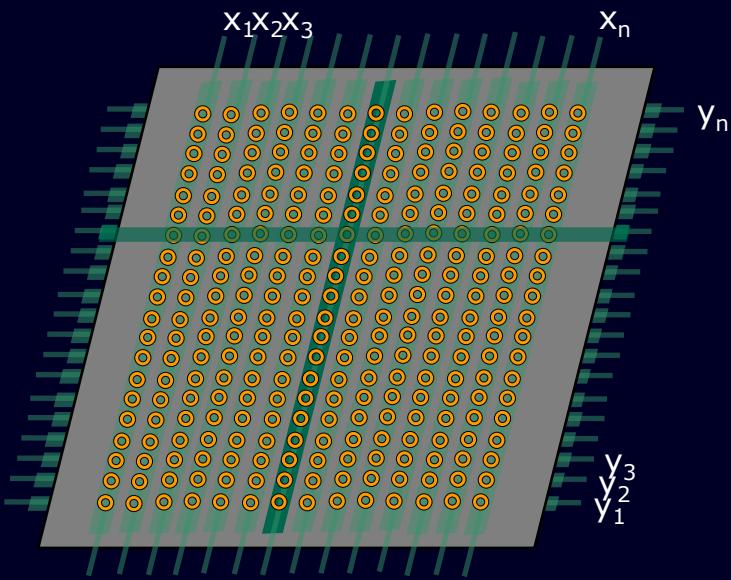
Mechanical resonance
 $\omega_0 \sim (k/m)^{1/2} \sim 1/r$



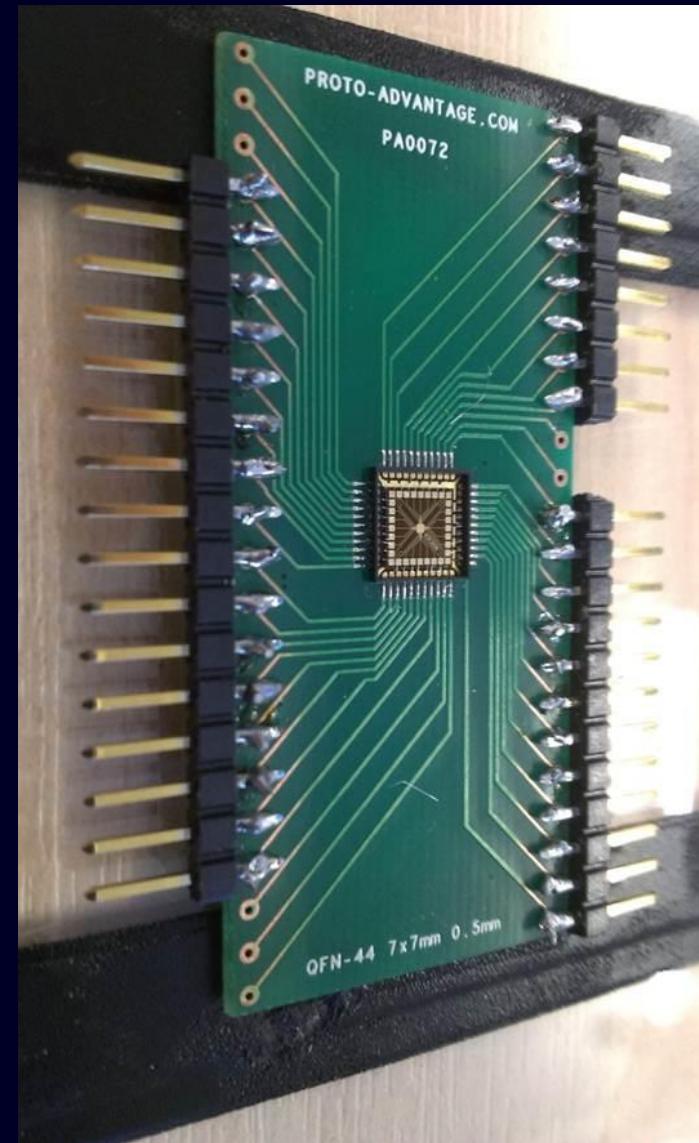
Randomly Reconfigurable Metamaterials



1D Randomly
reconfigurable
metamaterial

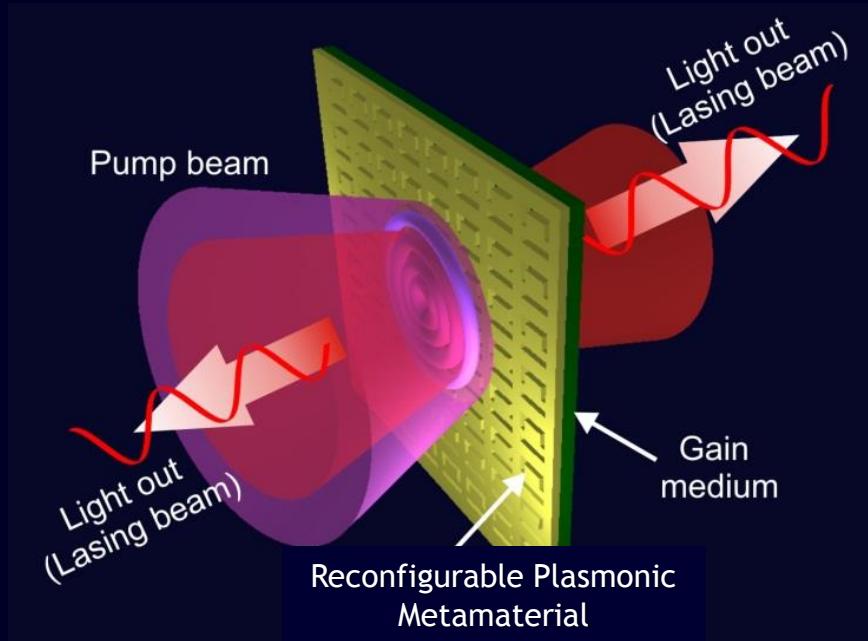


2D Randomly
reconfigurable
metamaterial

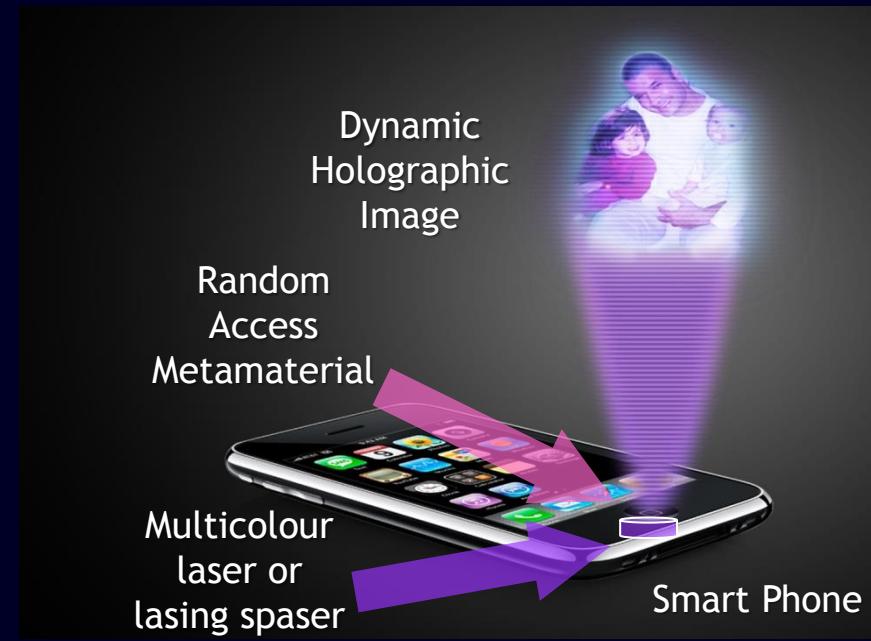


Where future “killer applications” may come from?

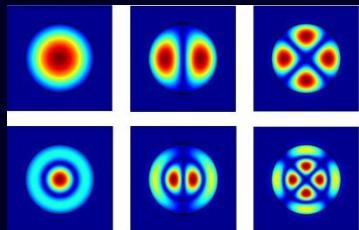
Tuneable Lasing Spaser



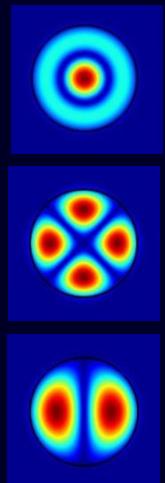
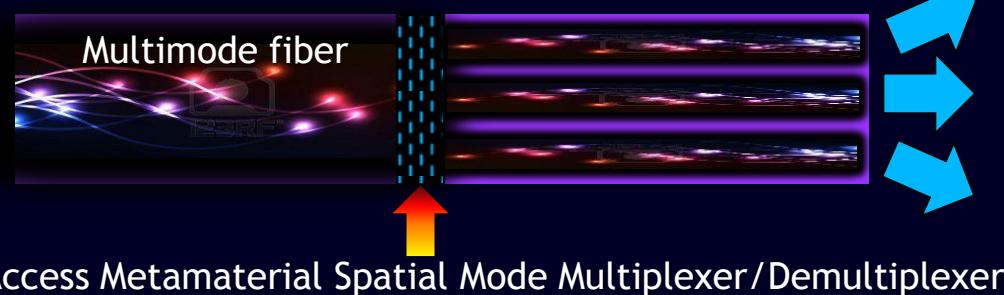
Mobile dynamic 3D display



“In fact, the only remaining unused dimension in fiber telecommunication networks is space...” Nikia-Siemens



Space Division Multiplexing in fiber networks



Conclusions

- Research on metamaterials is rewriting optics textbooks as we know them
- Metamaterials is emerging enabling technology in all applications of light
- Main technology drivers for developing metamaterials are:

Telecoms (reduction of energy consumption and increase of bandwidth)

Energy conversion and re-distribution

Sensors

Light sources

Cognitive & Data processing systems?

- Metamaterials - >> Metadevices ->> Metasystems

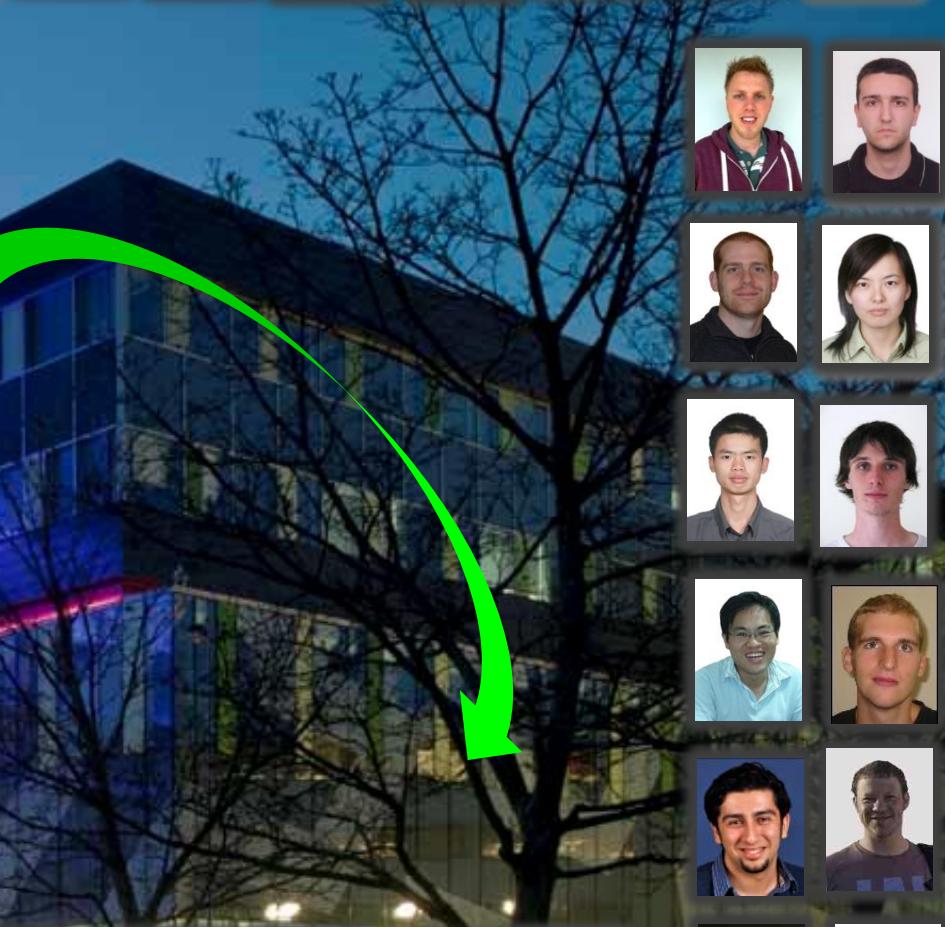




Chiral Fractal Metamaterial



Southampton
University
Mountbatten
Building



Light



THANK YOU!

The talk may be found at:

http://www.nanophotonics.org.uk/niz/niz_talk.pdf

