From Photonic Metamaterials to Metadevices: Exploiting Forces and Fields at the Nanoscale

Nikolay Zheludev

10:30 -11:15 Plenary talk at SPIE Optics and Photonics 13, San Diego, CA. 26 August 2013

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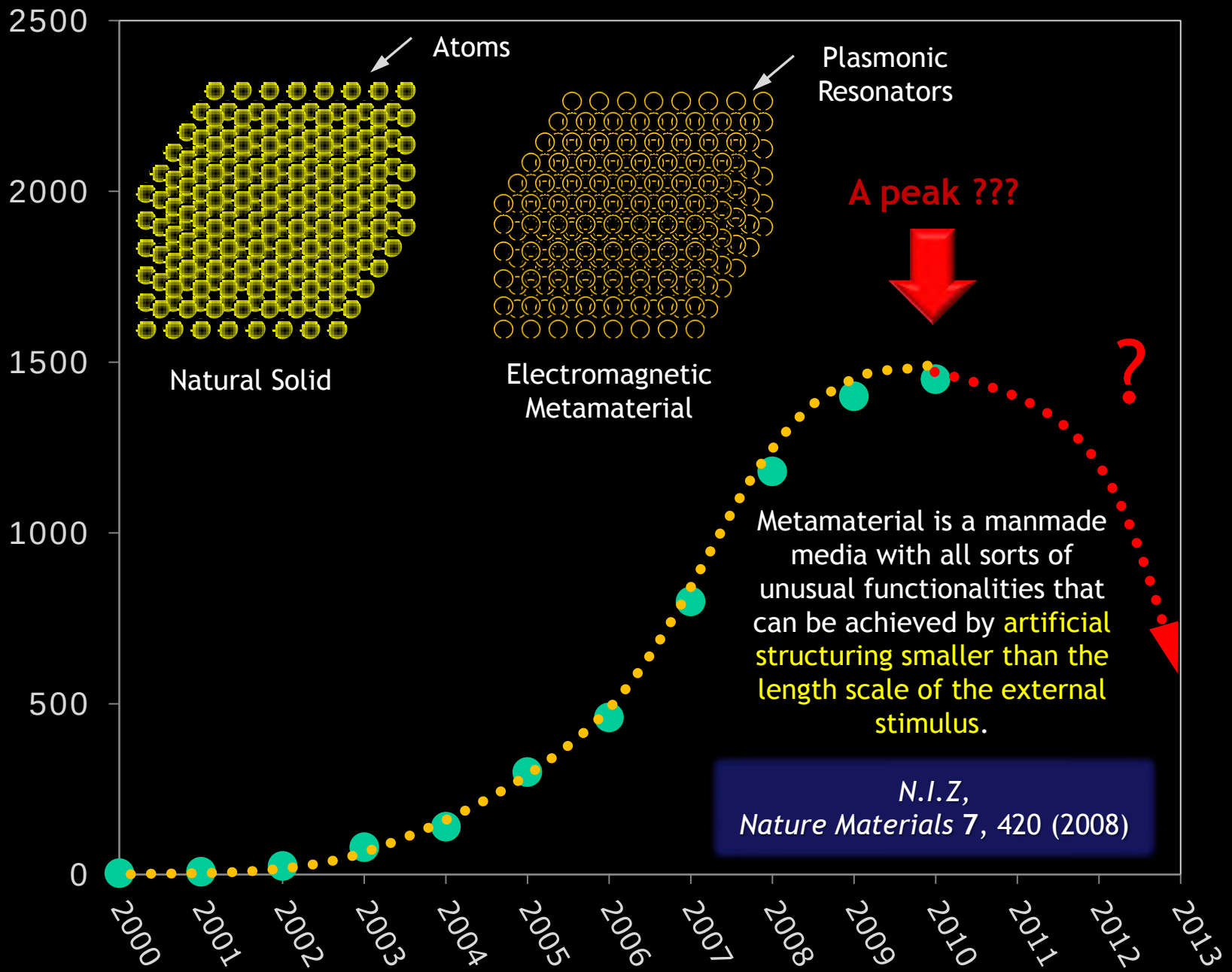
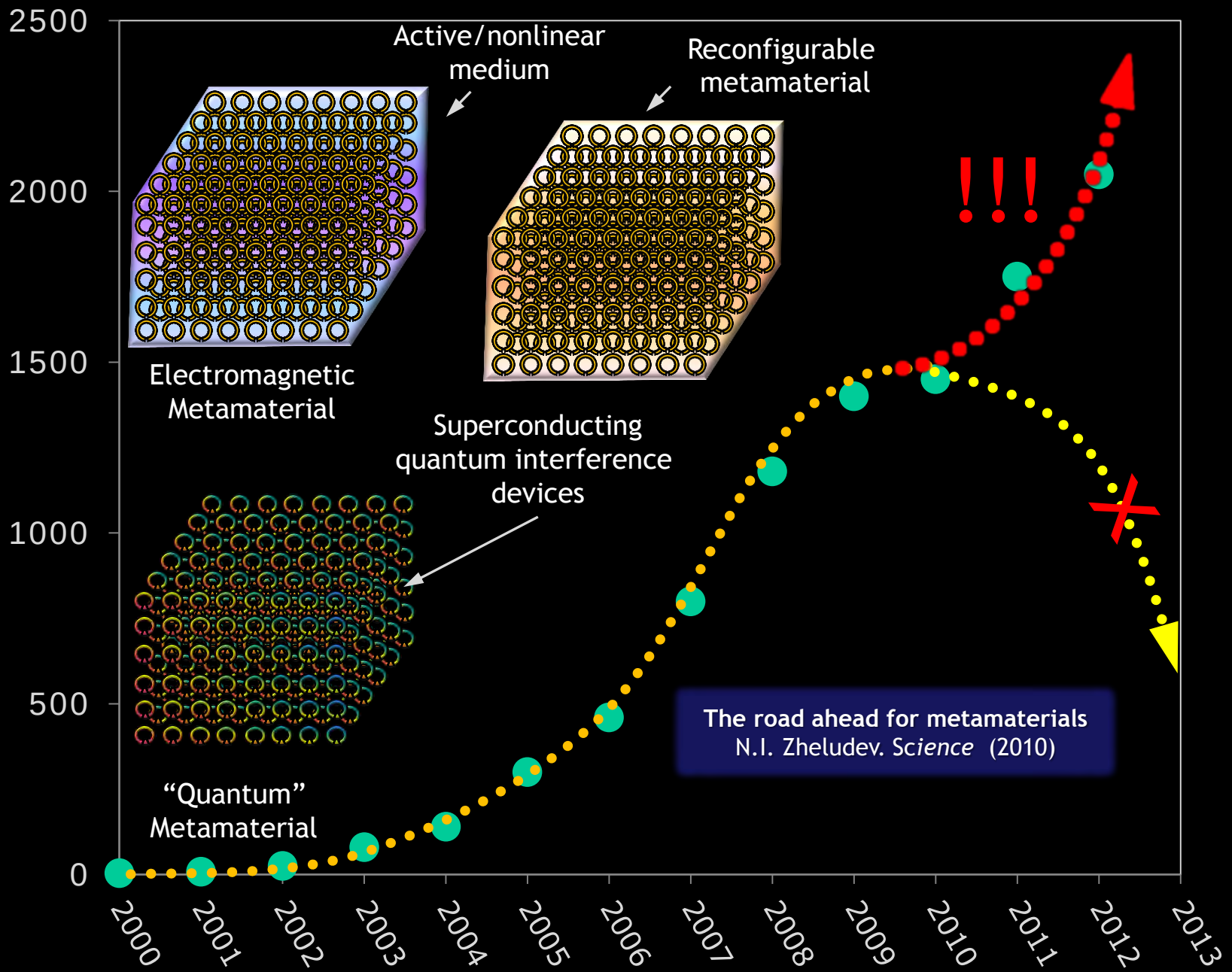
www.nanophotonics.org.uk

Metamaterials: mimicking Nature, step 1

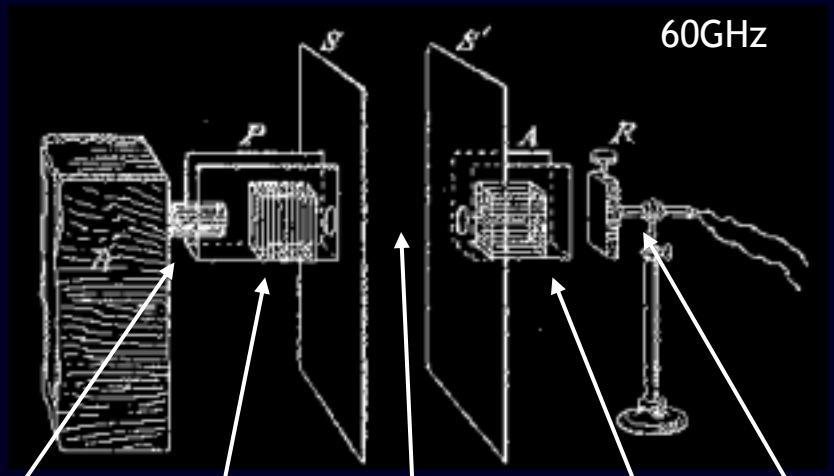


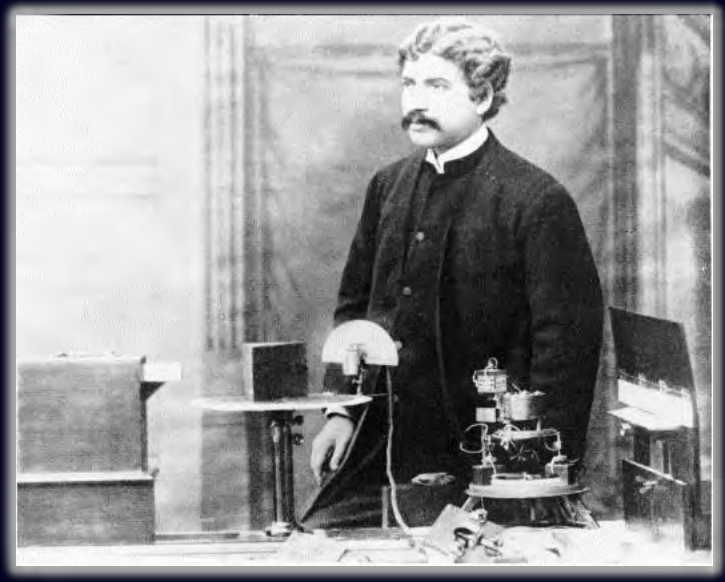
Metamaterials: mimicking Nature, step 2



1st Metamaterial (J.Bose, 1898)

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





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

Chiral meta-Molecule
(twisted jute)

Anisotropic meta-Molecule
(metal sheets alternated with paper)

The main questions

Why the metamaterials technology development curve became a saddle point in 2010 (and not a local maximum)?

What is the domain of metamaterial research beyond negative index & transformation optics?

Topics left outside of the talk:

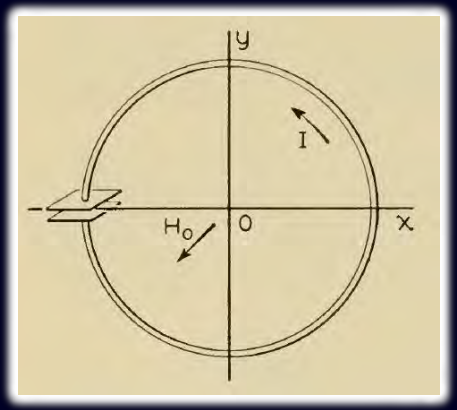
- I huge body of work on Negative index & Super-hyper lens
- I huge body of work on Transformation optics and cloaking
- Gradient metamaterials (F. Capasso)

Impact of Metamaterials on Fundamental Physics #1
Optical Magnetism & Negative Refraction

Hundtreds of papers

L. D. Landau, E. M. Liftshitz, 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



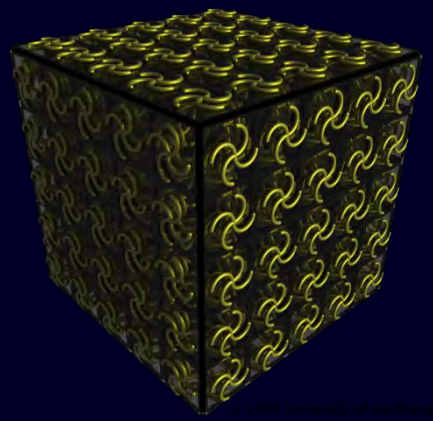
S.A.Schelkunoff & H.T. Friis
Antennas Theory and Practices. J.Wiley & Sons, 1952

Negative Permeability and Permittivity ("left-handed")

San Diego!

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

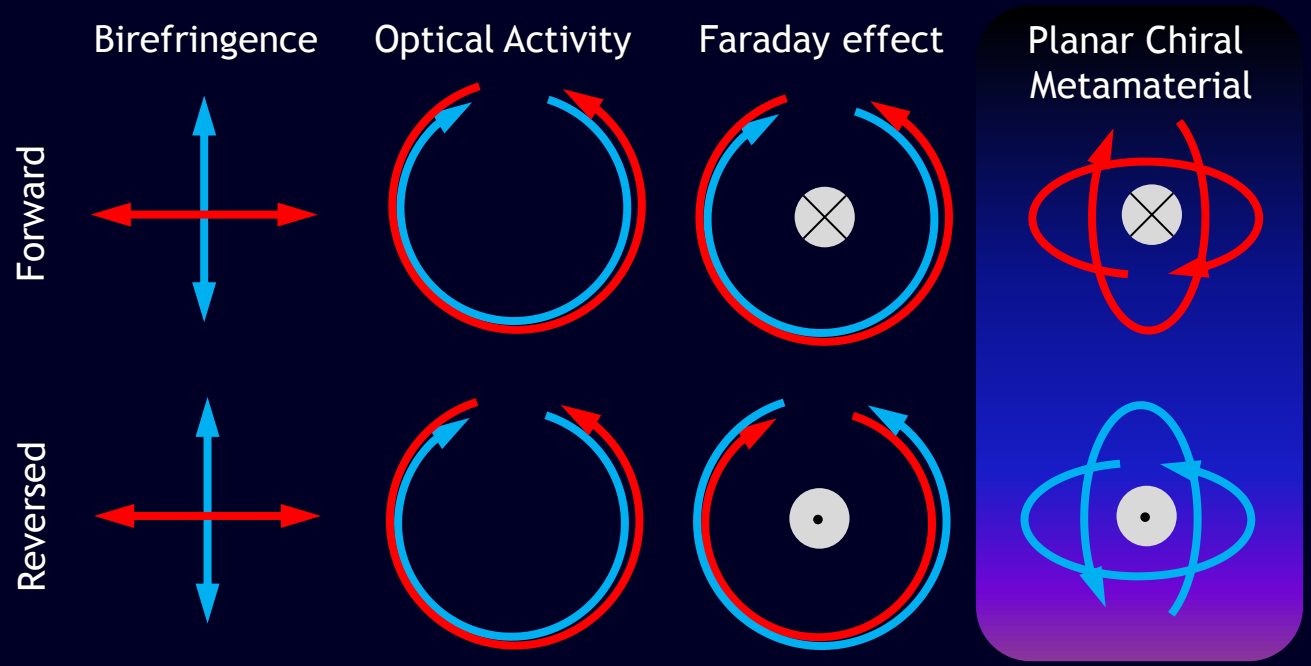
Negative refraction due to chirality ~ Im { m_{kn} d_{nk})

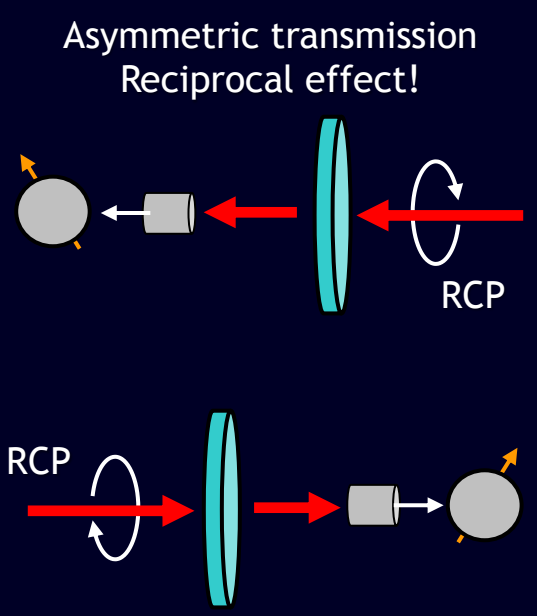


Tretyakov (2003)
Pendry (2004)
Rogarcheva… Zheludev PRL. (2006)
Plum …. Zheludev, PR B (2009)

THz:	Yen, Padilla … Pendry, Basov, Zhang, Science (2004)
IR:	Zhang … Brueck, PRL (2005)
Optical:	Grigorenko, Geim … Petrovic, Nature (2005)
	Kildishev … Shalaev JOSA-B(2006)
	Shvets and Urzhumov, J. Opt. A (2006)
	Klein, Enkrich and Wegener, Opt. Lett. (2006)

Impact of Metamaterials on Fundamental Physics #2
Reciprocal Asymmetric Transmission

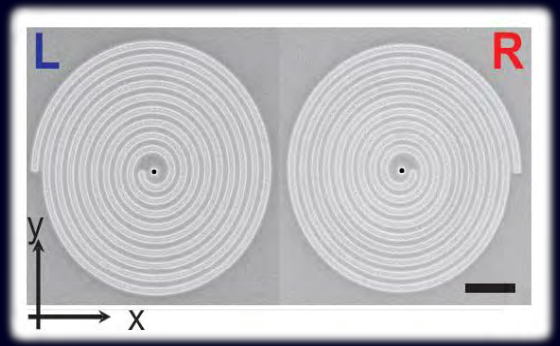




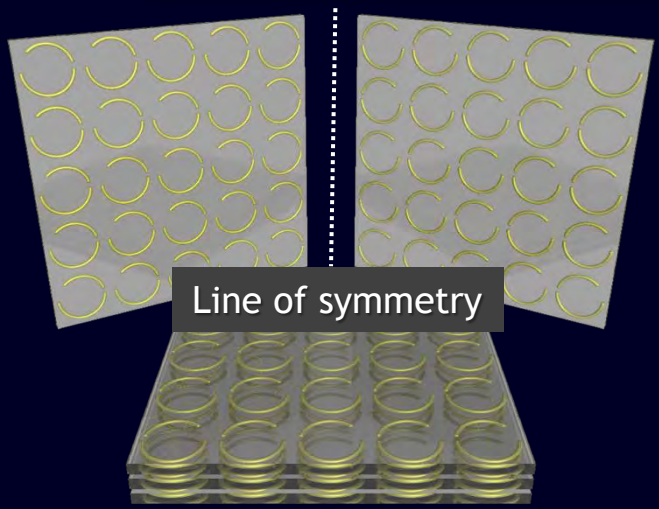
Fedotov ...Zheludev. PRL (2006)

Plum... Zheludev. APL (2006)
Fedotov, Schwanecke,
Zheludev. Nanoletters (2007)
Schwanecke ...Zheludev
Nano Lett. (2008)
Reichelt ... Zheludev
App. Phys. B (2006)

>20 papers



Drezet... Ebbesen Optics Express, (2008)



Impact of Metamaterials on Fundamental Physics #3
Toroidal Dipole

Magnetic Multipoles

(transverse currents)

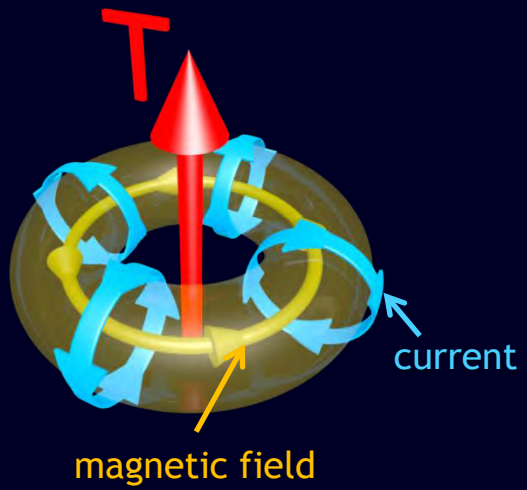
Electric Multipoles

(Charges)

Zeldovich. Sov. Phys.JETP (1953)

Toroidal Multipoles

(Radial Currents)



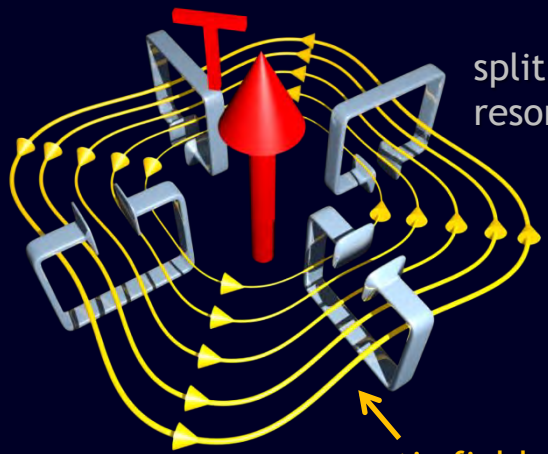
T is difficult to detect!

Fedotov, … Zheludev
NJPh (2007)

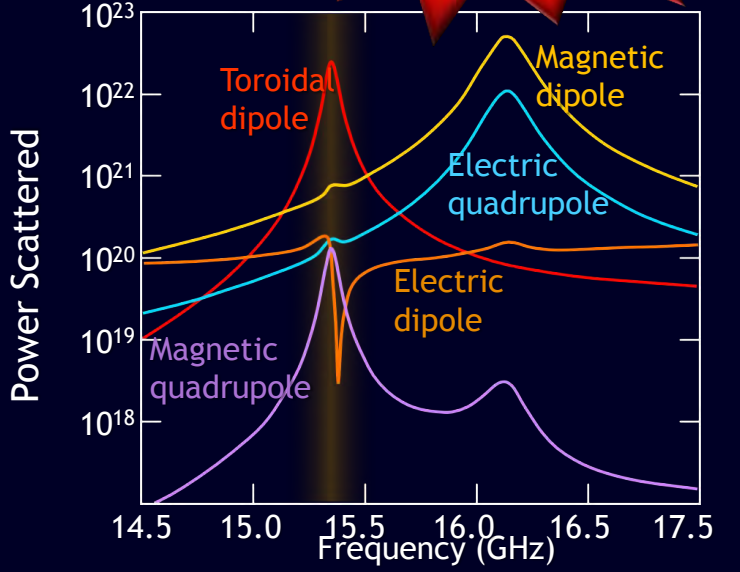
Bacteriophages

Proteins

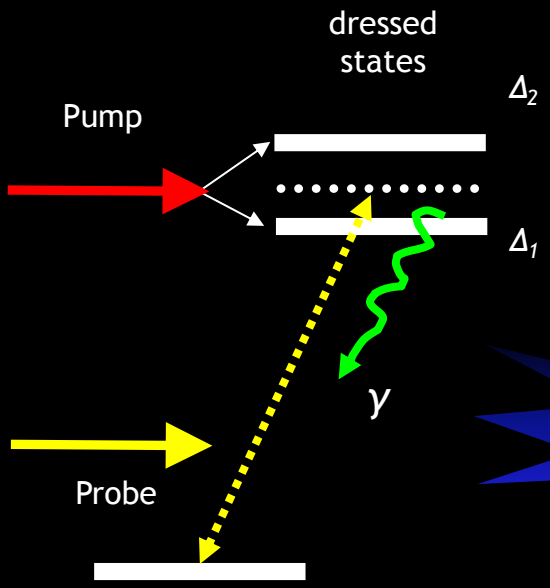
>15 papers
(and grows fast)



Kaelberer … Zheludev
Science (2010)

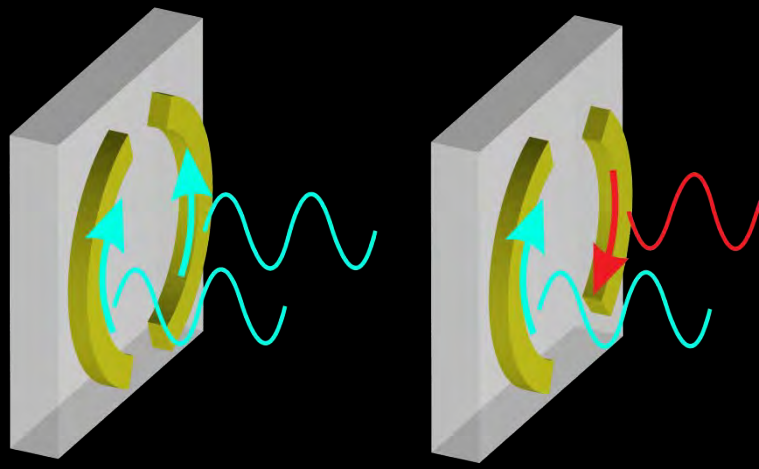


Designing Resonances: EIT & Fano resonances

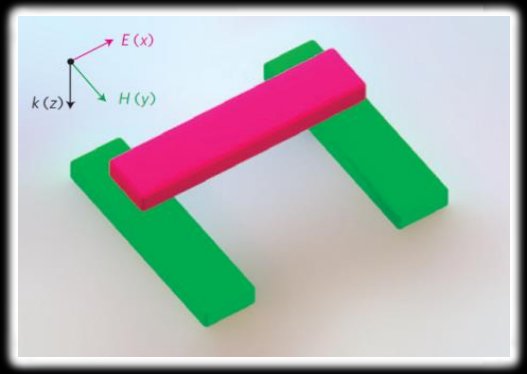


Fedotov … Papasimakis, Zheludev. PRL (2007)

>300 papers

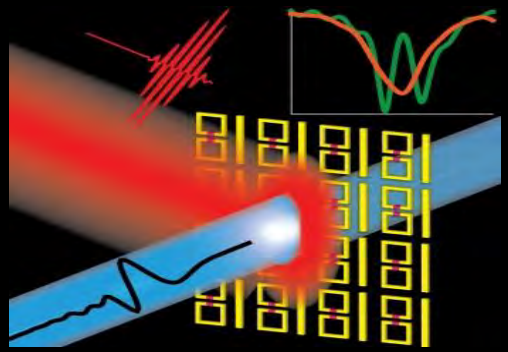


Plasmonic EIT



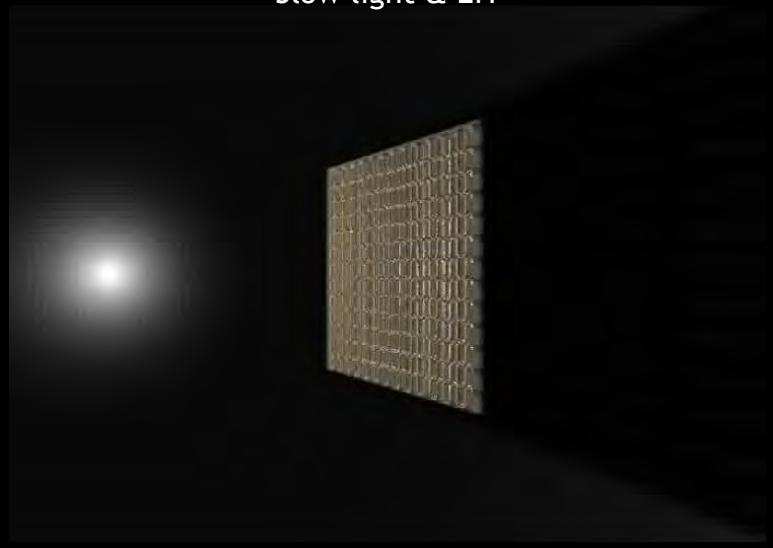
Zhang … Zhang. PRL (2008)
Liu … Giessen. Nat. Mat (2009)

Controlling EIT



Gu … Zhang.
Nat. Com. (2013)

Slow light & EIT

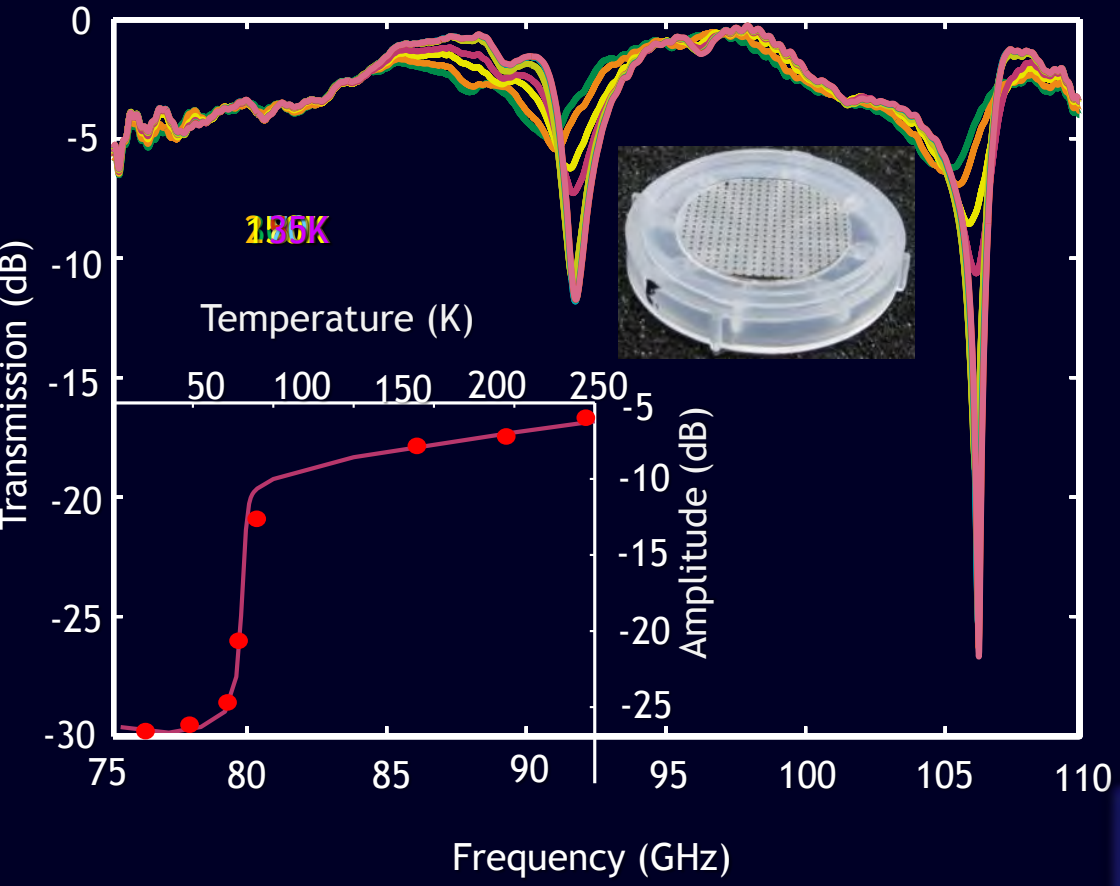


Papasimakis, Fedotov, … Zheludev
PRL (2008)

Luk'yanchuk, Zheludev … Chong. Nat. Mat. (2010)

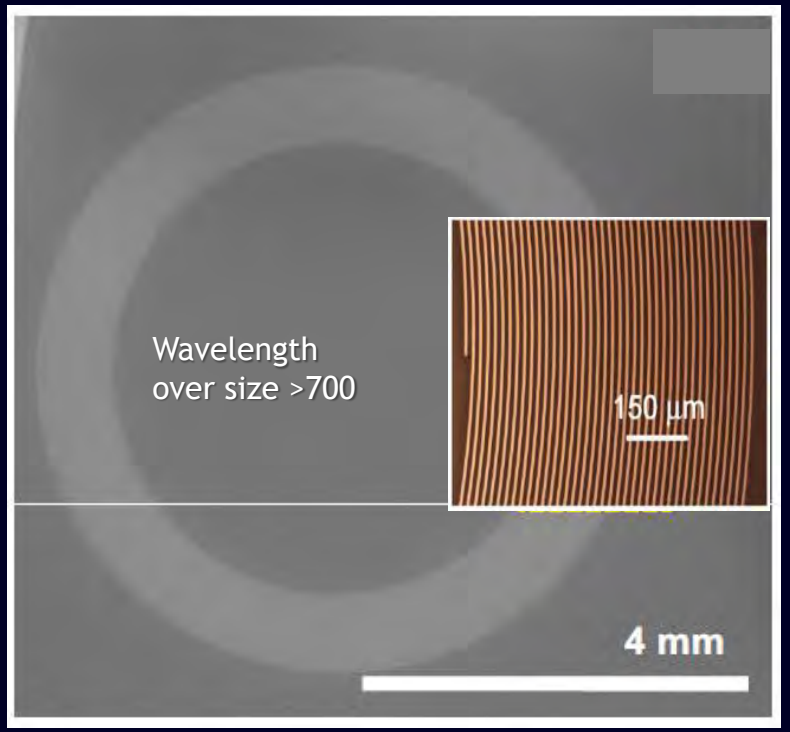
Sharp resonances in superconducting metamaterials

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



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

Spiral meta-molecule in supercond. niobium



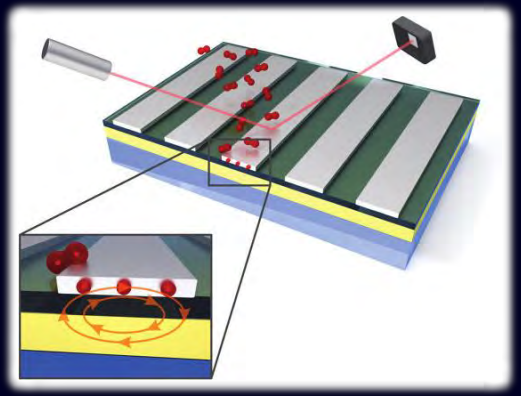
Kurter … Anlage
IEEE Trans. Appl. Supercond. (2011)

>20 papers

Sensor Metamaterials

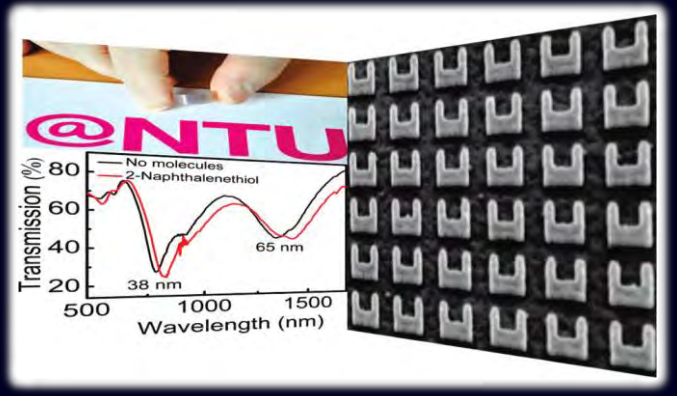
>90 papers

Hydrogen Palladium Sensing



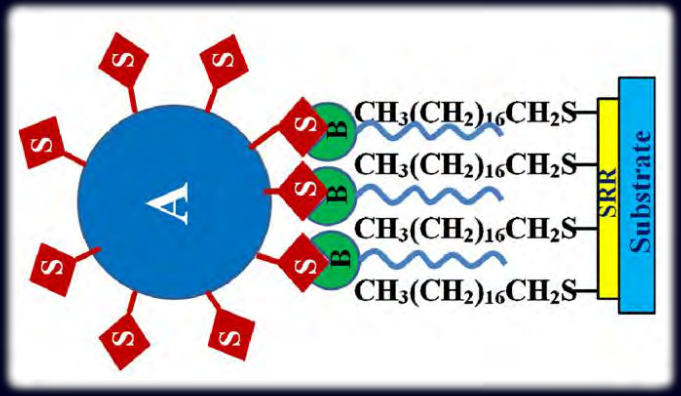
Tittl, … Giessen
Nano Letters (2011)

Non-specific Protein Sensing



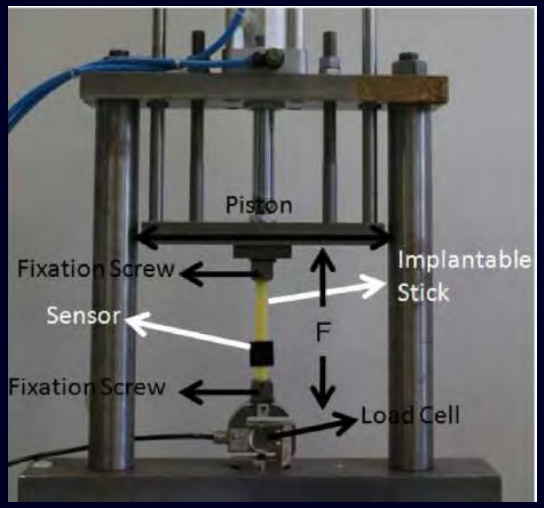
Xu, Xiong.
Nanoletters (2011)

Specific streptavidin prot. sensor

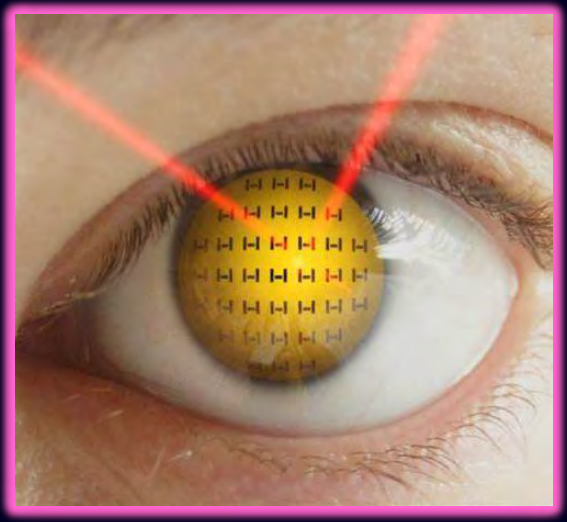


Xiaojun Wua, … LiWang
Biosensors and Bioelectronics (2013)

Strain sensors for orthopaedics



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



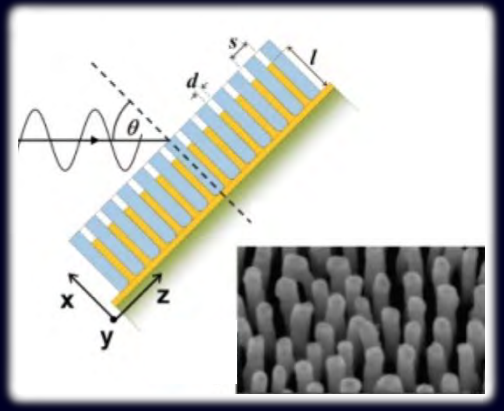
N. Liu ….Giessen *et*. Nano. Lett.. 2010); Wang, … Zhao. APL (2013)

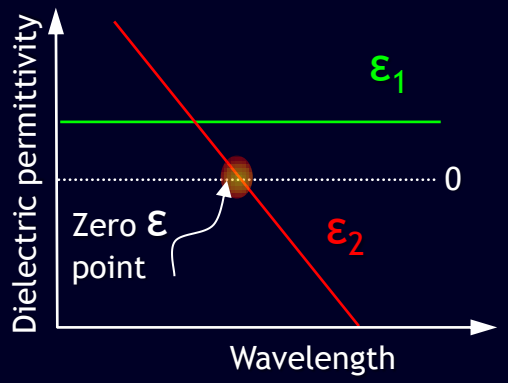
Glucose sensor

>100 papers

Designing Anisotropy & birefringence

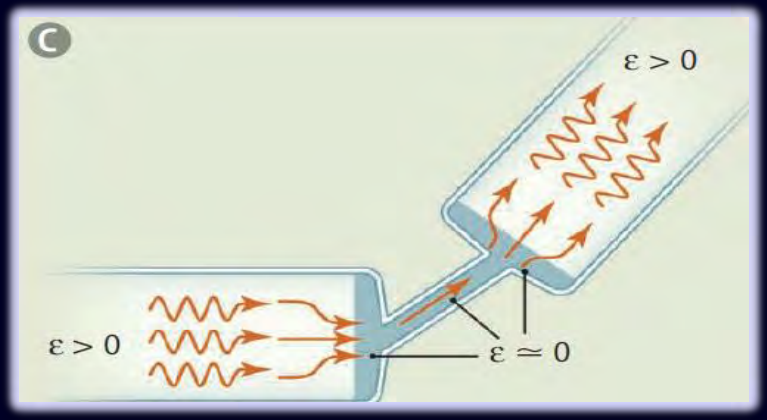
Epsilon zero metamaterials





Silveirinha … Engheta. PRL (2006)
Elser, … Narimanov. APL (2006)
Noginov, …. Narimanov. APL (2009)
Pollard ….Podolskiy. PRL (2009)

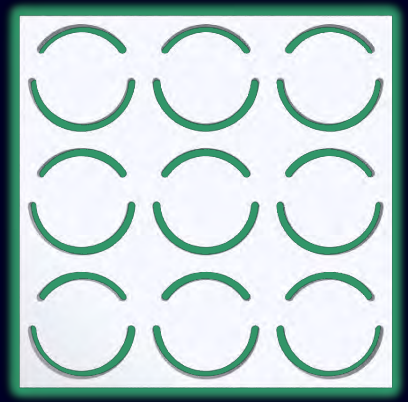
Wave guiding in Epsilon zero MMs & Metatronics

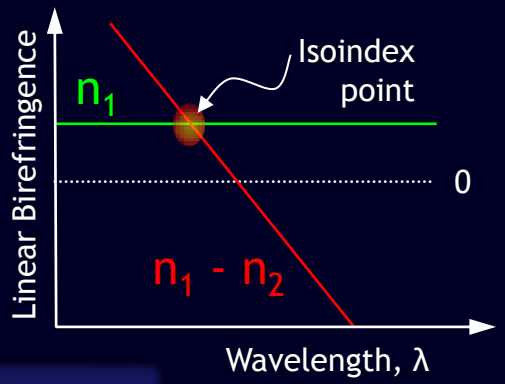


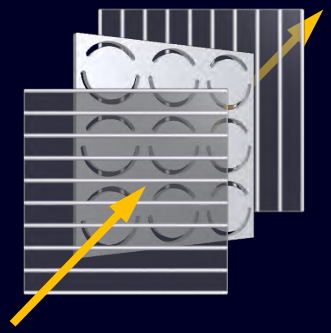
Negative-index in waveguides
Podolskiy & Narimanov. PR E (2005)

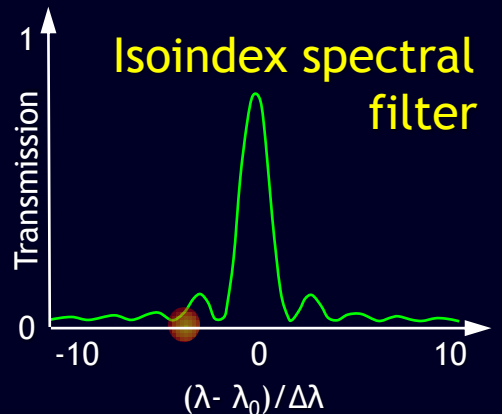
Zero-index waveguides
Silveirinha … Engheta. PRL (2006)
Metatronics : Engheta . Science (2007)

Isoindex (index zero-crossing) metamaterials



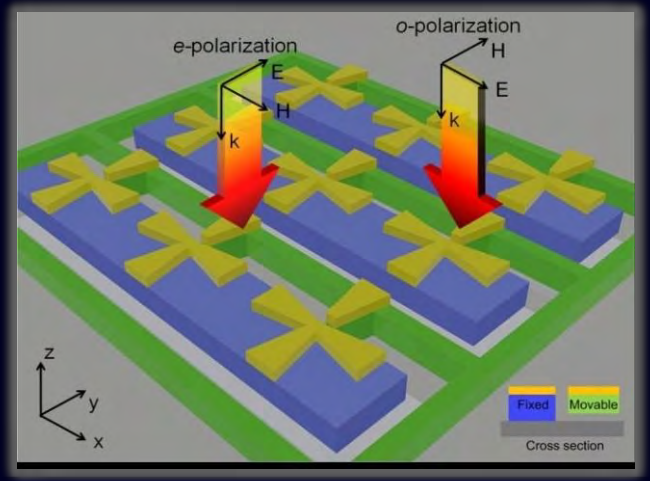


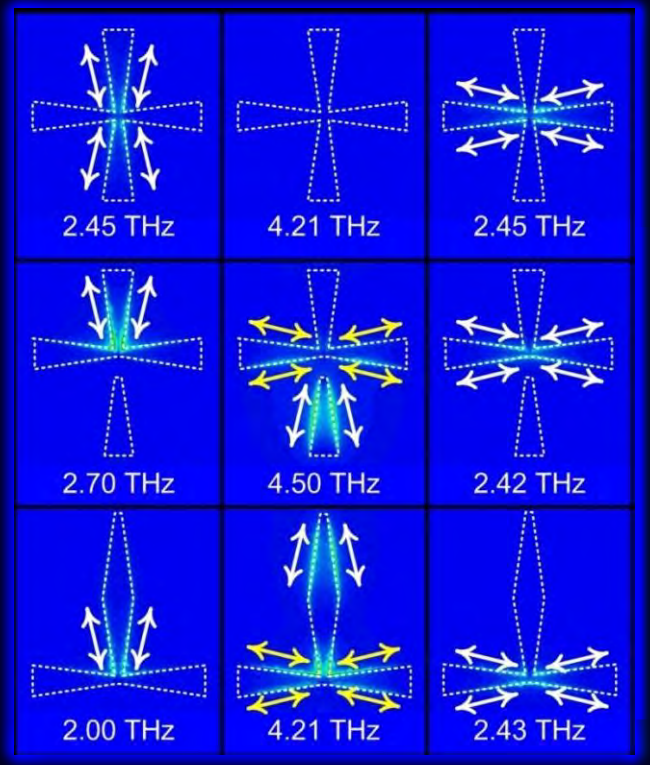




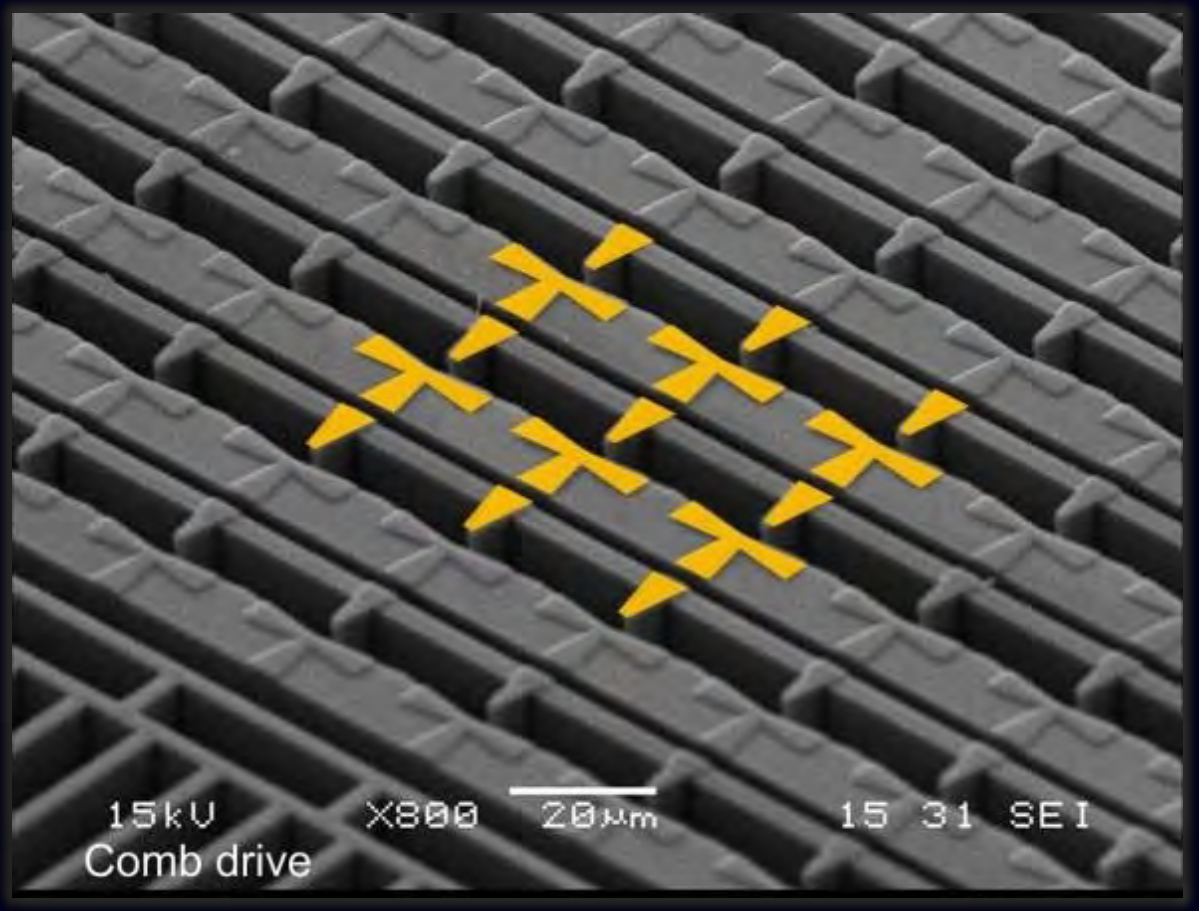
Zheludev, Plum, Fedotov. APL (2011)

Anisotropy: THz reconfigurable Metamaterial





Tuneable MEMS iso-index material

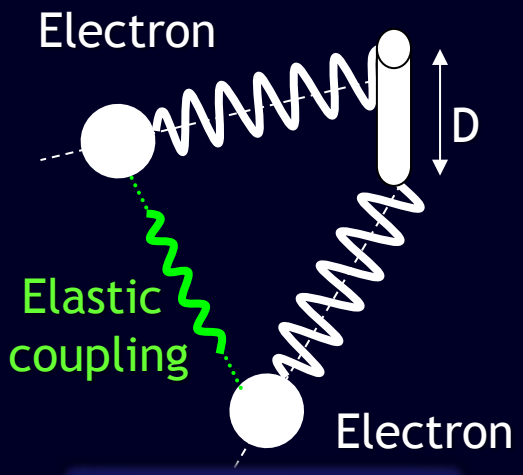


- micro machined actuators.
- Tuneable anisotropy
- Terahertz variable wave plates
- Tuneable filters, Polarimetry

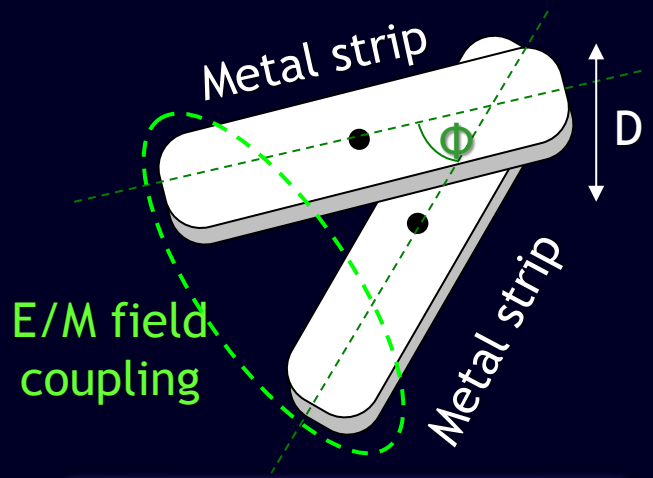
Zhu … Liu, Zheludev, Nat. Com. (2012)

Controlling polarization: chirality

>275 papers

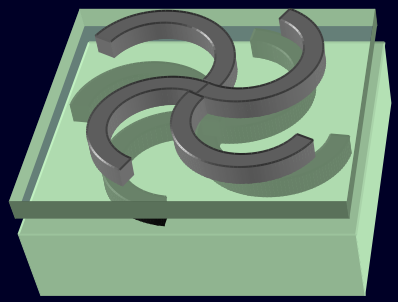


The Born-Kuhn
Molecular model (1915)



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

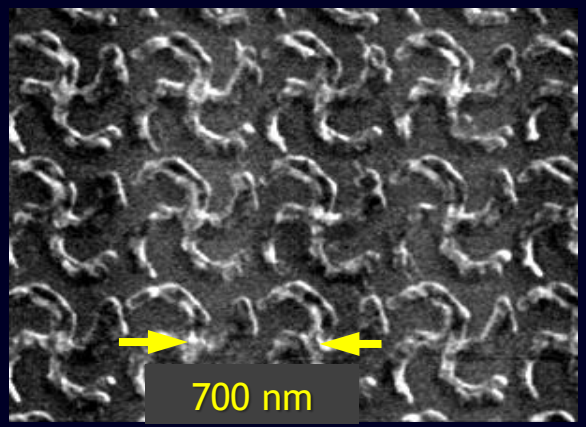
Chiral MMs



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

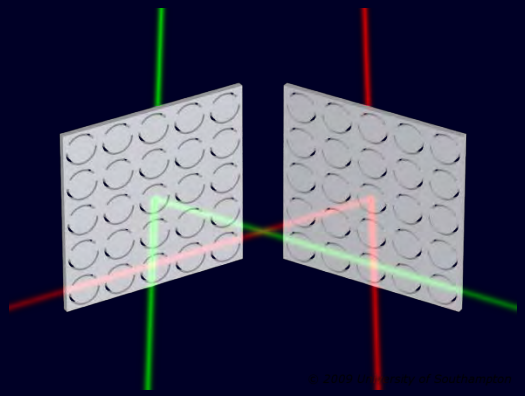
Rotatory power orders of magnitude stronger than in natural media!

Optical "Stereo" Metamaterials



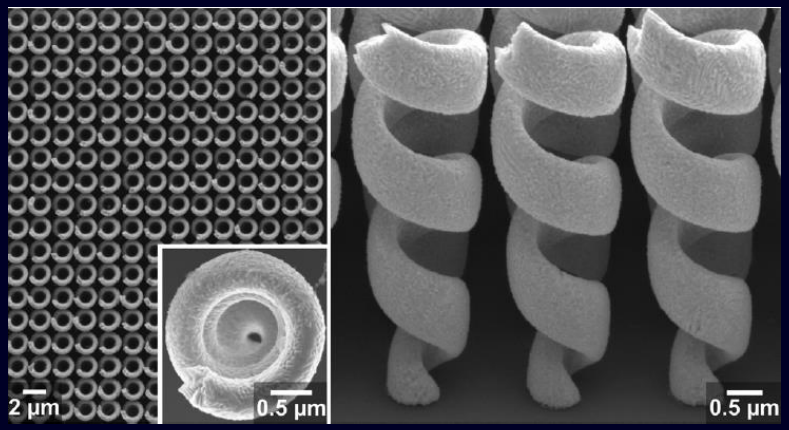
Plum … Zheludev. APL (2007)

Extrinsic Chirality



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

Metamaterials" Circular polarizers

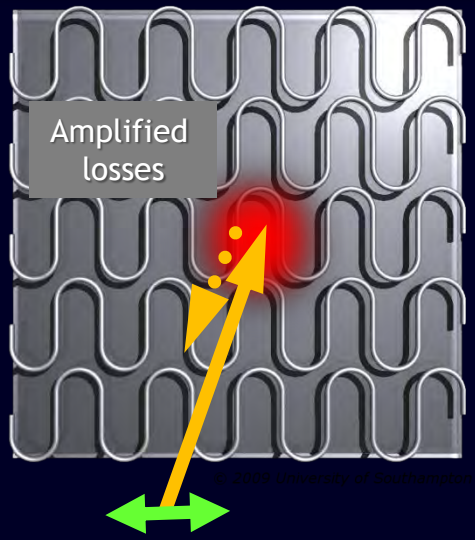


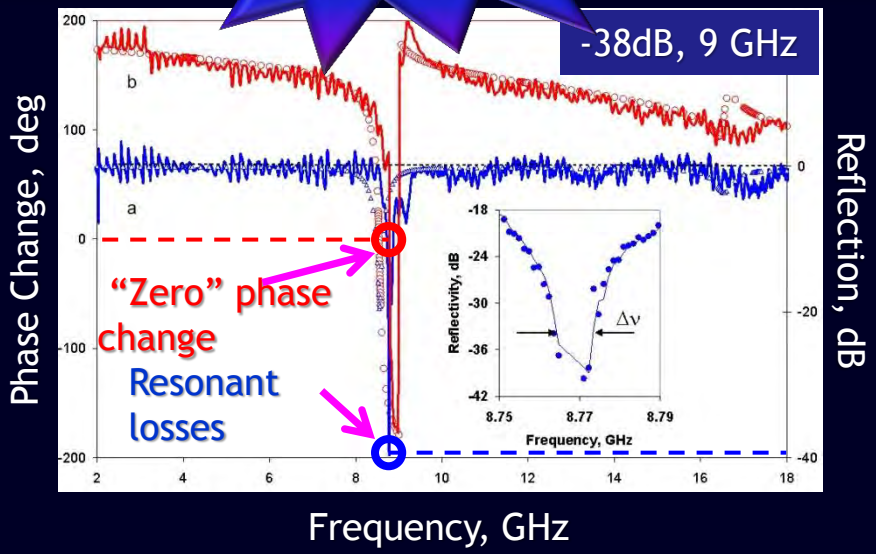
Gansel … Wegener. Science (2009); APL (2012)

Controlling boundary conditions: Perfect absorber

"We discovered that the structure acts as a … of losses in the underlying dielectric"
Fedotov, Mladyonov, Prosvirnin, … 056613 (2005); APL (2006)

>80 papers

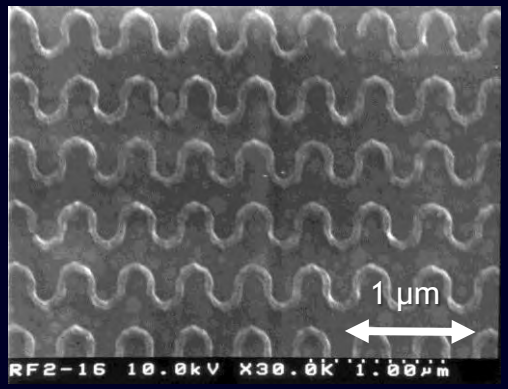




+ "Transparent metal" (no intensity and phase change fro transmitted light)

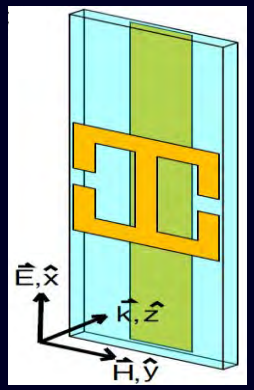
Fedotov … Zheludev
PR-E (2005)
Alu &Engheta
PR-E (2005)

75%, λ= 600 nm



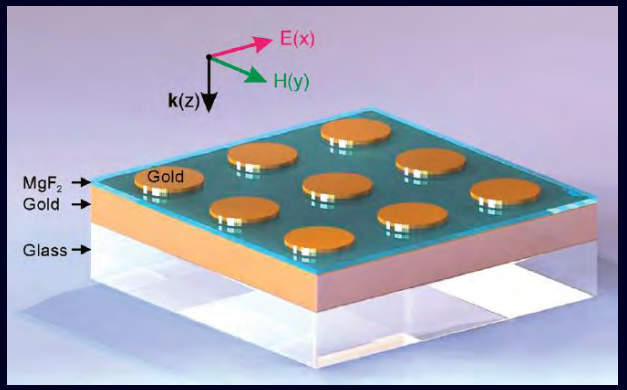
Schwaneckeb... Zheludev
J. Opt. (2007)

88%, 11 GHz



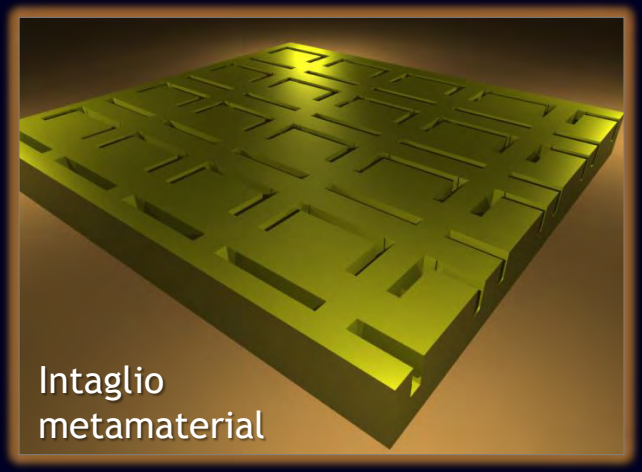
Landy … Smith, Padilla.
PRL. (2008)

99%, λ= 1.6μ

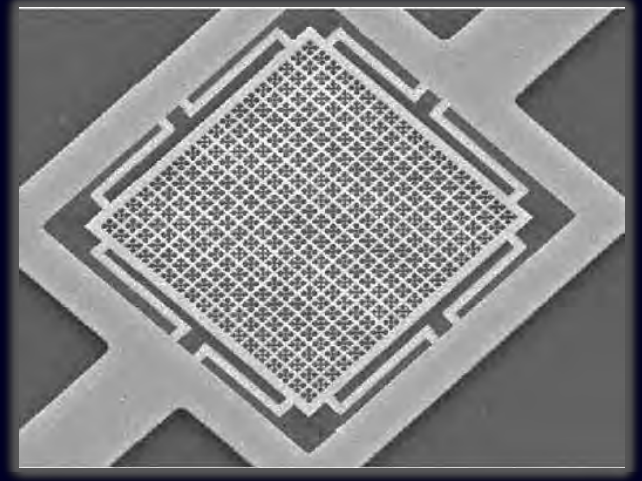


Liu… Giessen.
Nano Lett. (2010)

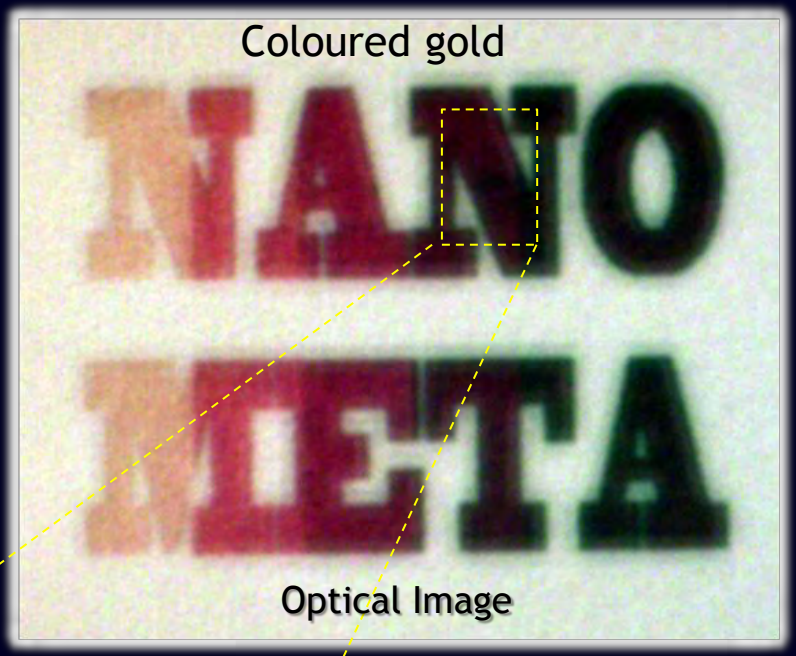
Making good use of losses: colouring metal

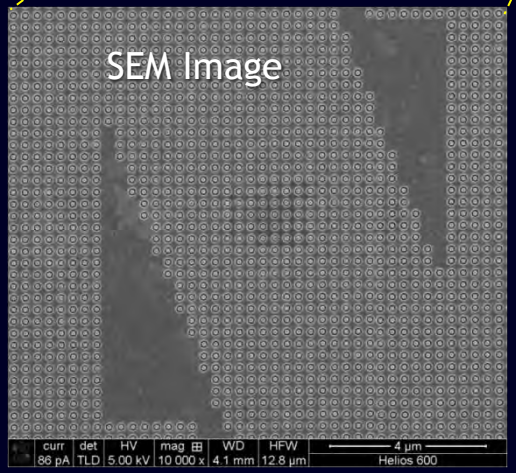


IR Metamaterial with
switchable absorption

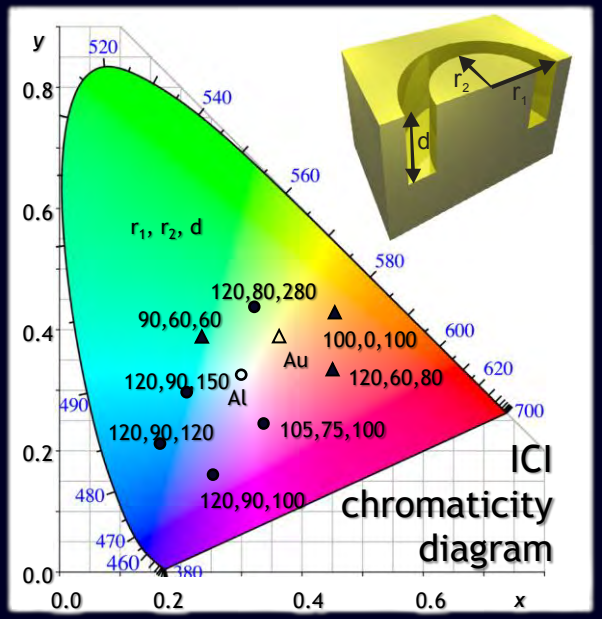


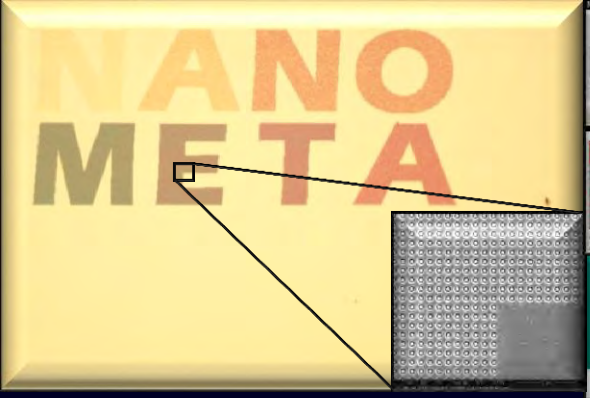
Liu and Padilla
Adv. Opt. Mat (2013)





Zhang, MacDonald … Zheludev
Opt. Express (2011)





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Scientists shed new light on the essence of gold

Southampton British scientists have changed the colour of gold by altering the way it absorbs or reflects light. So gold no longer has to be golden: it can be red or green, or many other hues.

The technique involves embossing tiny patterns on to the surface, and can be used on other metals. Scientists say it could be used in jewellery, or to make banknotes harder to forge.

Nikolay Zheludev, of the University of Southampton, said: "The colours of objects are determined by the way light interacts with those objects. An object that reflects red light but absorbs other wavelengths will appear red to the human eye." The team received funding from the Engineering and Physical Sciences Research Council.

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26 October 2012

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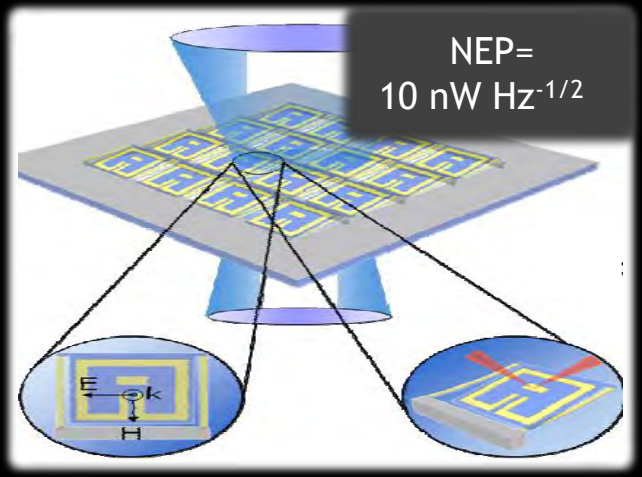
Experts change the colour of gold

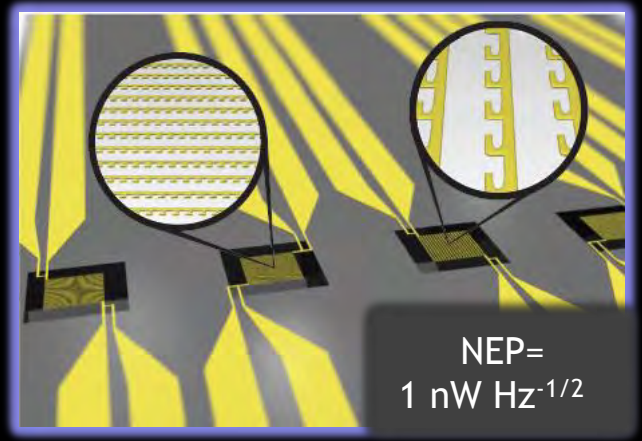
Light-Harvesting metamaterials: thermal detectors & bolometers

Infrared Detection with cantilever pixels deflection

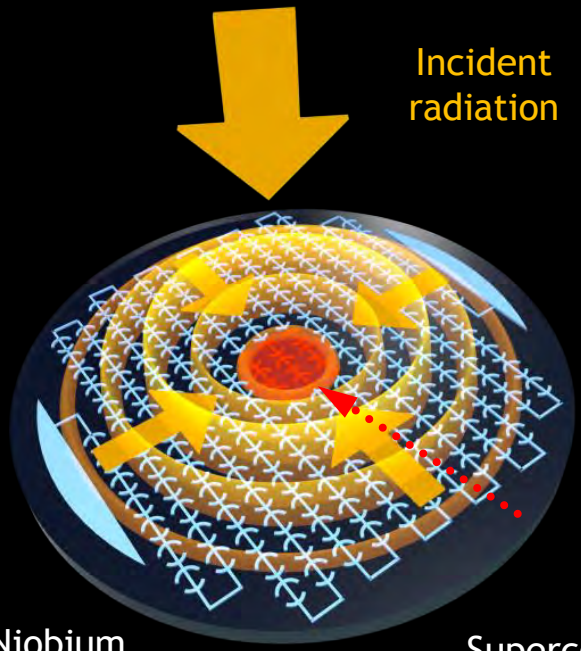


Tao, … Padilla, Averitt. Opt.Exp. 2011

Enhanced optical Bolometer



Niesler … Wegener . APL (2012)

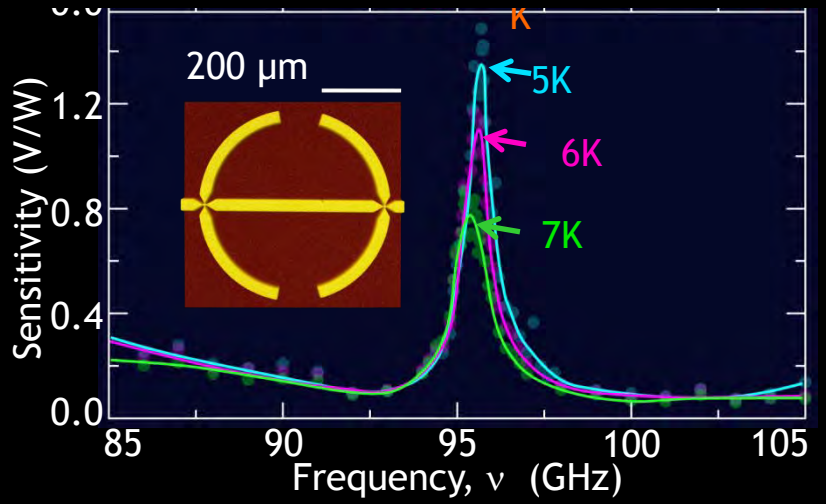


NEP=
0.3 nW Hz$^{-1/2}$

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

Niobium on Sapphire

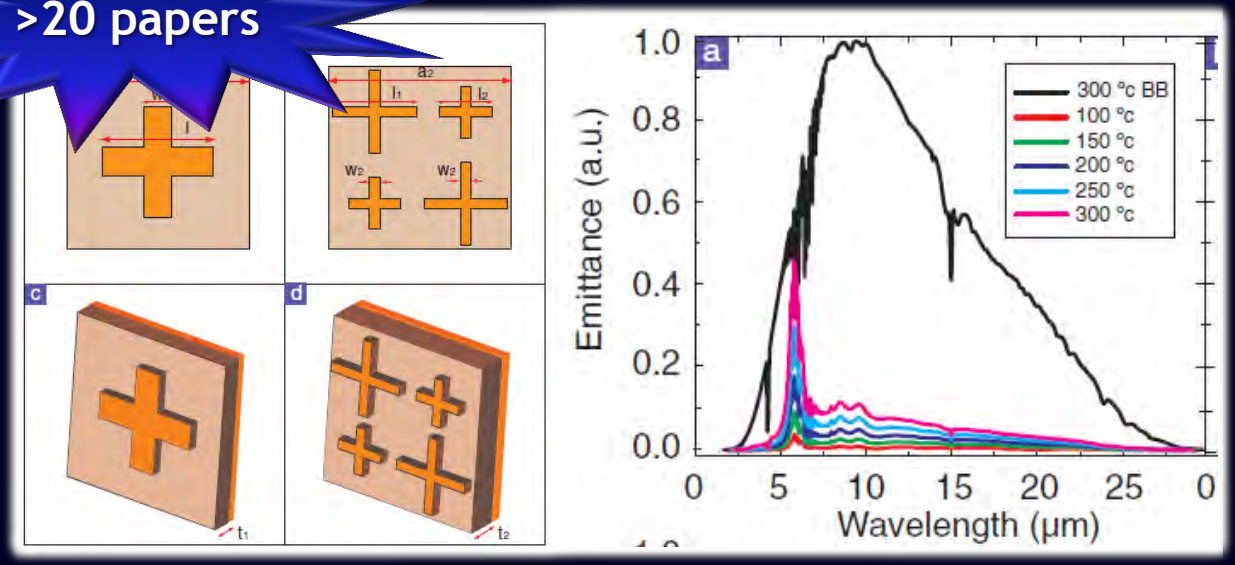
Superconducting Meta- Bolometer



Tailoring emission lines with metamaterials

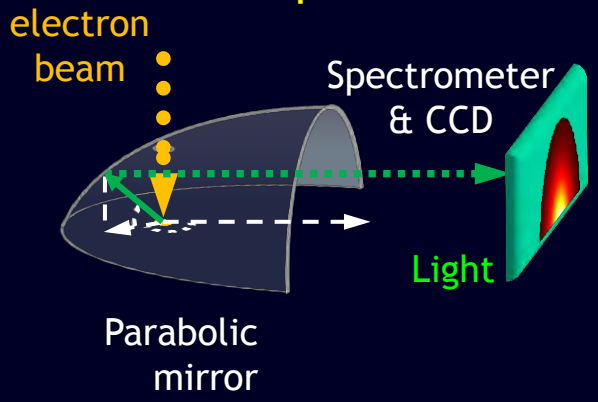
>20 papers

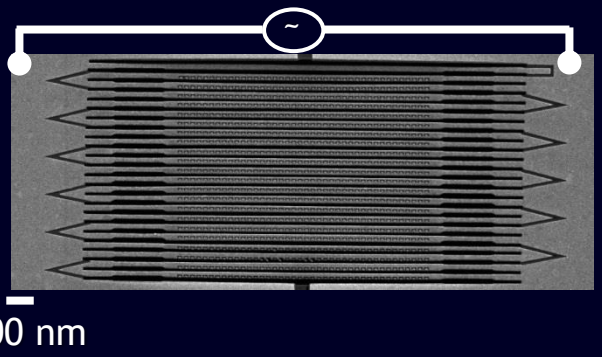
Control of thermal radiation with metamaterials



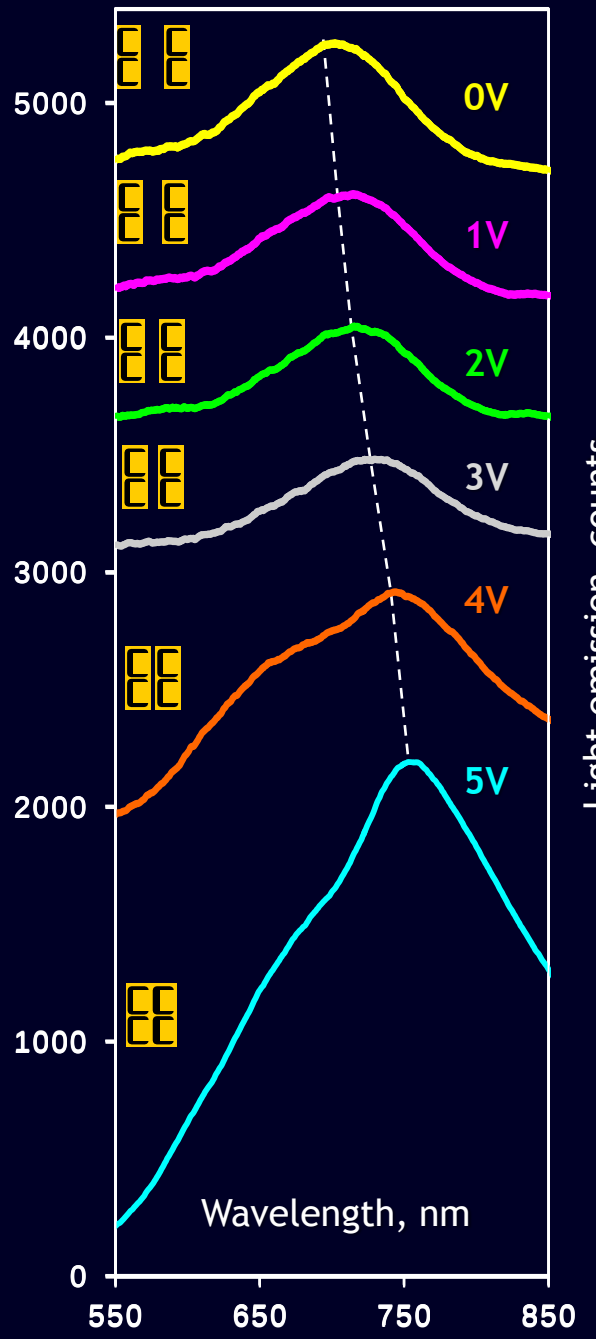
Liu … Padilla. PRL (2011)

Tuneable plasmonic emission in reconfigurable MM





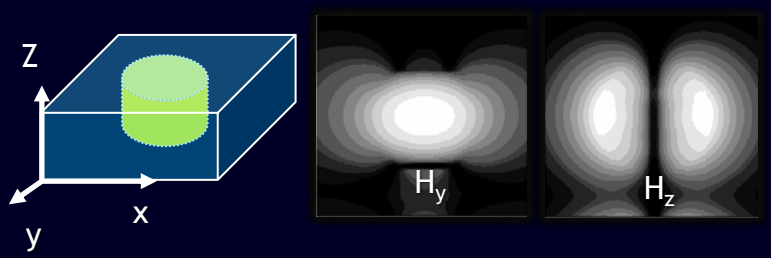
Adamo … Zheludev. CLEO-Europe (2013)

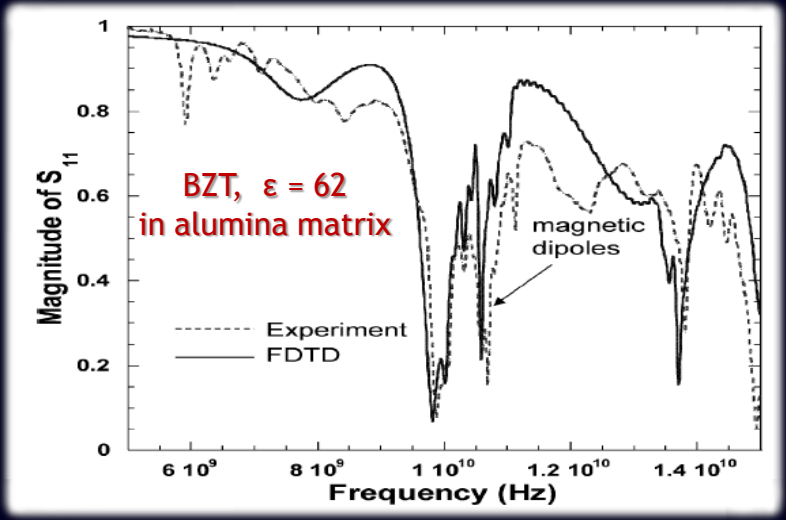


Metals not needed: Dielectric metamaterial

>20 papers

Magnetic response in dielectric metamaterial

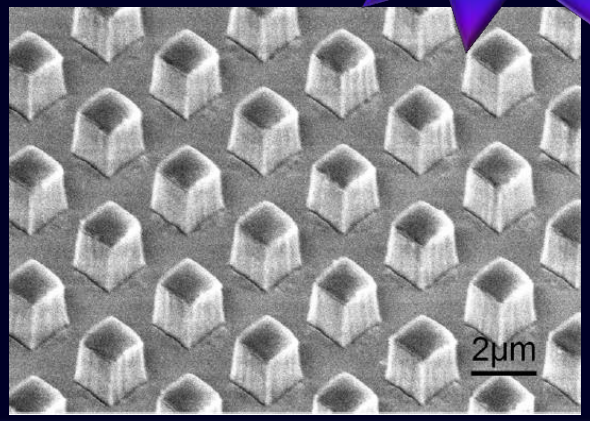




Semouchkina … Randall. IEEE TRANS. MT&T (2005)

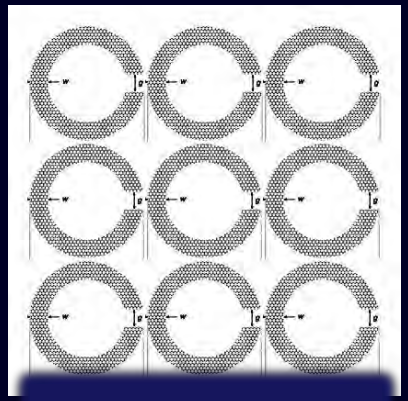
Wheeler … Mojahedi, PR B (2005)
Schuller …. Brongersma. PRL (2007)
Lepetit … Ganne. Electr. Lett.(2008), APL (2009)
Prosvirnin (2011)

IR magnetic response in r… …e



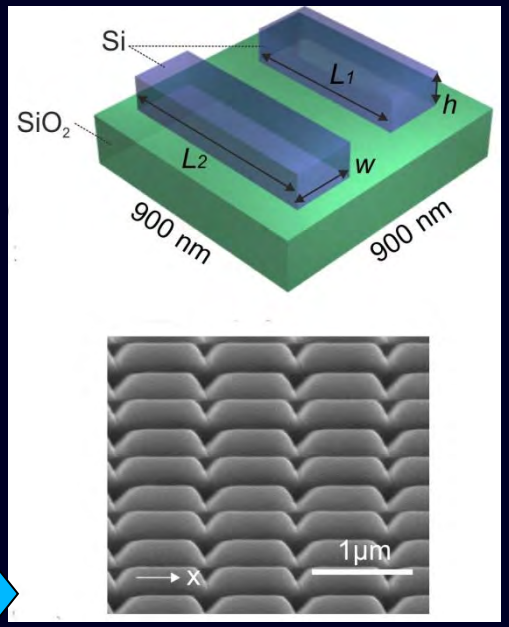
Ginn, Brener … Sinclair. PRL (2012)

Magnetic response in graphene metamaterial



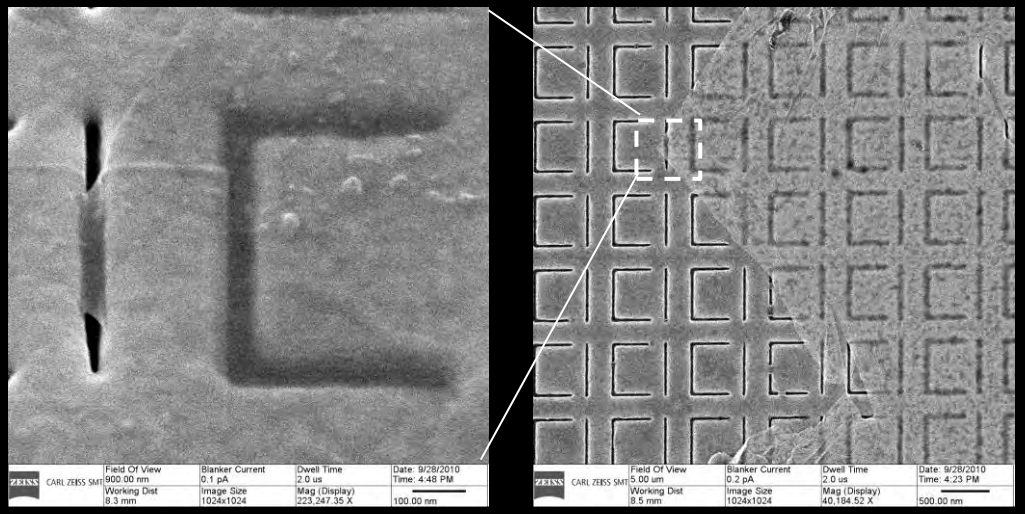
Papasimakis …
Zheludev, de Abajo .
NPG Light (2013)

Zheng … Zheludev
ICTON (2013)

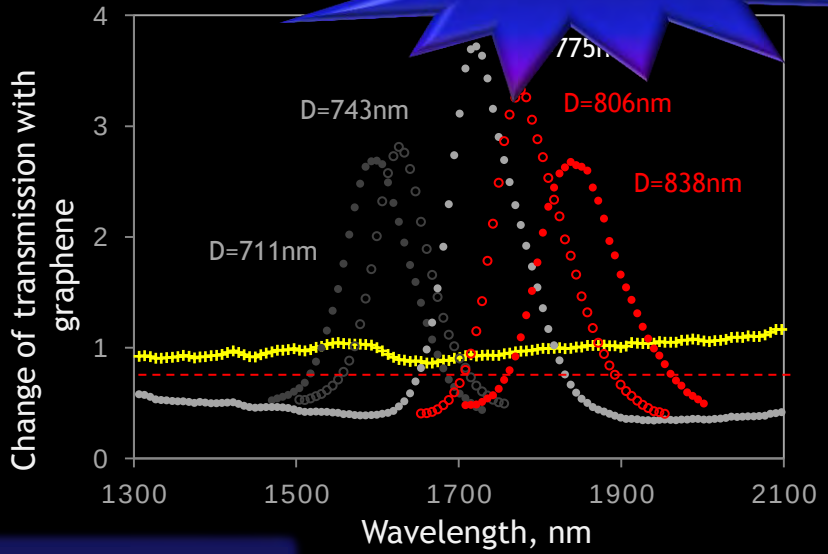


Graphene metamaterials

>40 papers

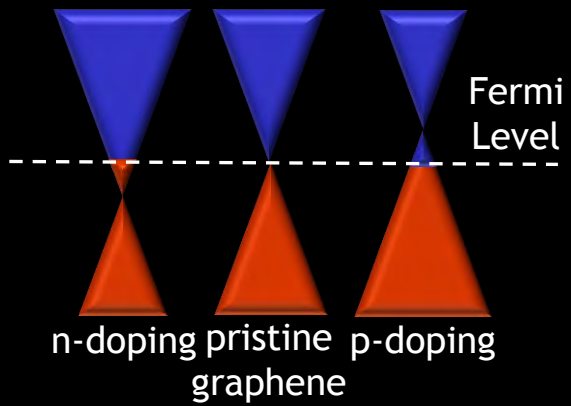


Helium-Ion microscope images

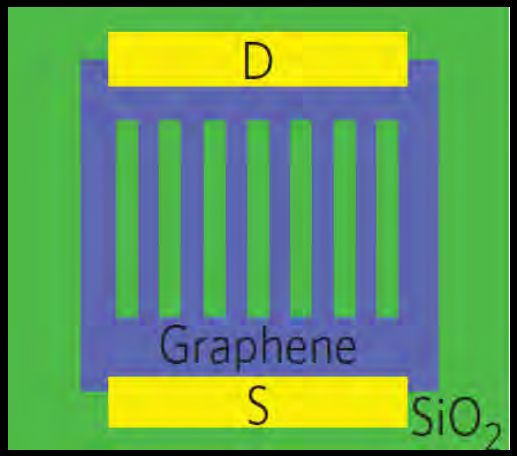


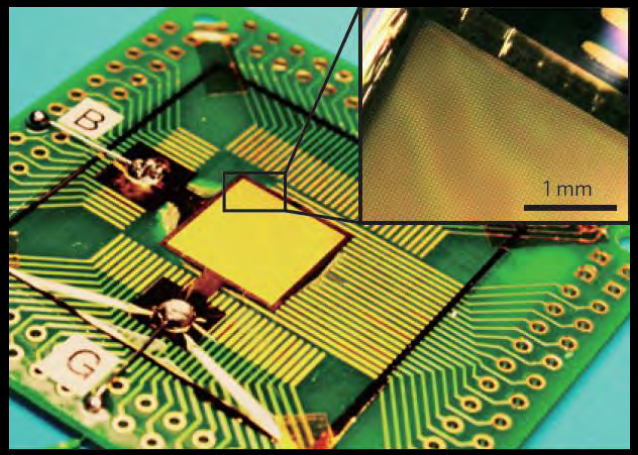
Papsimakis ...Zheludev. Opt.Expr. (2010)

Modulating graphene properties by carrier injection



Terahertz modulation with Graphene metamaterials



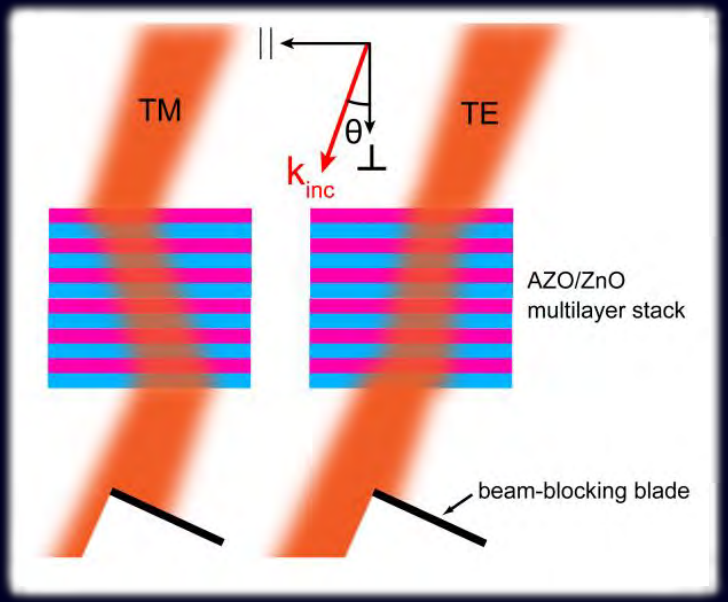


Ju, et al. Nature Nanotech (2011)

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

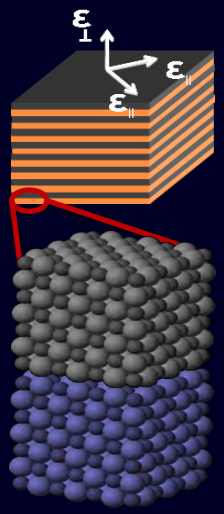
Conductive oxides and nitrides metamaterials; topological insulators

Negative refraction in Metal-free Metamaterial (conductive oxide)



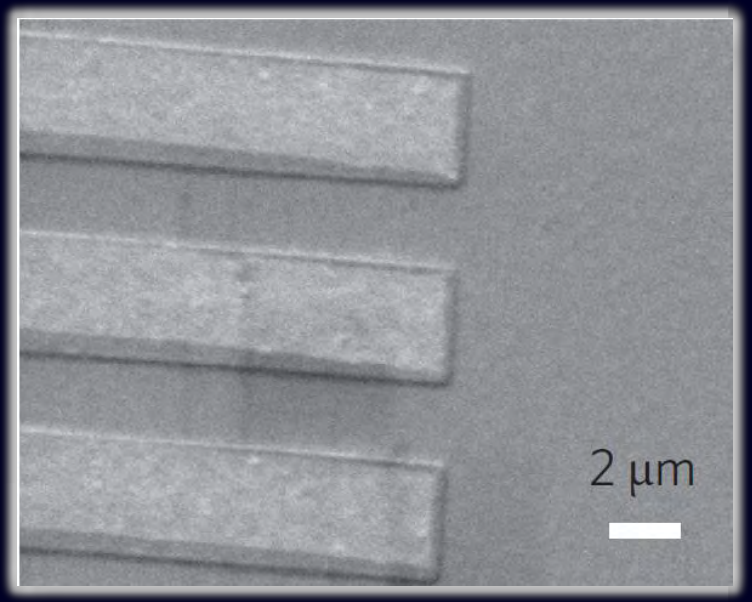
Naik … Boltasseva.
Proc. Nat. Acad. Sci. (2012)

TiN-based metamaterial: enhanced emission



Naik … Boltasseva.
TBP (2013)

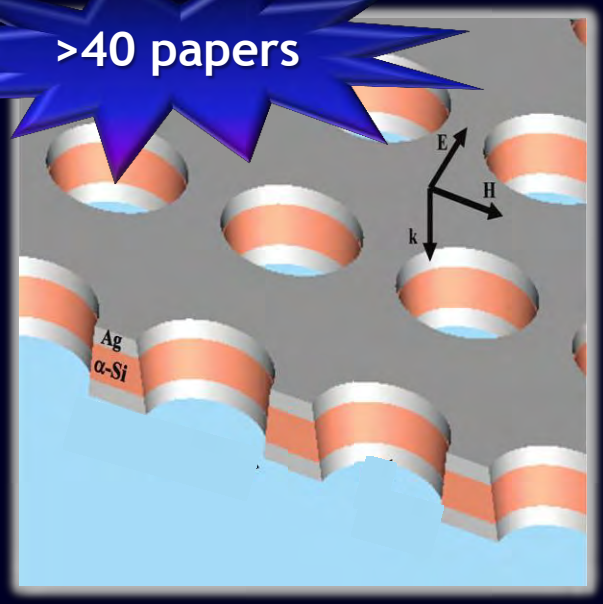
THz plasmons on topological insulator surface



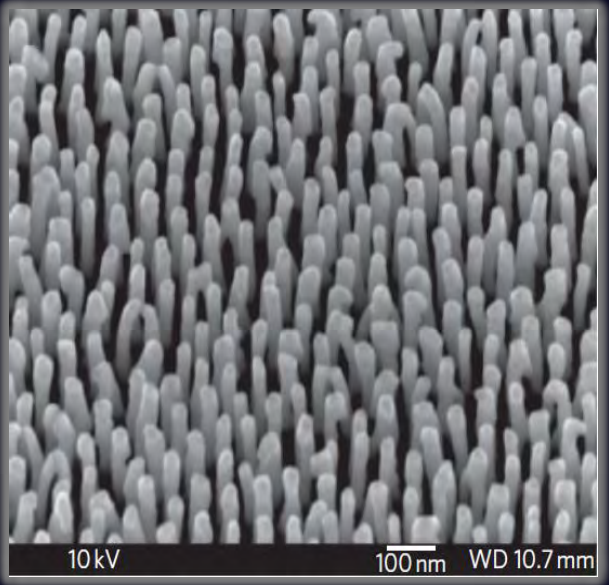
Pietro ... Lupi.
Nat.Nanotech. (2013)

Ultrafast switching with metamaterials

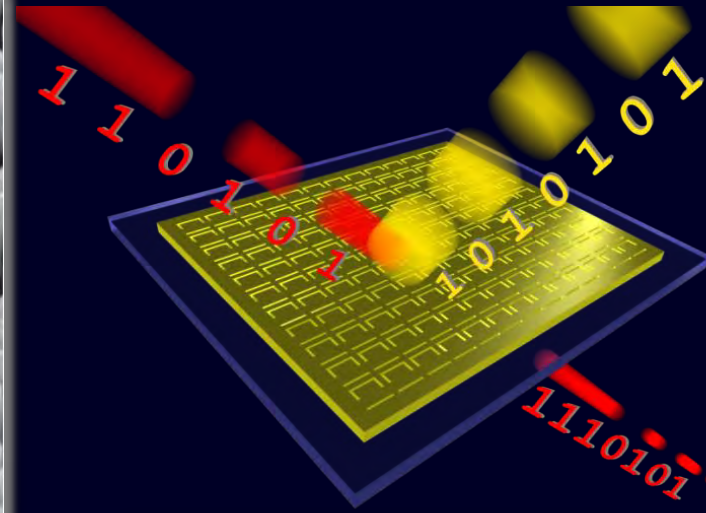
>40 papers



Padilla … Averitt. PRL (2006).
Chen … Averitt. *Opt. Lett.* (2007).
Cho … Shen. *Opt. Exp.* (2009).
Dani… Taylor. *Nano Lett.* (2009).

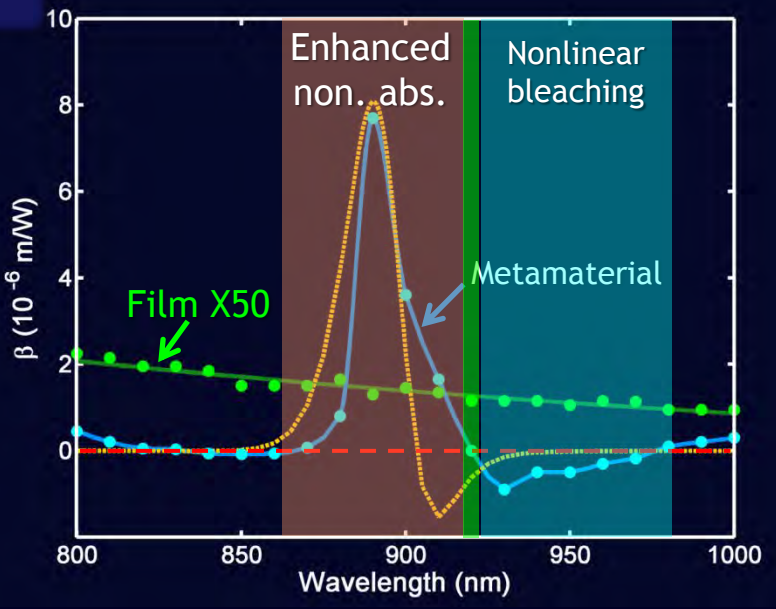


Wurtz … Zayats . Nature Nanotech. (2011)

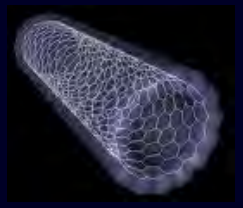


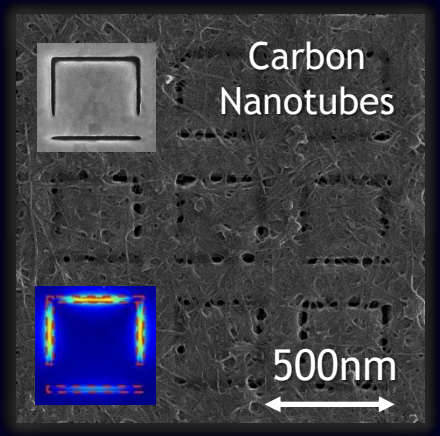
Ren … Zheludev. *Adv. Mater.* (2011)

System	% T modulation	Fluence, μJ/cm²	Response time, fs	fs x J/cm²
Gold metamaterial	40 %	270	~ 40fs	0.01
Metamaterial + α-Si	30 %	300	>750fs	0.2
Plasmonic nanorods	80 %	7000	~1ps	7

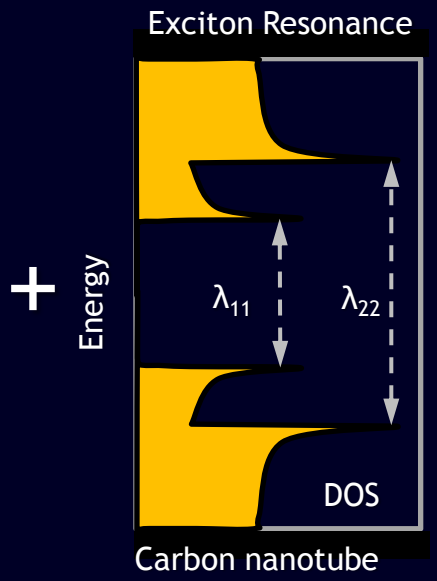


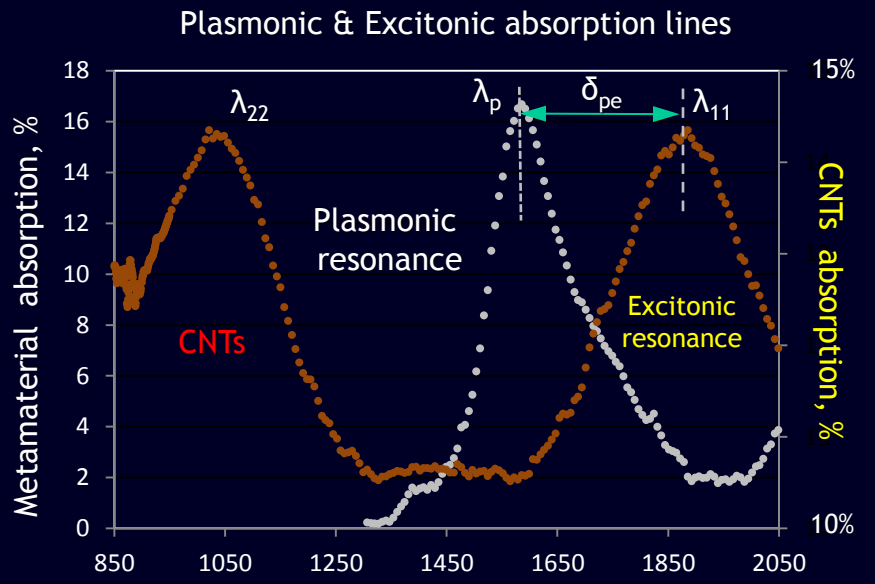
Improving nonlinearities with metamaterials

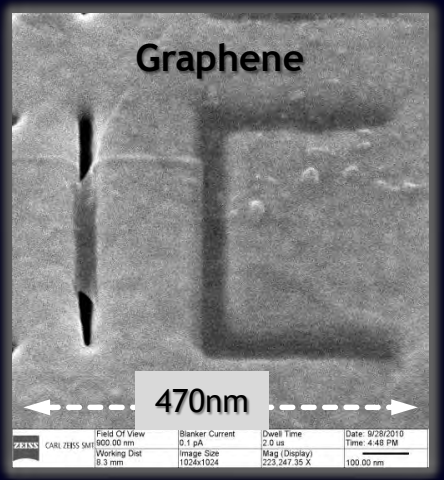




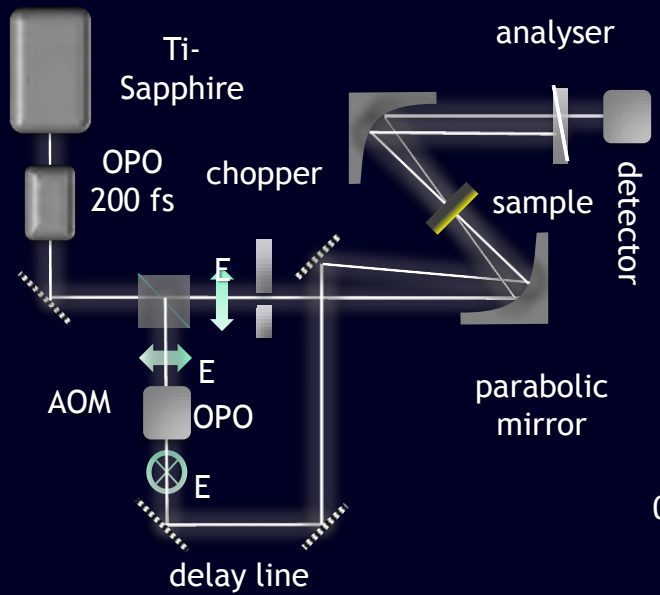
Nikolayenko… Zheludev
PRL (2010)

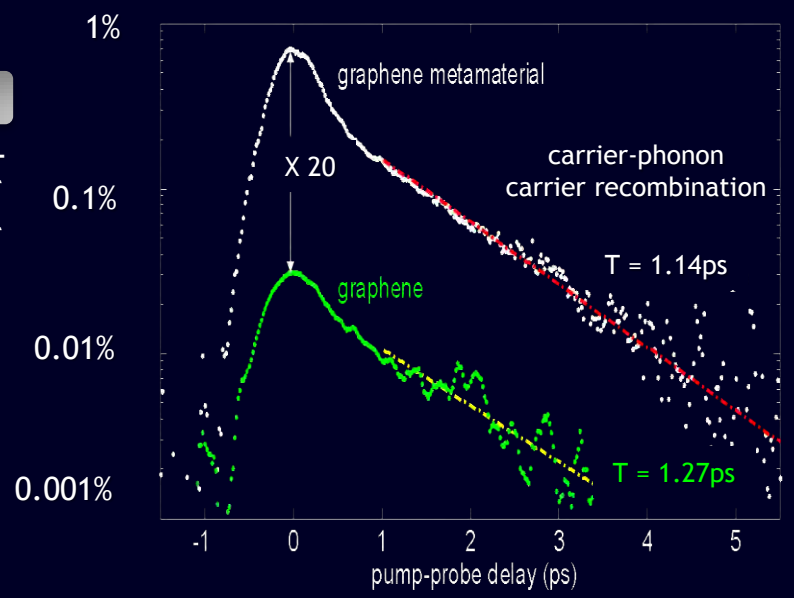




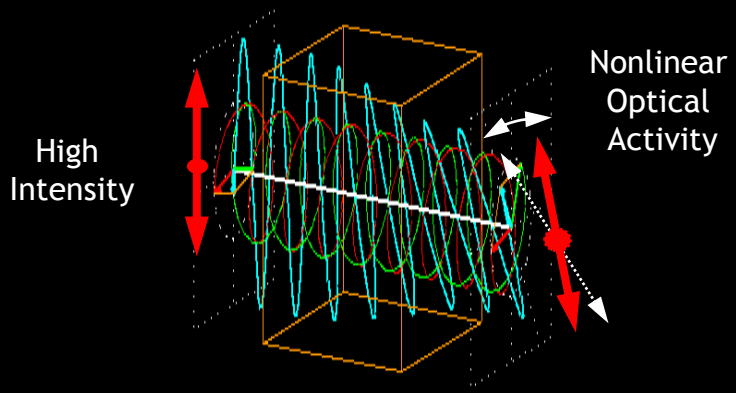


Nikolayenko… Zheludev
APL (2012)



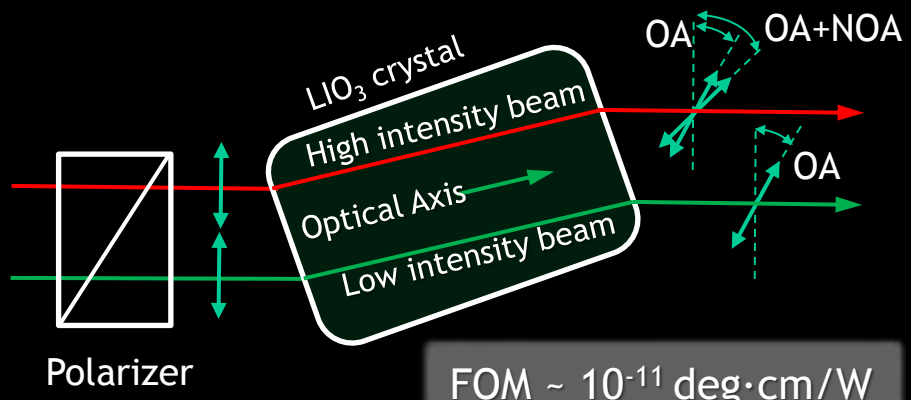


Nonlinear optical activity in metamaterial:
10^7 times stronger than natural media

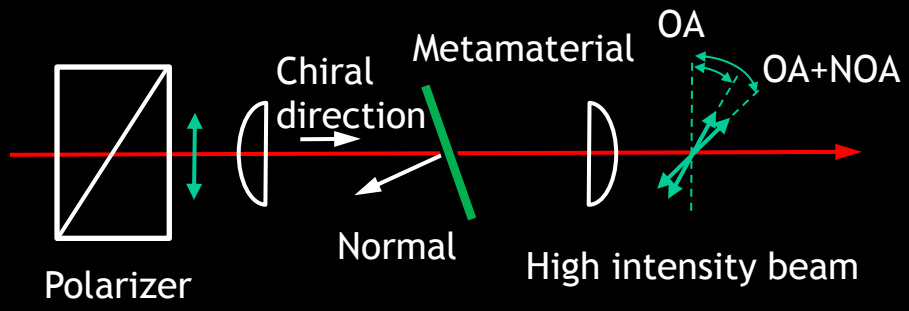


NONLINEAR OPTICAL ACTIVITY, 1972

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

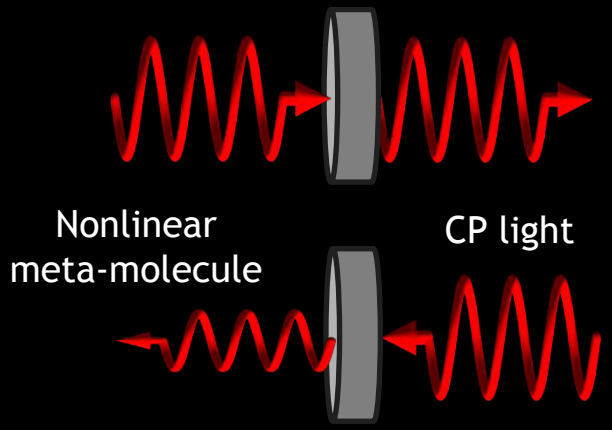


FOM ~ 10^{-11} deg·cm/W



FOM ~ 10^{-4} deg·cm/W

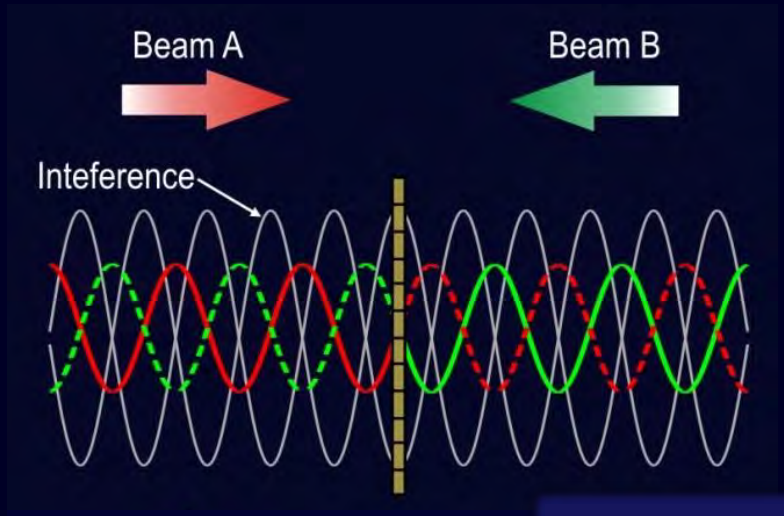
NOA Optical Diode

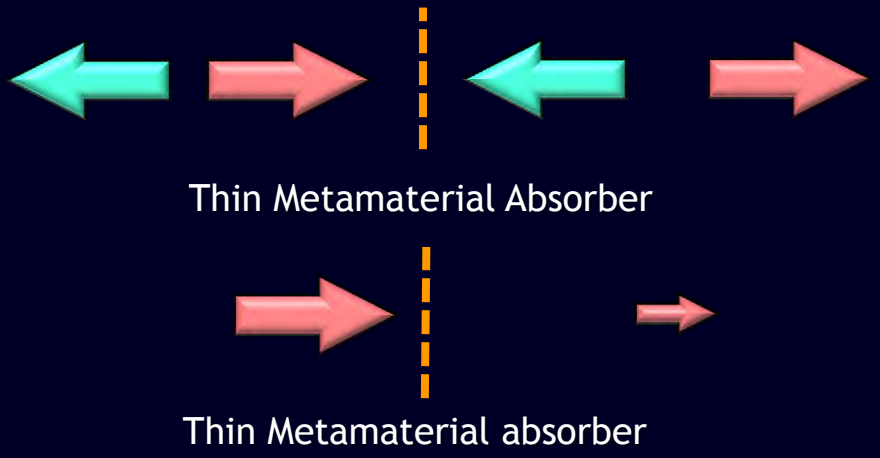


2012: Giant nonlinear optical activity in a plasmonic metamaterial
Ren, Plum, Xu and Zheludev. *Nat. Commun.* **3**, 833 (2012)

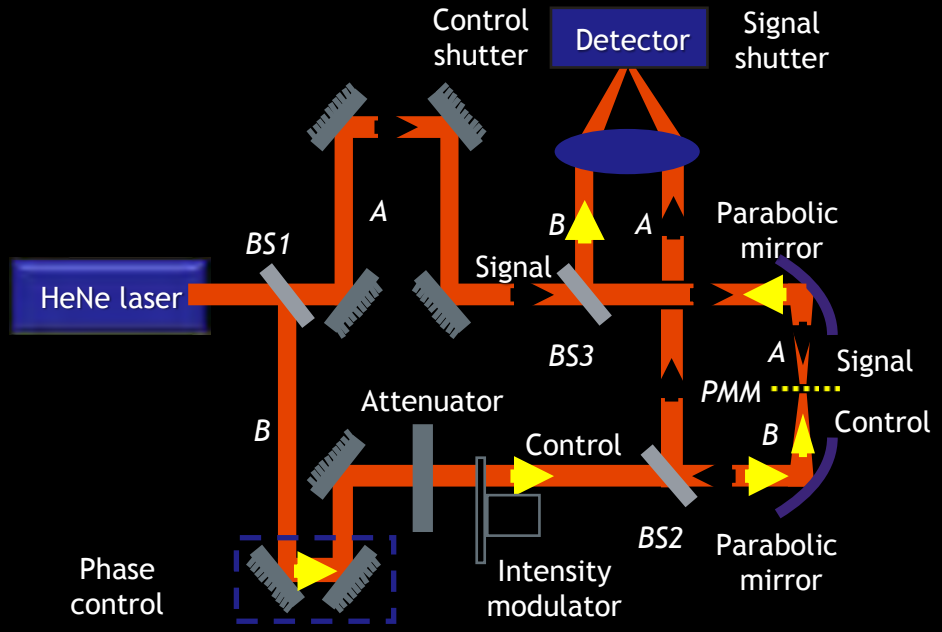
Shadrivov .. Kivshar, Zheludev
NJP (2011)

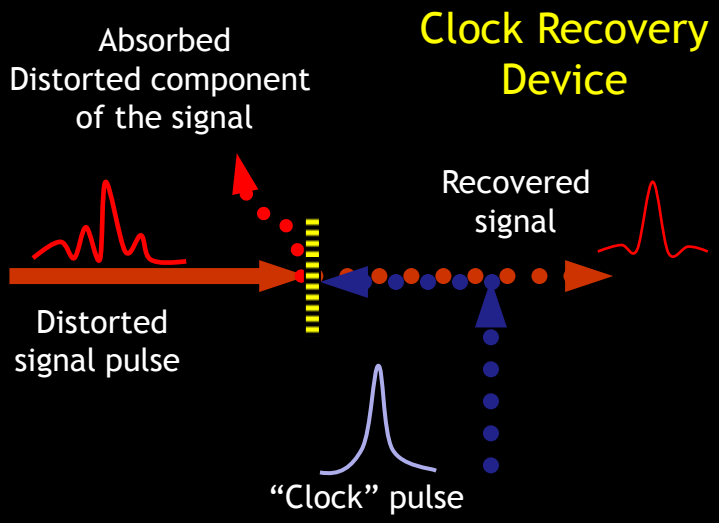
Modulating light with light in metamaterial without nonlinearity





Zhang … Zheludev. NPG Light 2012)

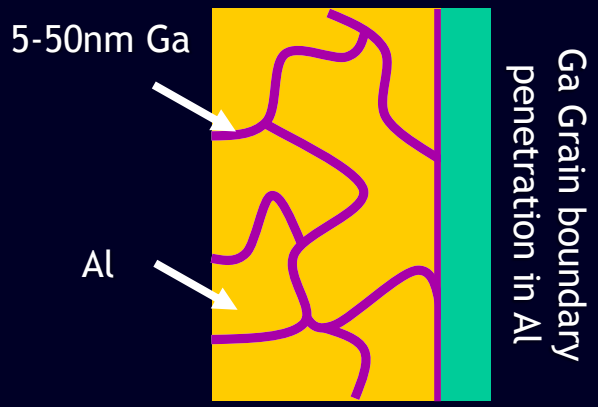




- Low intensity
- THz bandwidth optical switching

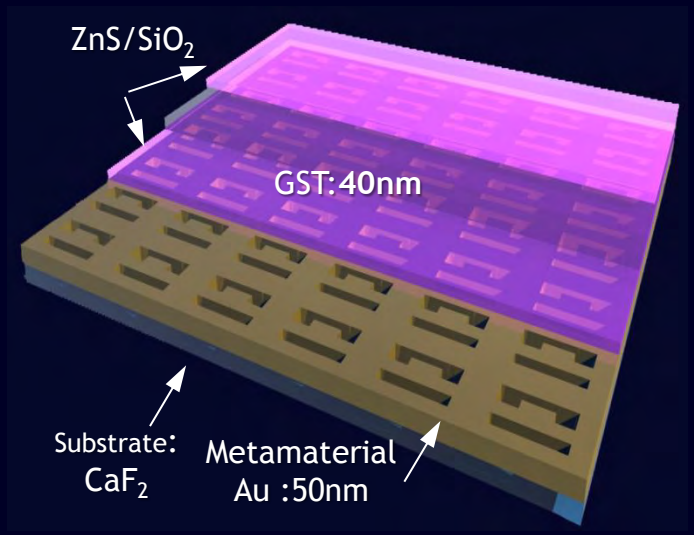
Phase Change Metamaterials & Optical memory

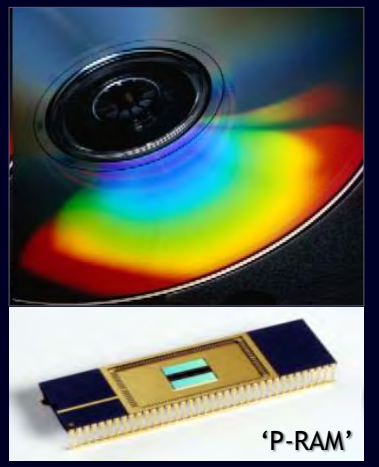
Ga/Al nano-composite plasmonic MM



Krasavin ...Zheludev
APL 2006

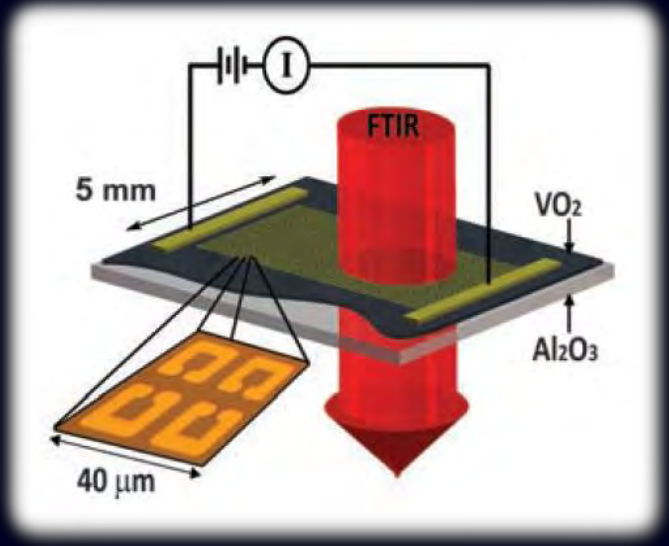
Electrical optical switching





Samson ... Zheludev
APL (2010)

Electrical THz frequency tuning

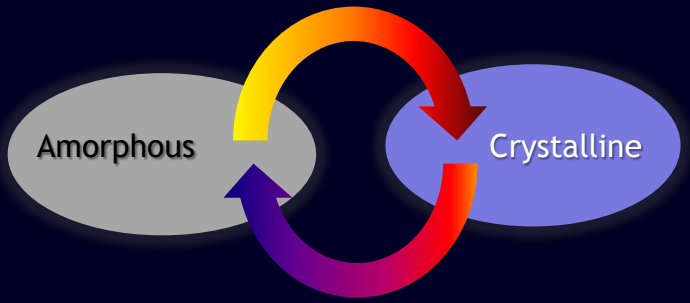


Driscoll. Basov. *Science* (2009)

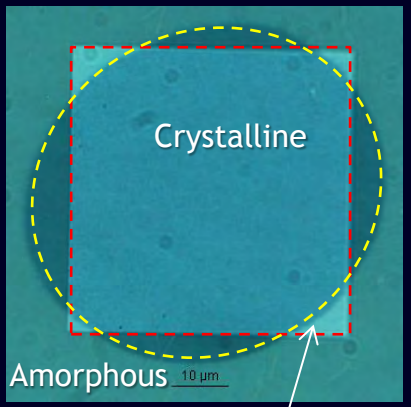
All-optical, non-volatile, bidirectional switching

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

Optical Pulse 660nm
100 ns, 0.1 mW/μm²



Optical pulse 660nm
50 ns, 0.25 mW/μm²

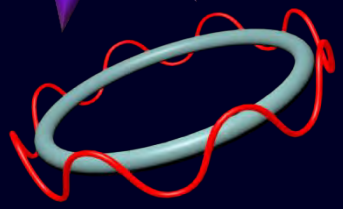


Metamaterial domain

Quantum Metamaterials

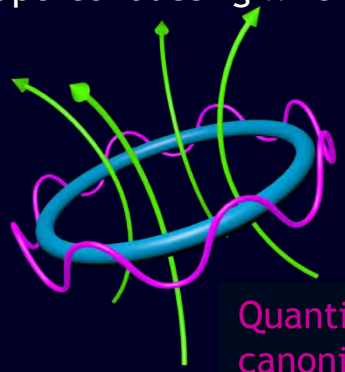
Quantum effects in MM >300 pps

Light in a fibre loop



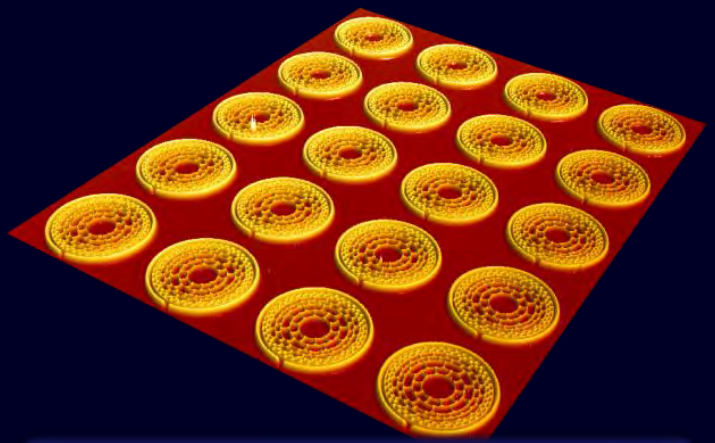
Quantized magnetic flux

Superconducting wire loop

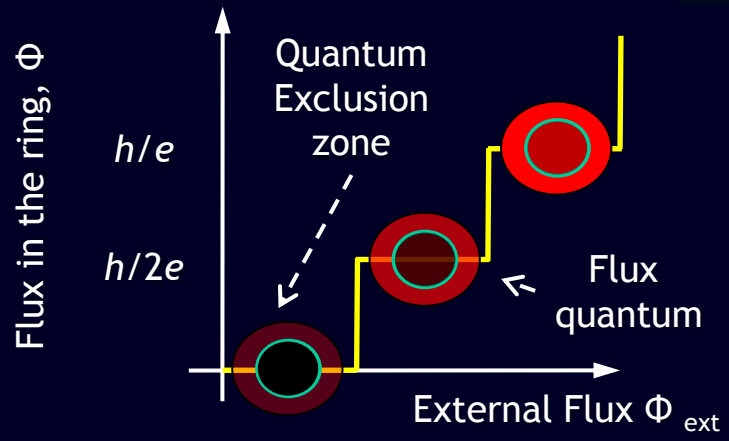


Quantized canonical momentum

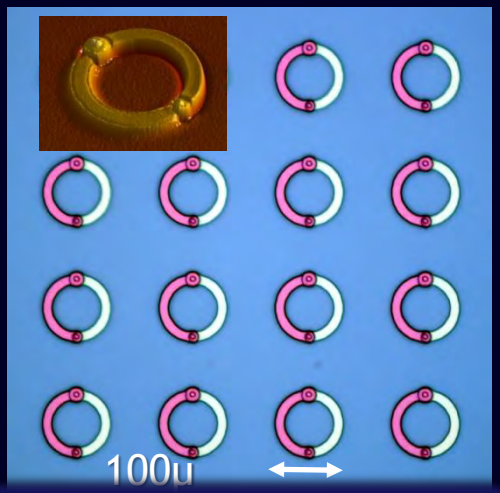
YBCO metamaterial



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



Quantum SCQID Metamaterial ??



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

Conventional SR metamaterial

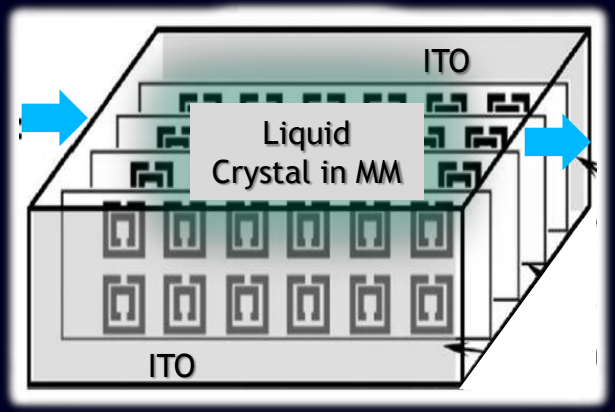
High intensity

Low intensity

Metamaterials and LC devices

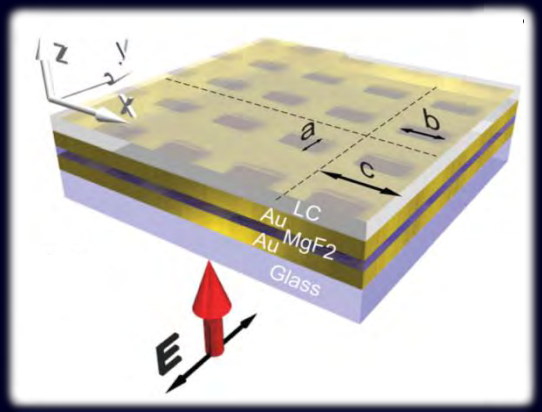
>50 papers

Microwave

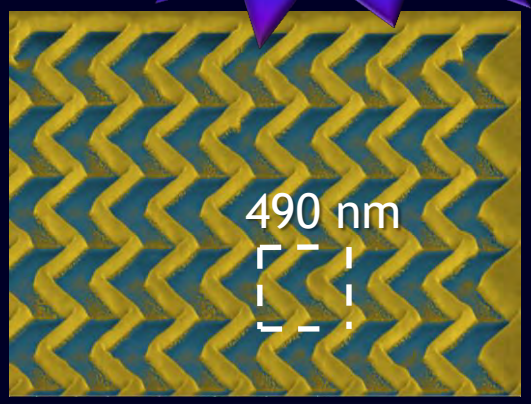


Zhao… Zhang. *APL* (2007).

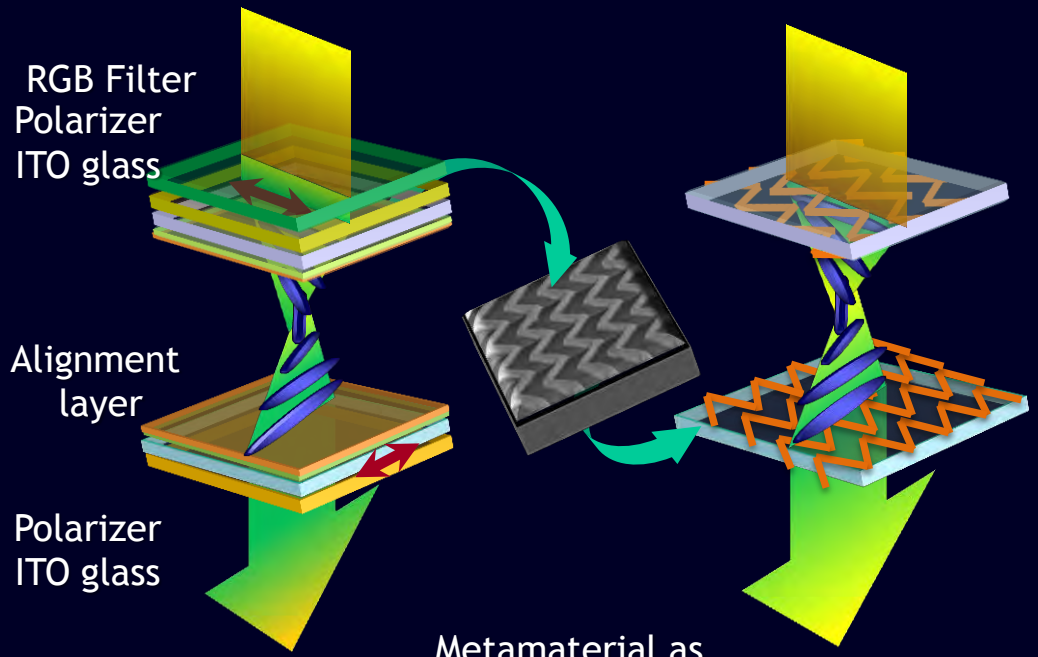
Optical



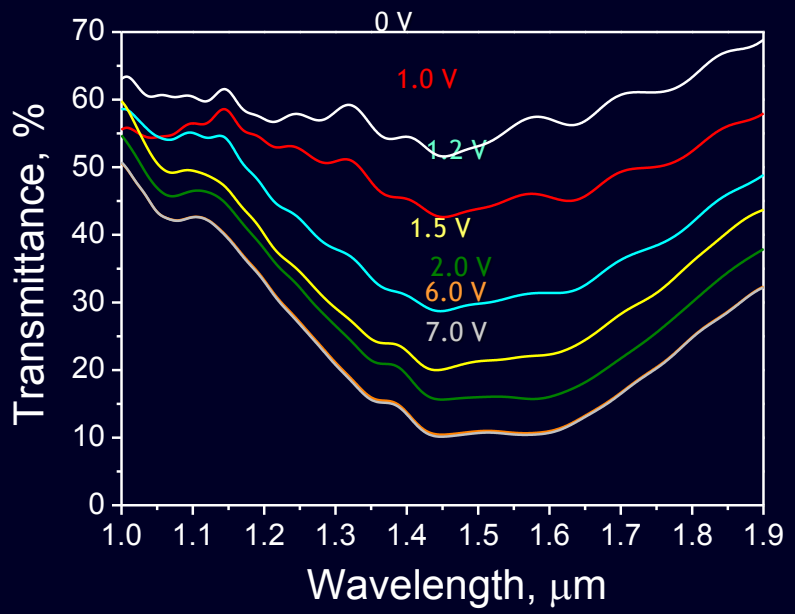
Minovich … Kivshar APL (2012)



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



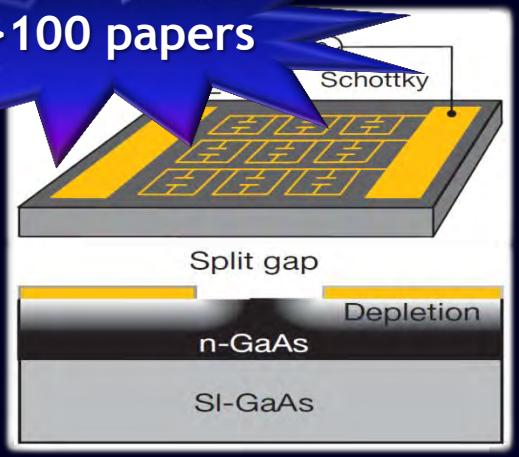
Metamaterial as
polarizer, transparent electrode and alignment layer



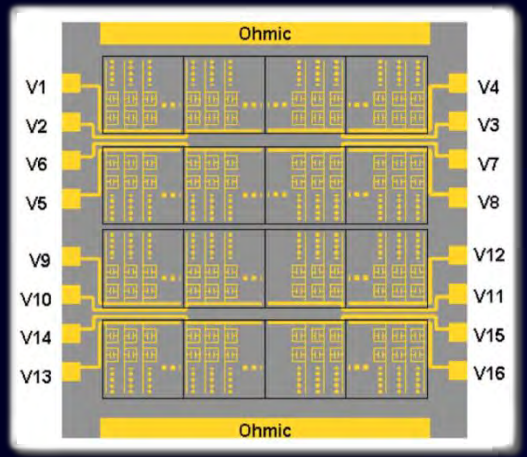
EO & MO modulation with metamaterials

THz m ulation in metamaterial: carrier injection

>100 papers

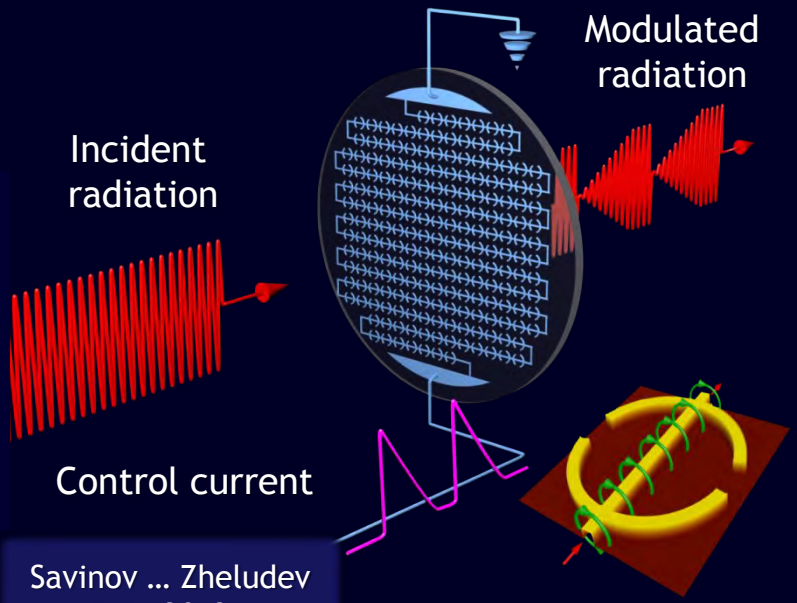


Chen… Aweritt
Nature (2006)



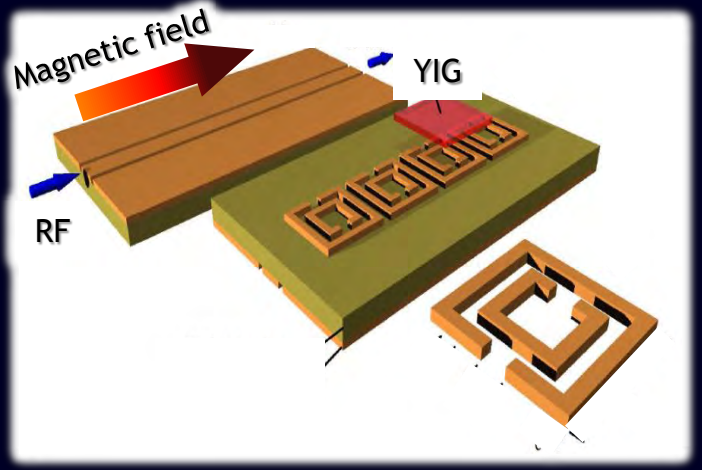
Chan… Mittleman
APL (2009)

EO Superconducting Metamaterial



Savinov … Zheludev
PRL (2012)

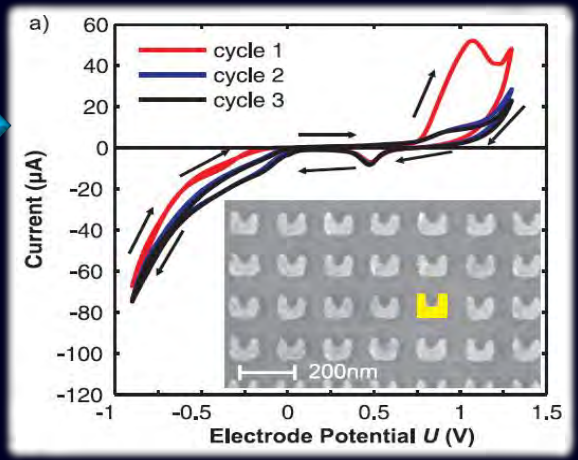
Magnonic Metamaterial Waveguide



Shao … Wegener.
Adv. Mat. (2010)

Stenning… Zheludev
Opt. Exp. (2013)

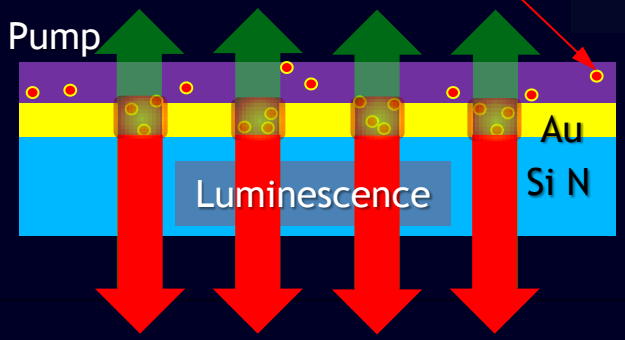
Electrochemical Modulation MM

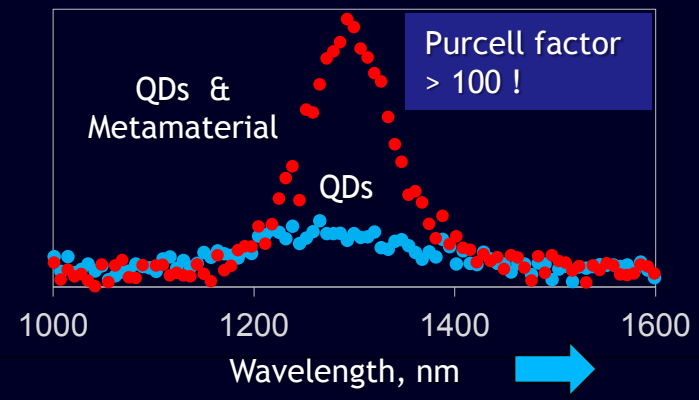


Control of Spontaneous Emission with MMs & "Lasing Spaser"

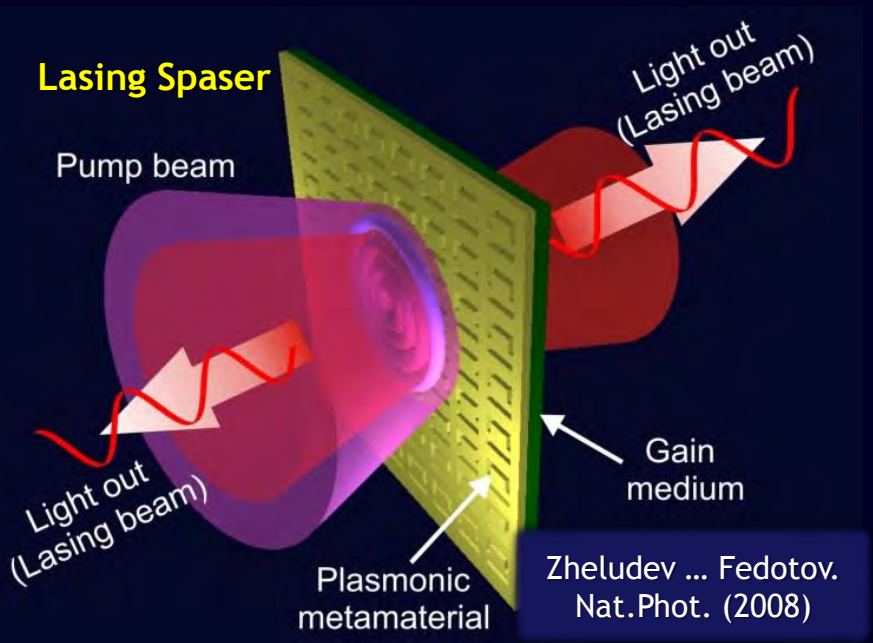
Enhanced Emission

PbS Quantum Dots



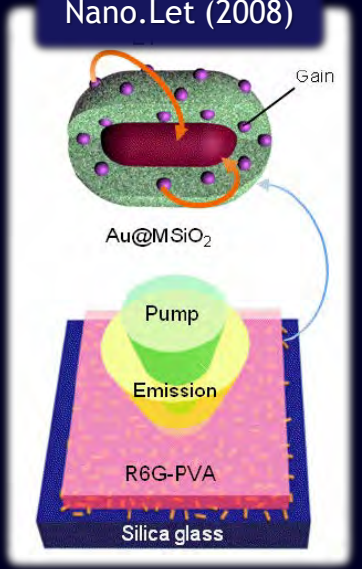


Lasing Spaser

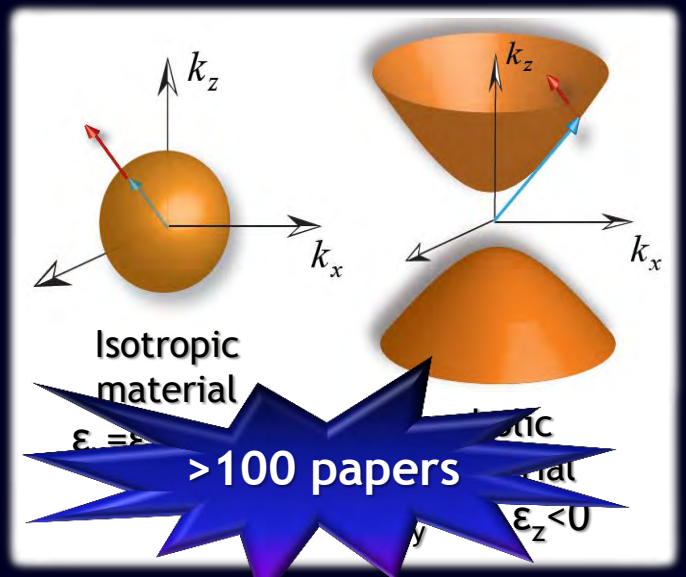


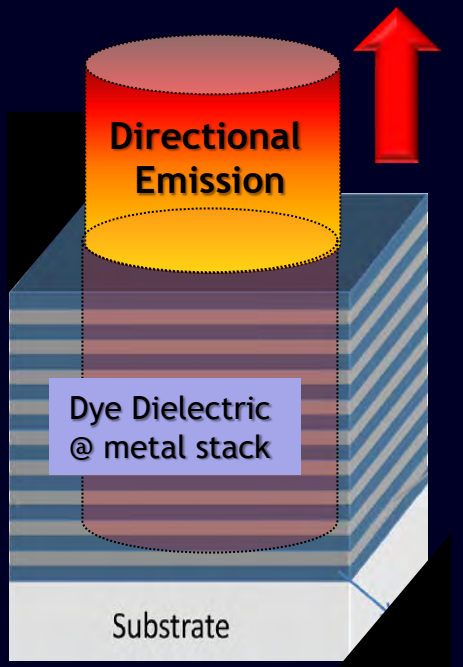
Zheludev ... Fedotov. Nat.Phot. (2008)

Meng ... Shalaev Nano.Let (2008)

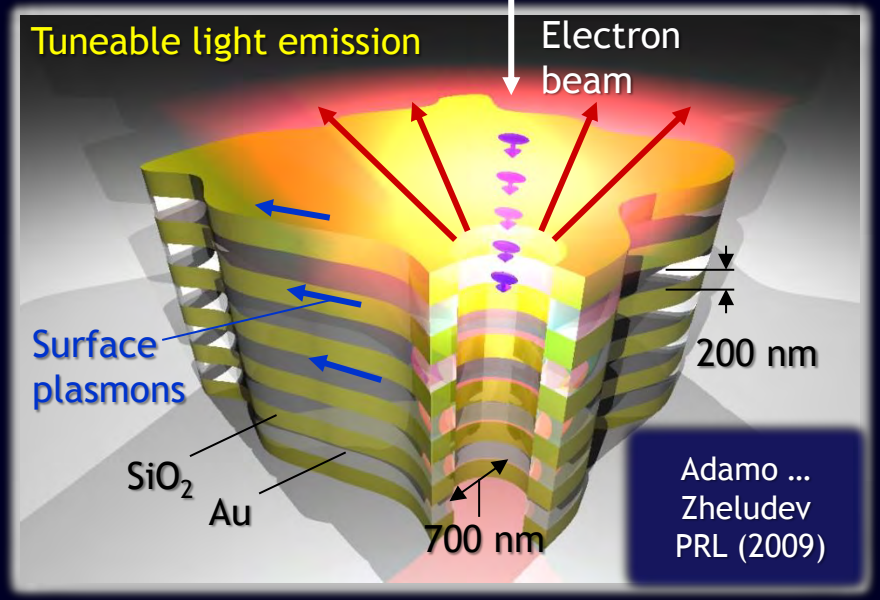


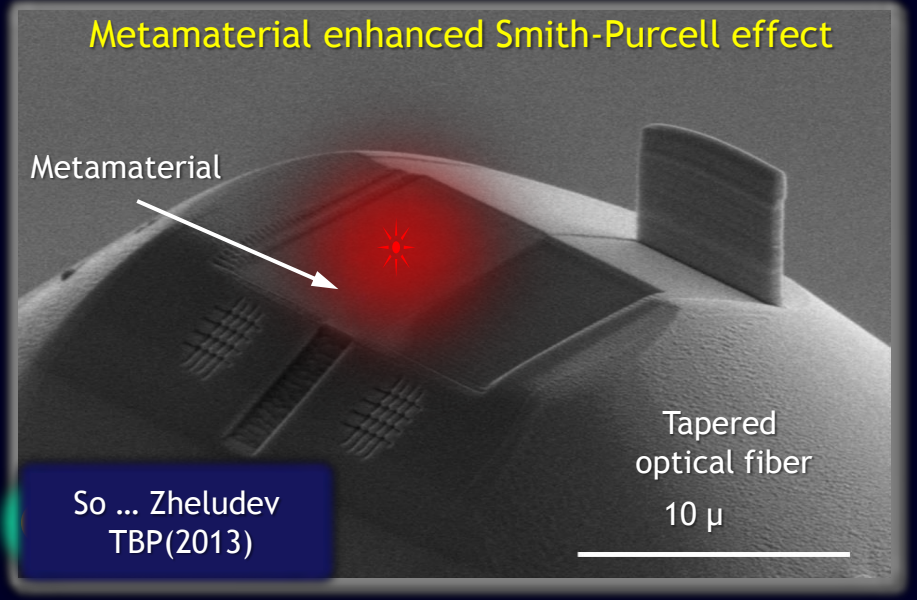
Nurimanov, ... Jacob APL (2011)
Tumkur.... Noginov, APL (2010)

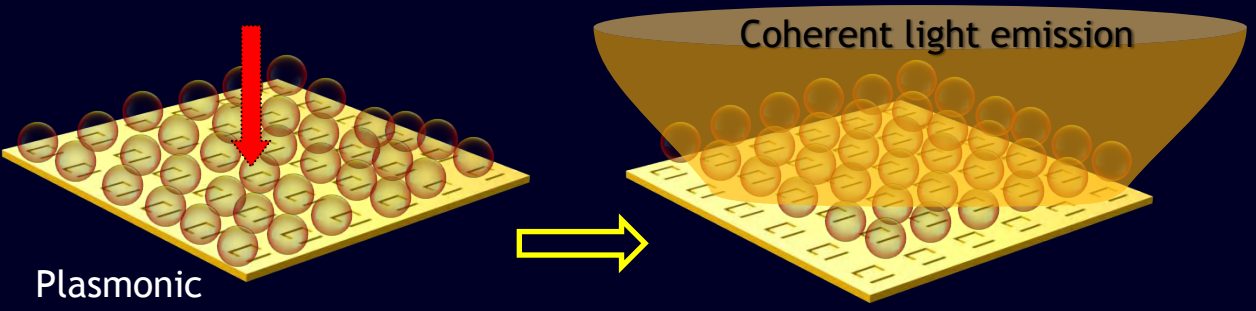




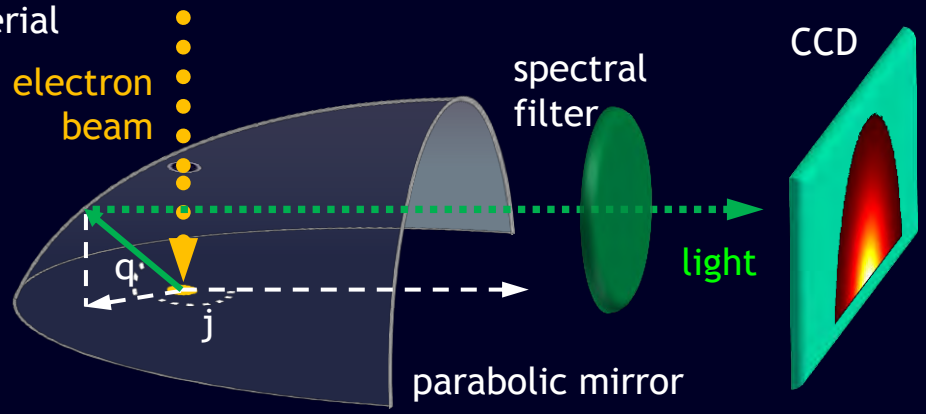
Free-electron driven metamaterial light sources

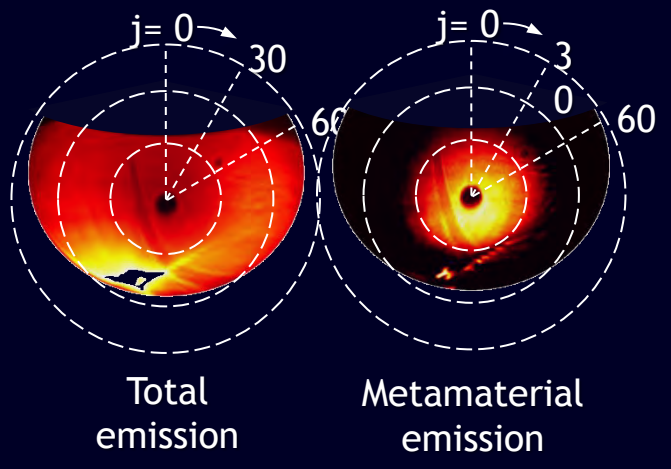






Adamo ... Zheludev PRL (2012)

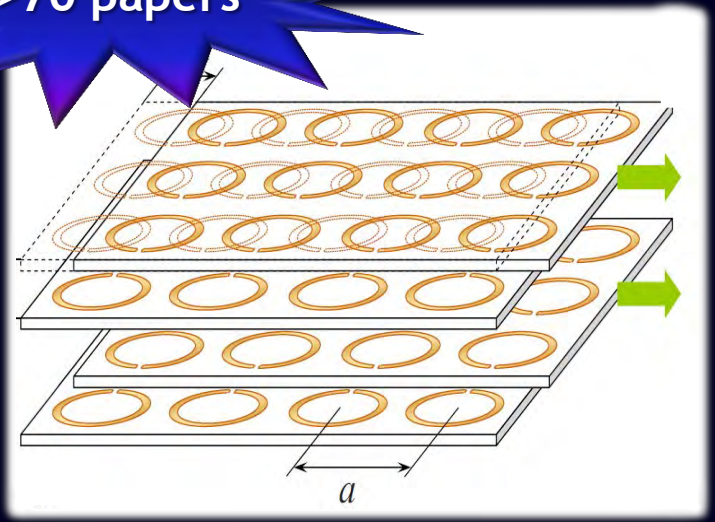




Reconfigurable Metamaterials

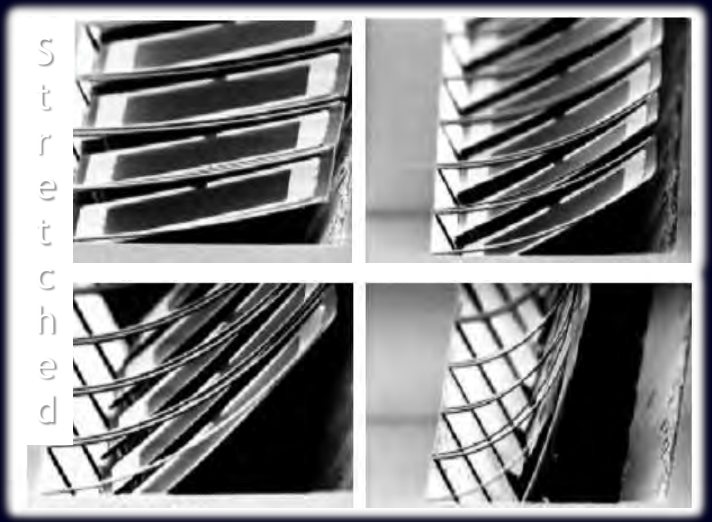
>70 papers

ity (Microwaves)



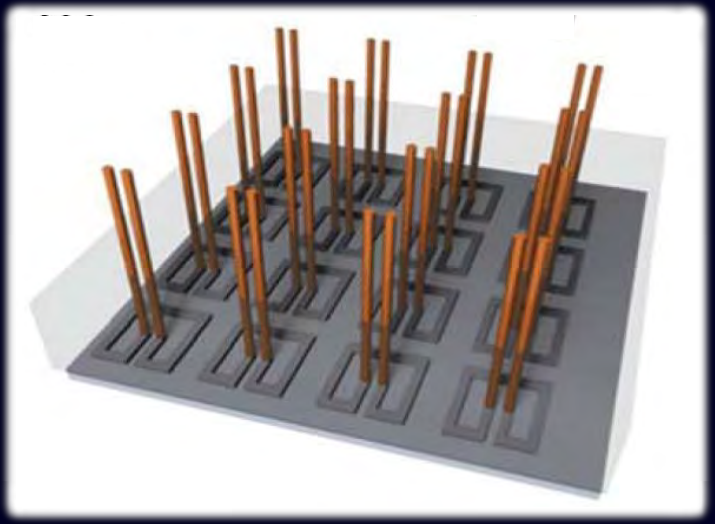
Aydin … Guven (2004); Lapine … Kivsha. APL (2009)

Differential thermal expansion (THz)



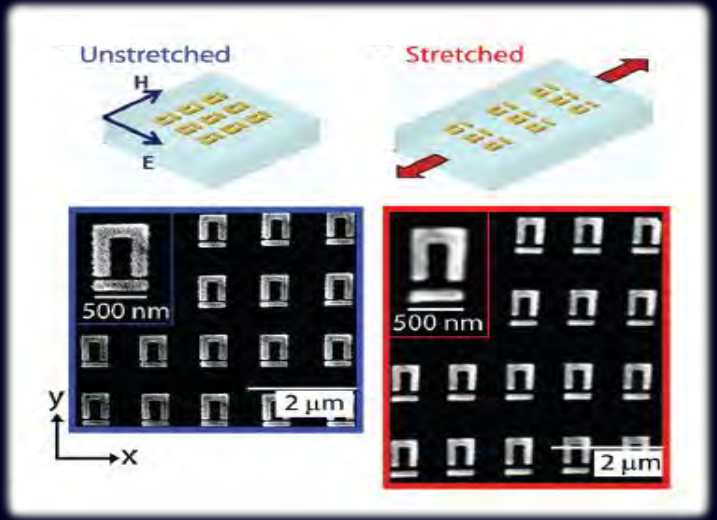
Tao …. Averitt . PRL (2009)

Microfluidic (MW Metamaterials)



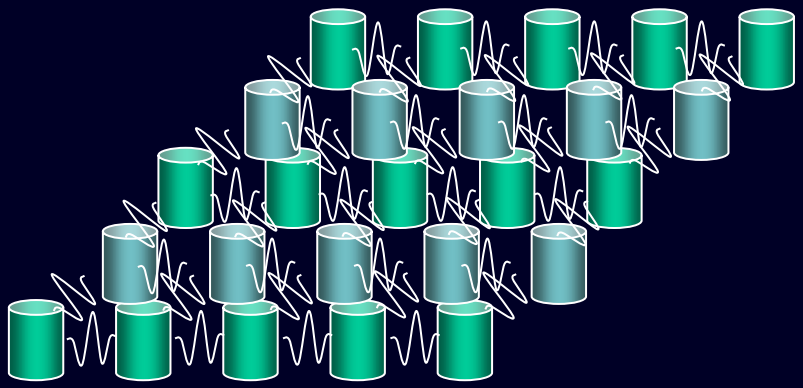
Kasirga, Bayindir . *APL* (2009)

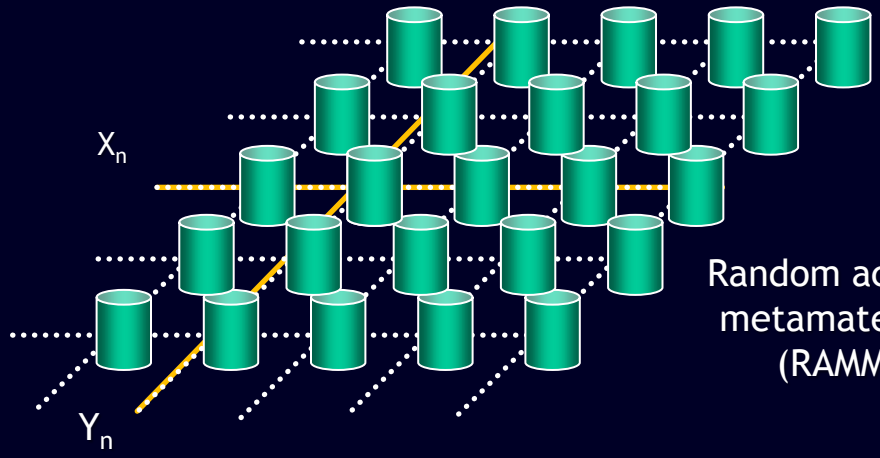
Stretchable (IR Metamaterials)



Pryce …. Atwater.(2010); Huang … Baumberg (2010)

Reconfigurable metamaterials: nanoscale forces

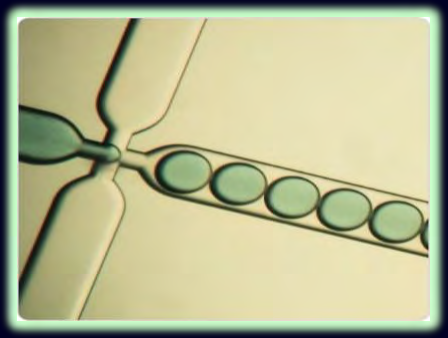




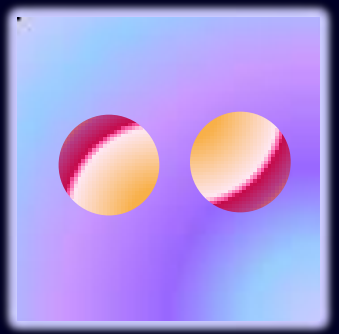
Random access metamaterial (RAMM)

Differential thermal expansion

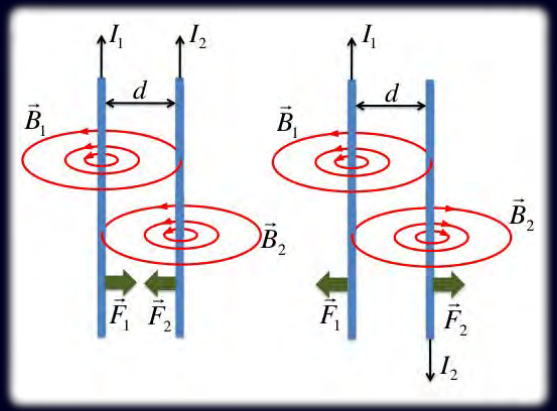
Micro/nano fluidics



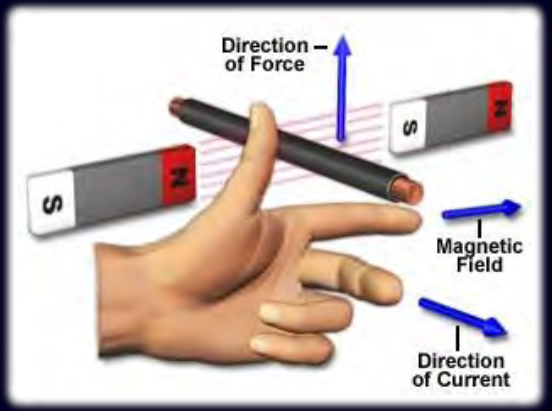
Optical Forces



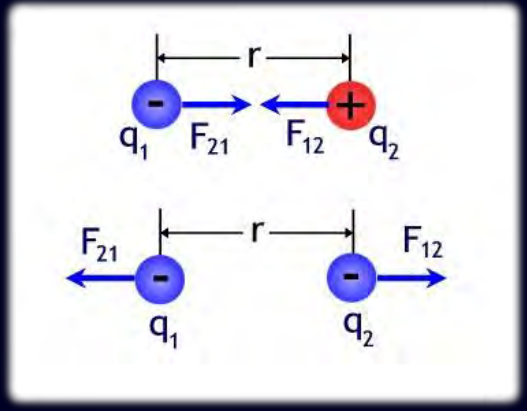
Ampere Force



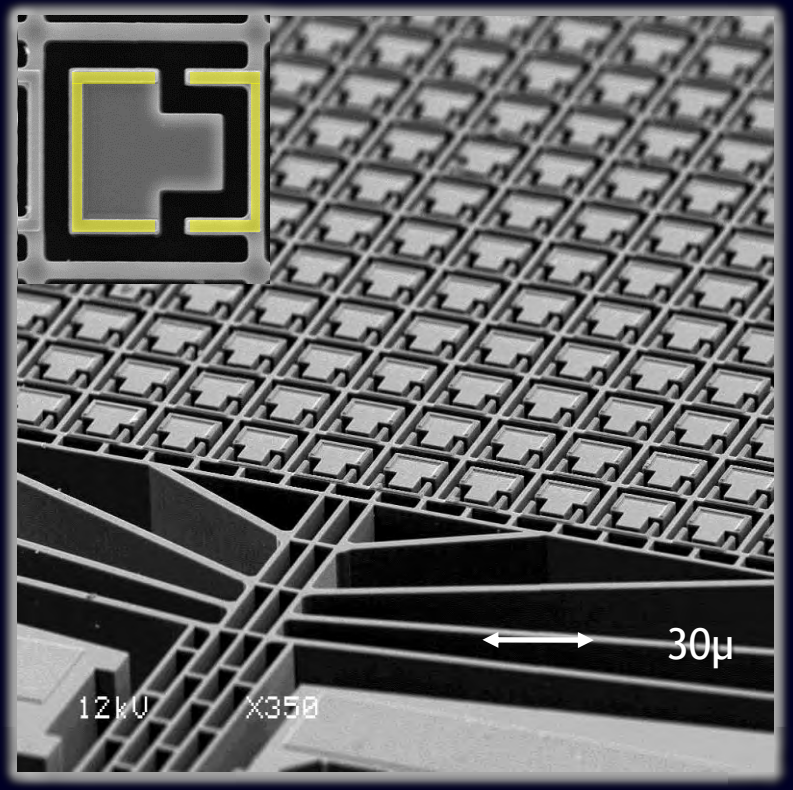
Lorentz-Laplace force Force



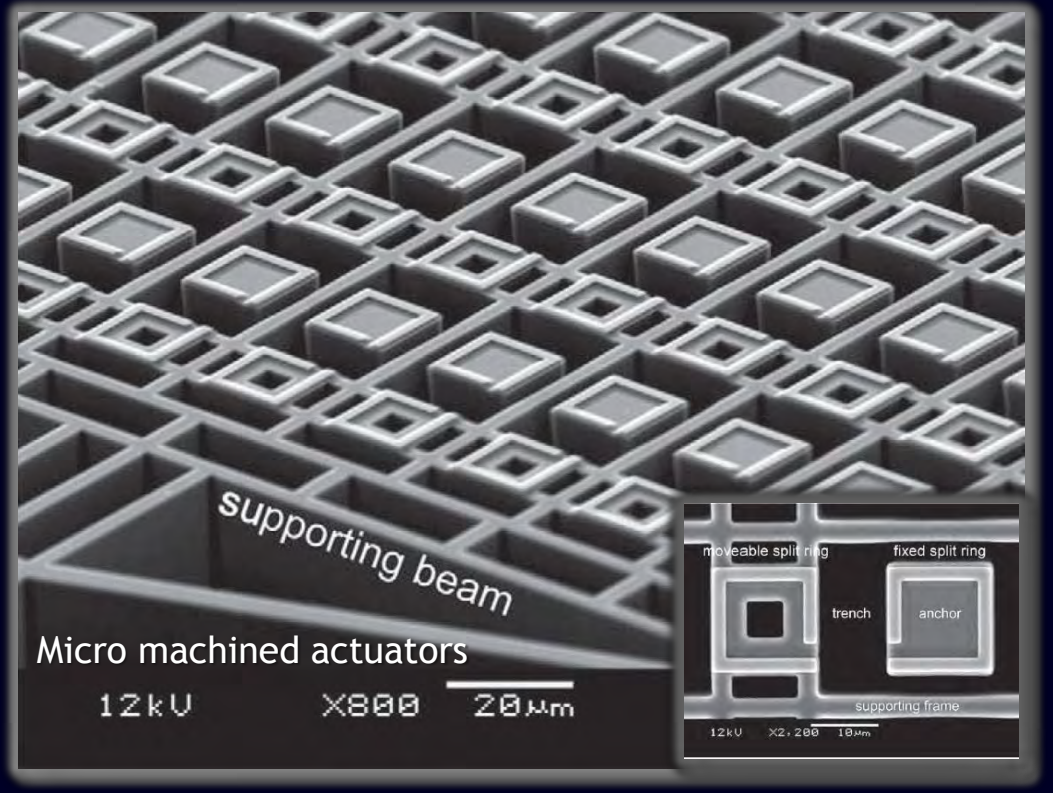
Coulomb Force Force



THz MEMS Reconfigurable Photonic Metamaterials

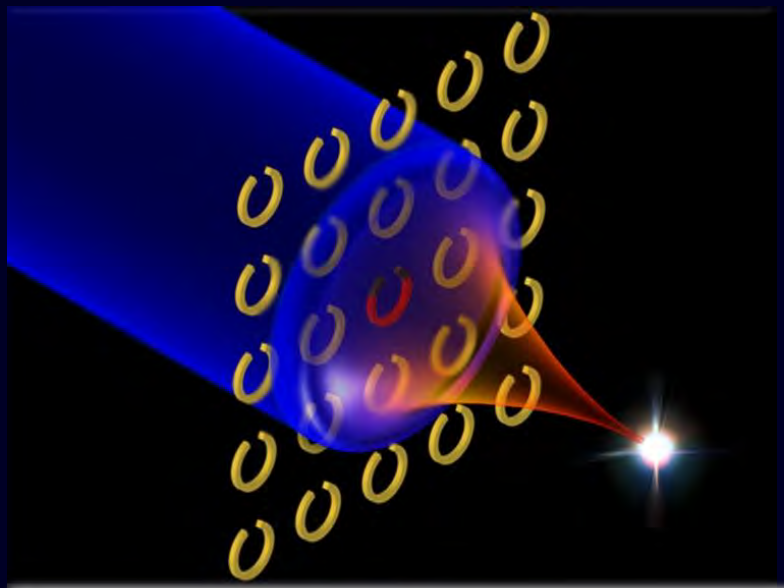


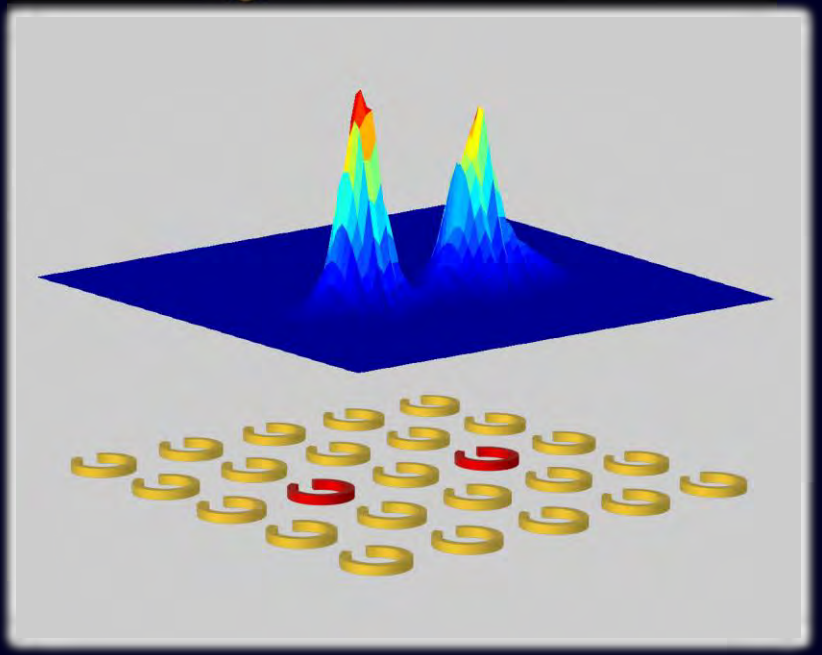
Zhu … Liu . *Adv. Mater.* (2011)

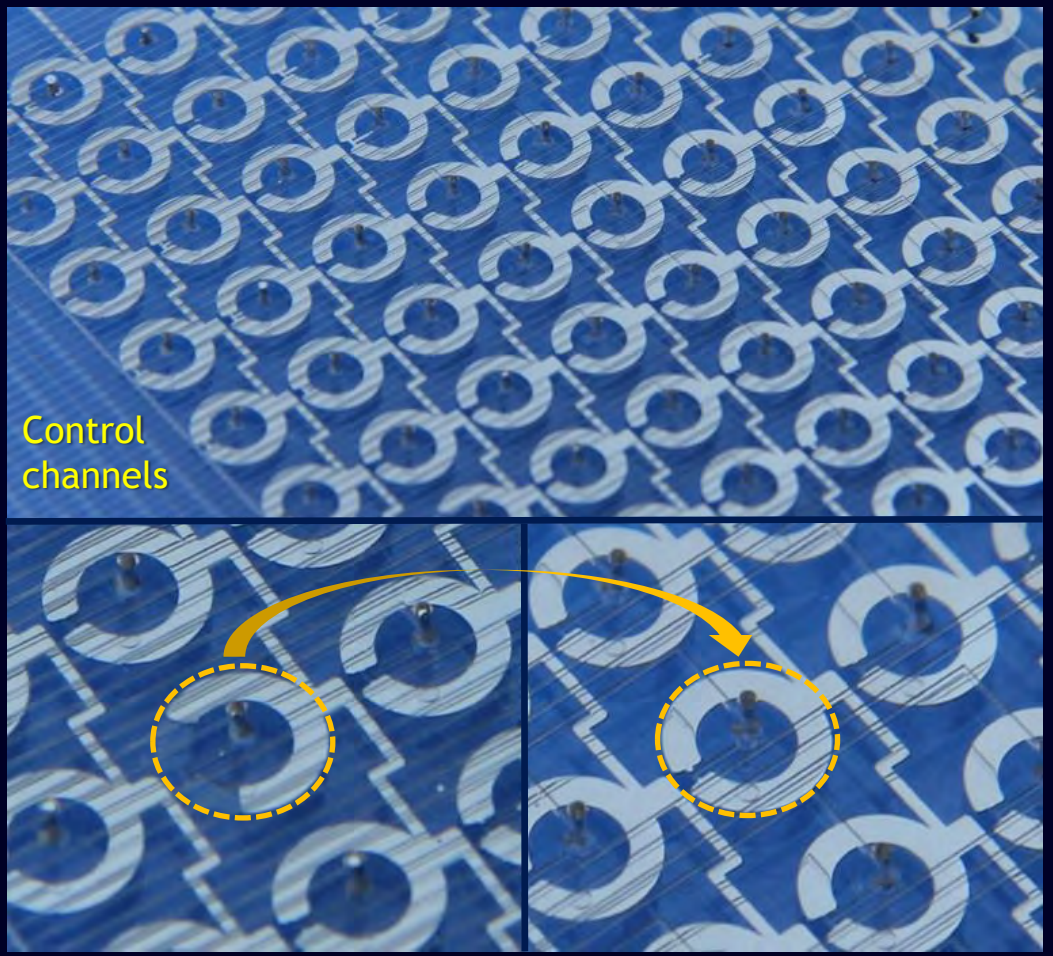


Fu ….Liu, Zheludev. *Adv. Func. Mat.* (2011)

Liquid Metal (Hydraulic) Random Access Metamaterial

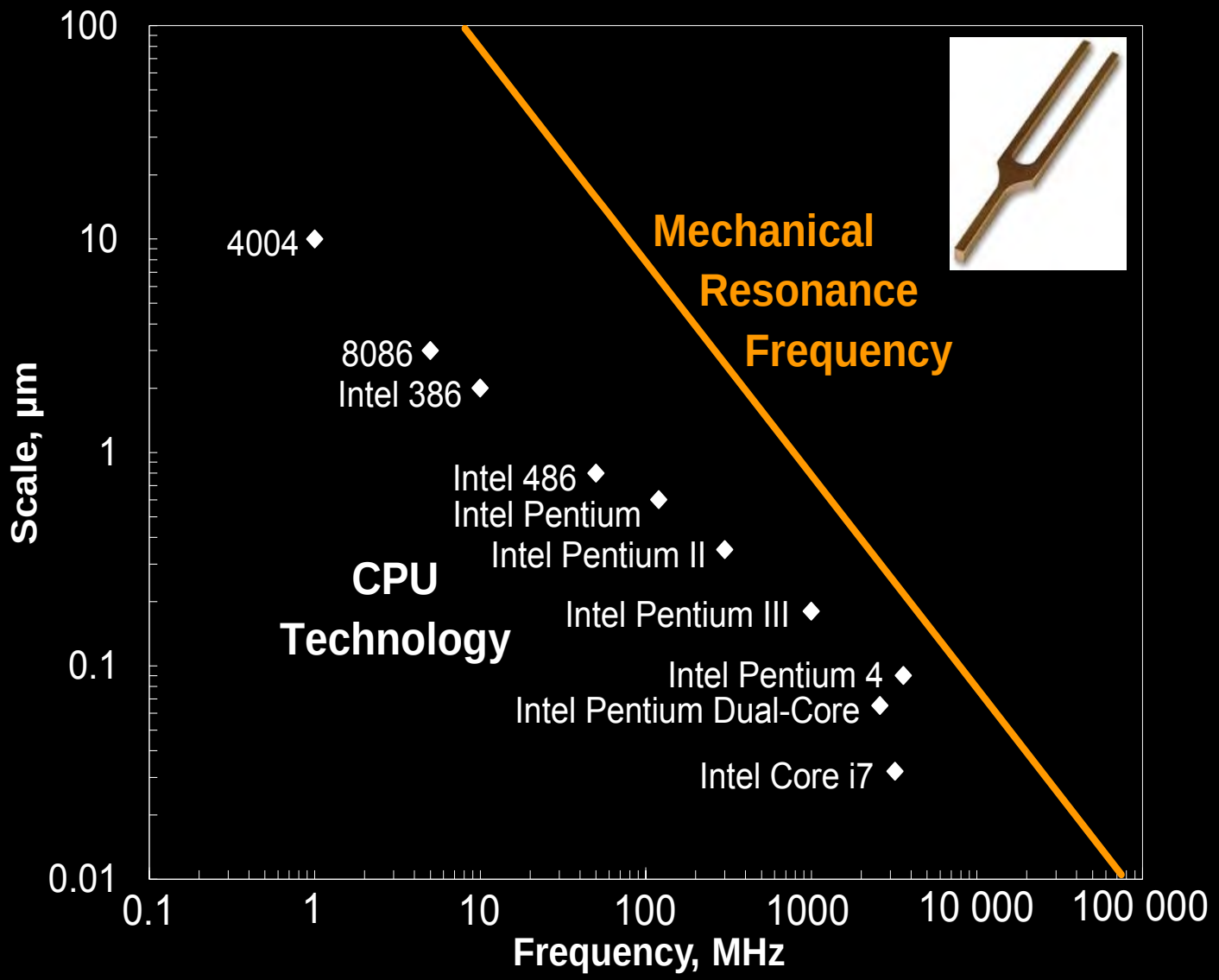




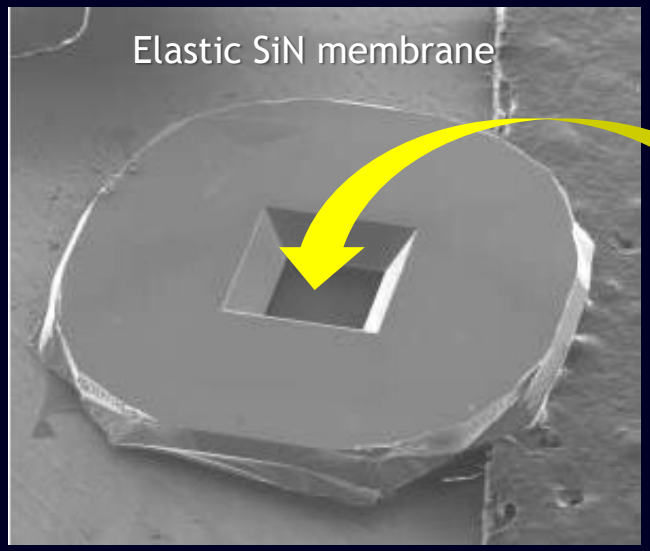


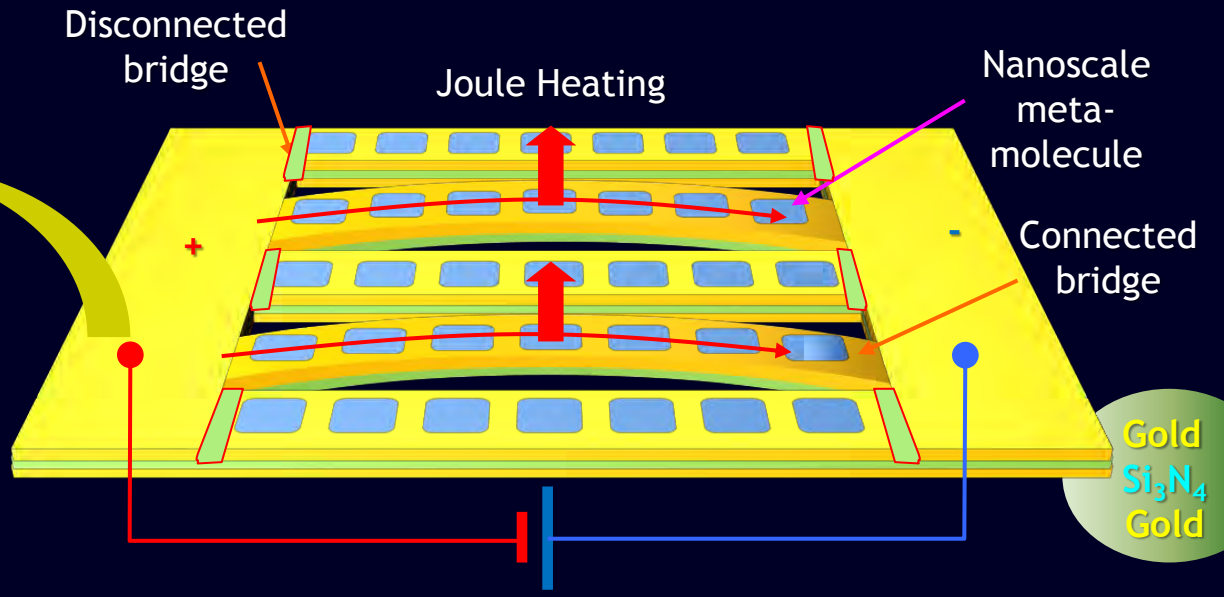
Zhu … Liu , Zheludev TBP (2013)

Size matters

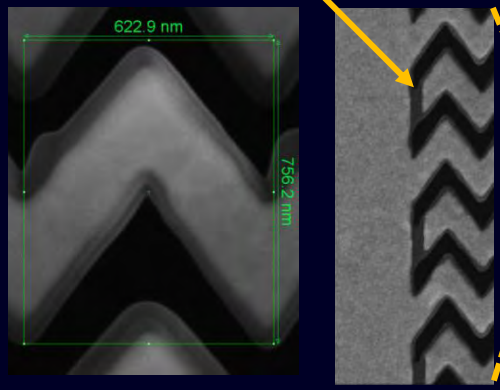


Joule reconfigurable metamaterial

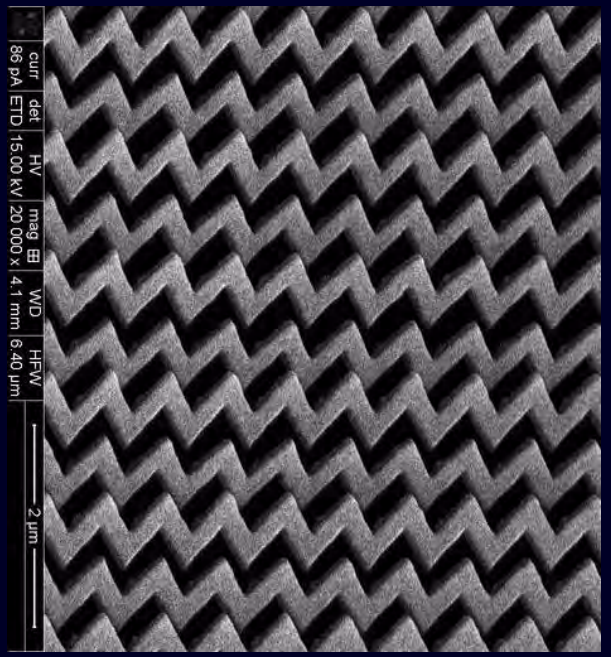




Broken loop

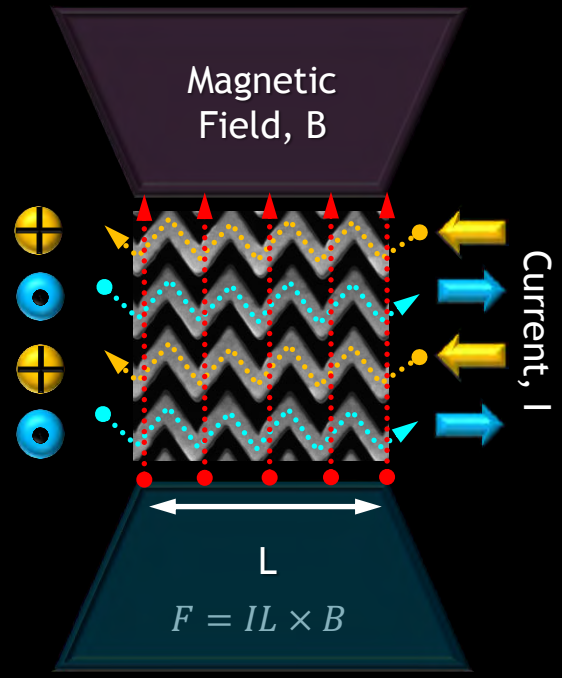


Elastic bridge design

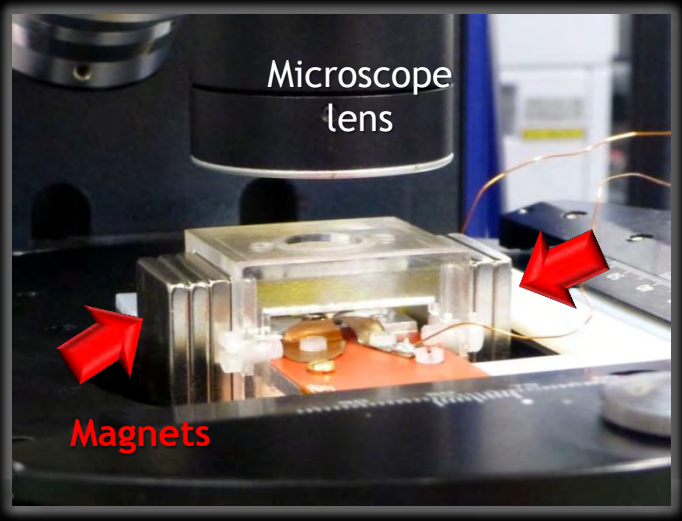


Ou.... Plum, Zheludev. Nano Lett. (2011)
Ou, Valente, Plum ... Zheludev. CLEO-Europe (2013)

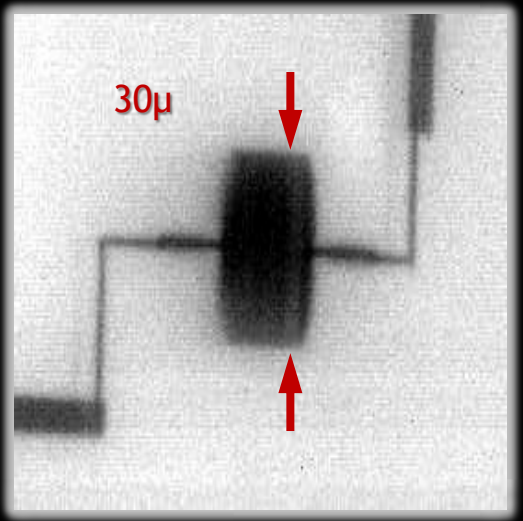
Lorentz-Laplace reconfigurable metamaterials



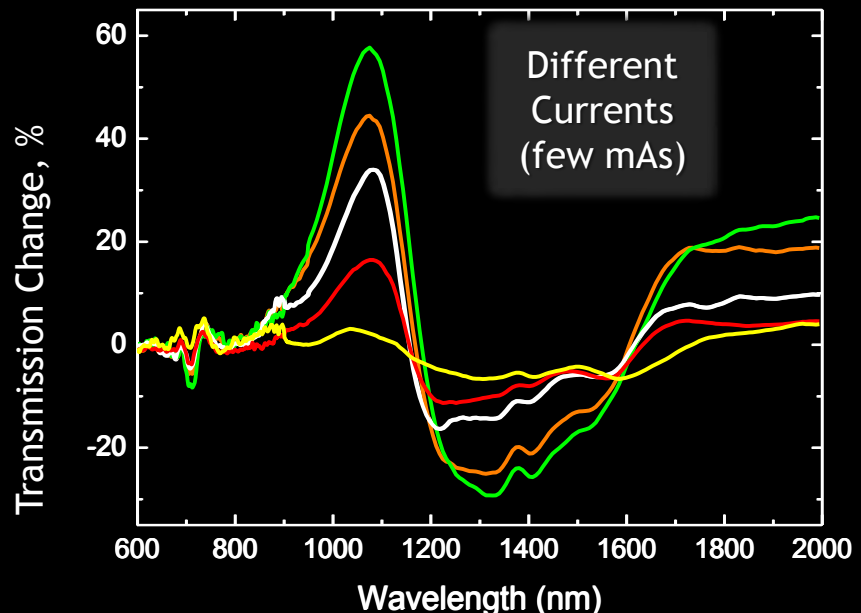
Ou, Valente, Plum … Zheludev. CLEO-Europe (2013)

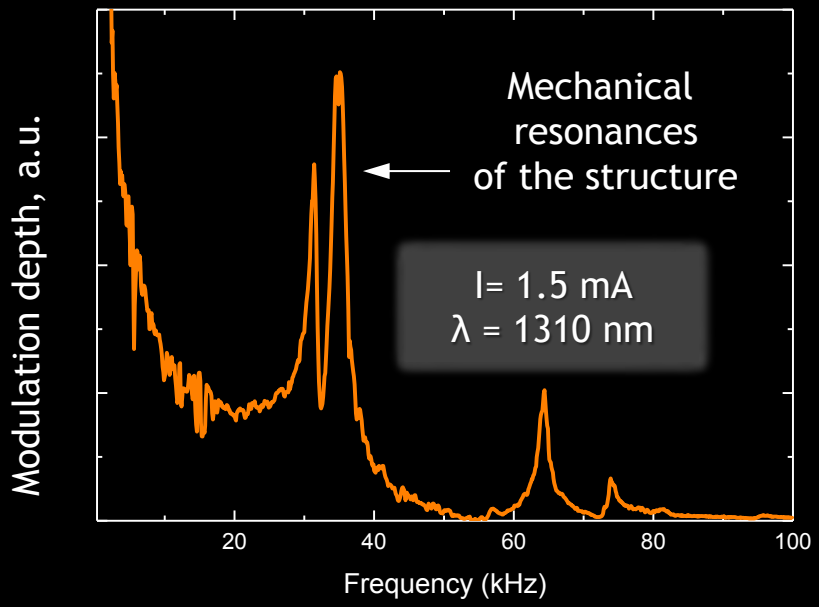


RPM in micro spectrometer



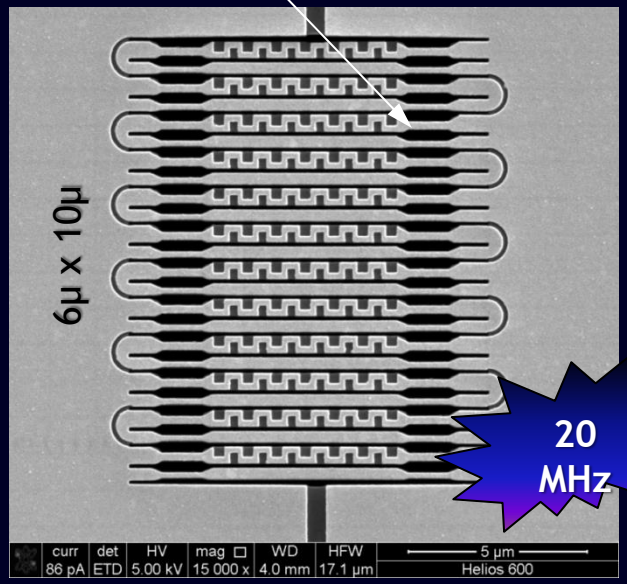
RPM with contact
wires on wafer



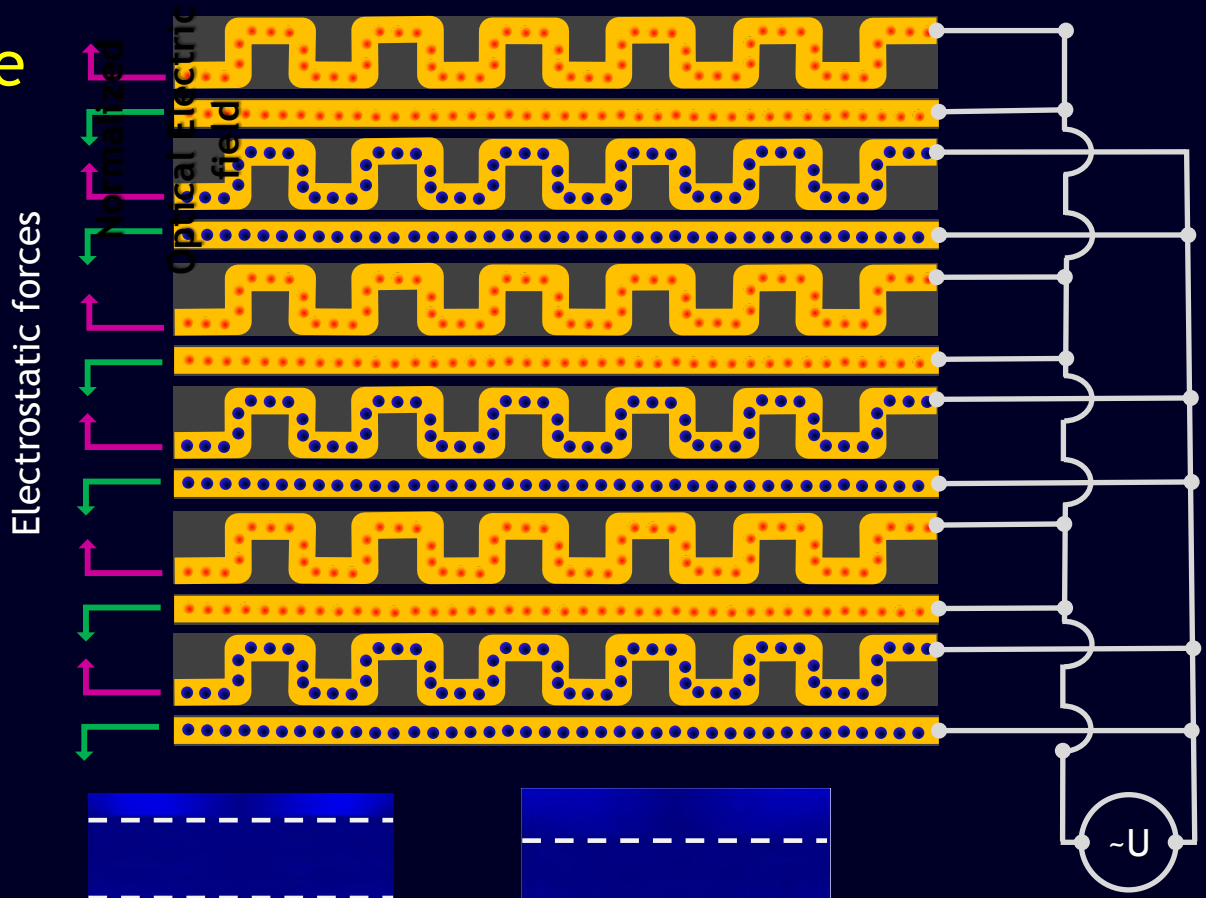


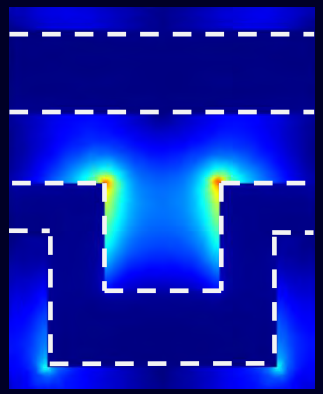
Coulomb reconfigurable metamaterials

Mass ~ 0.5 pg (pico-gram)

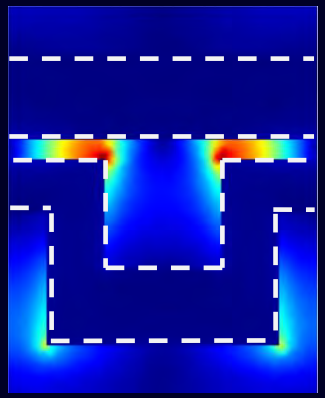


20 MHz





Off



On

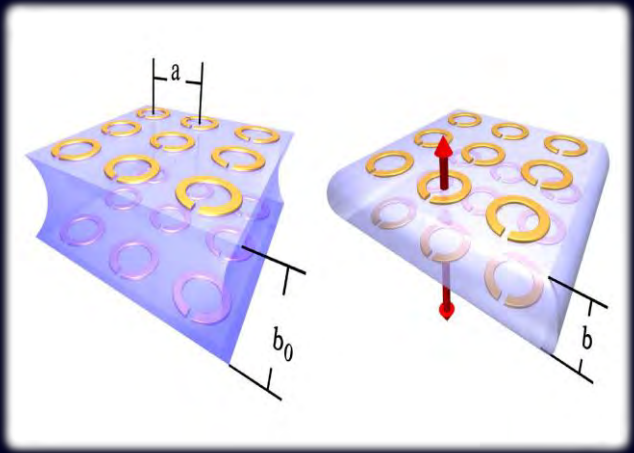
> 70% change in transmission/reflection

EO coefficient 5 orders of magnitude stronger that in $LiNbO_3$

Ou, Plum …Zheludev
Nat. Nanotech (2013)

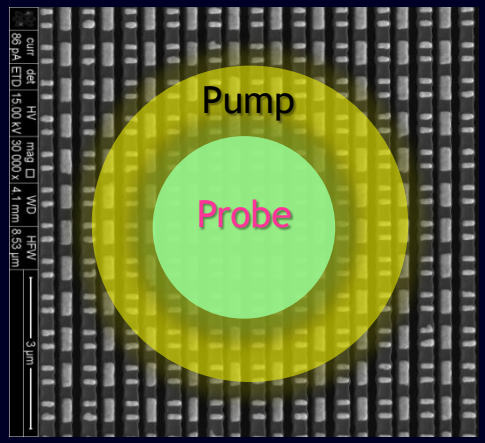
Reconfiguring metamaterials with light = giant nonlinearity

Magneto elastic metamaterial

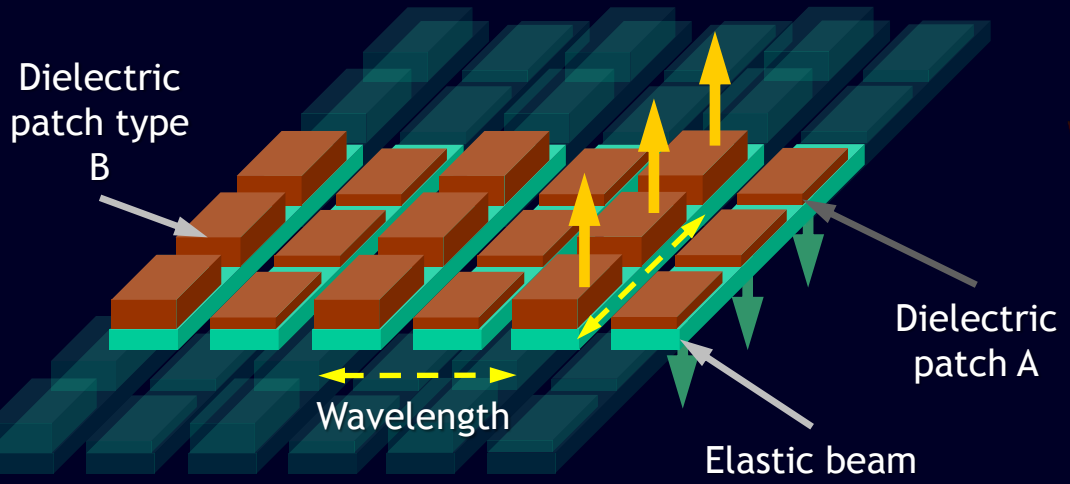


Lapine … Kivshar. Nat. Mat. (2012)

Telecom Frequencies: metamaterial reconfigurable with light

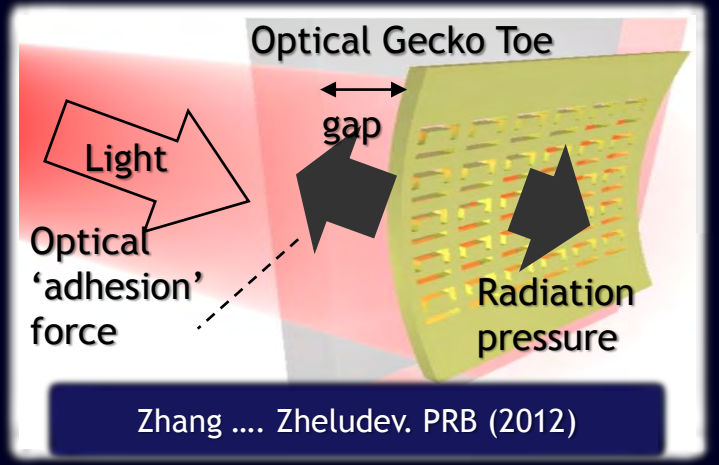


Ou, Valente, Plum, Zheludev TBP (2013)



Zhang, Macdonald, Zheludev NPG Light (2013)

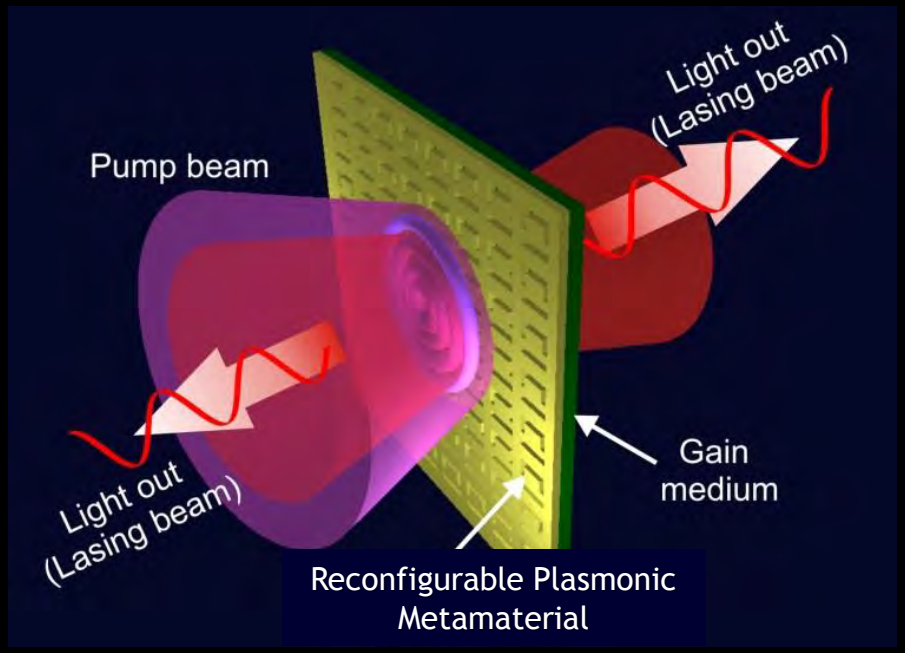
Pump



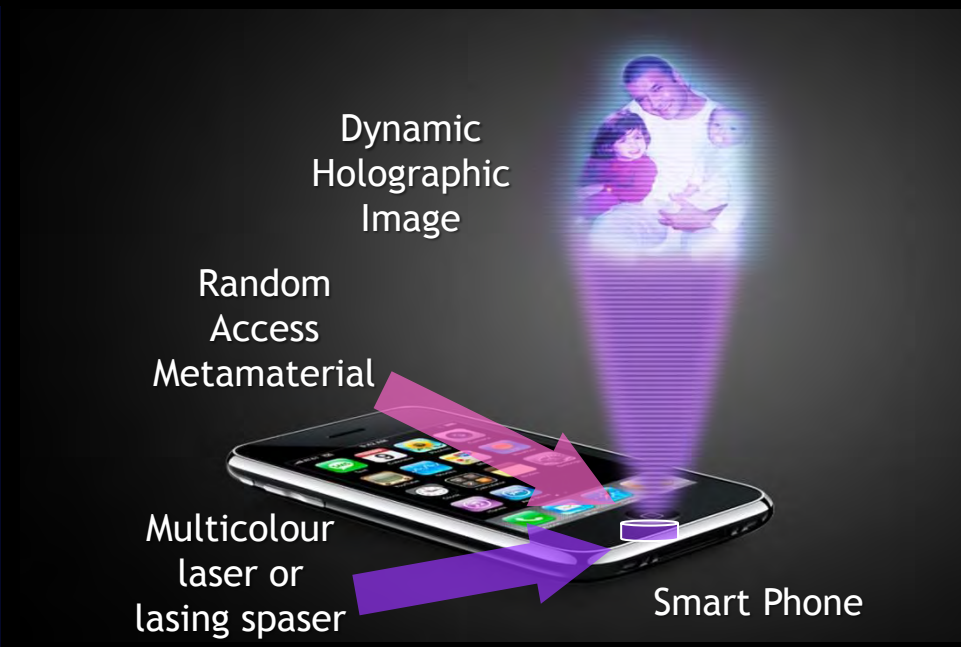
Zhang …. Zheludev. PRB (2012)

Where future “killer applications” may come from?

Tuneable Lasing Spaser

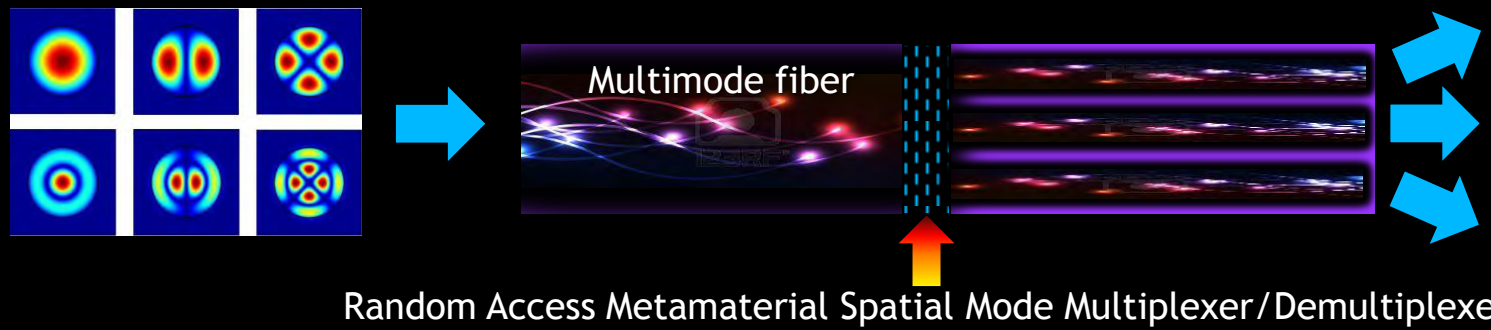


Mobile dynamic 3D display



“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

From metamaterials to metadevices
Zheludev & Kivshar.
Nature Mater. (2012)


Chiral Fractal
Metamaterial
Southampton
University
Mountbatten
Building


Light
Centre for Photonic Metamaterial. ORC
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THANK YOU!
Talk may be found at
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From Photonic Metamaterials to Metadevices: Exploiting Forces and Fields at the Nanoscale

By Nikolay Zheludev

10:30 -11:15. Plenary talk at SPIE Optics and Photonics 13, San Diego, CA. 26 August 2013

Author's References relevant to numbered slides

1. Title slide.
2. Metamaterials: mimicking Nature, step 1. [1]
3. Metamaterials: mimicking Nature, step 2. [2]
4. 1st Metamaterial (J.Bose, 1898).
5. The main question
6. Impact of Metamaterials on Fundamental Physics #1: Optical Magnetism & Negative Index. [3,4]
7. Impact of Metamaterials on Fundamental Physics #2: Asymmetric transmission. [5-8]
8. Impact of Metamaterials on Fundamental Physics #3: Toroidal Dipole. [9-11]
9. Designing Resonances: EIT & Fano resonances. [12-14]
10. Sharp resonances in superconducting metamaterials. [15,16]
11. Sensor Metamaterials.
12. Designing Anisotropy & birefringence. [17]
13. Anisotropy: THz reconfigurable Metamaterial. [18]
14. Controlling polarization: Chirality. [3,19-22]
15. Controlling boundary conditions: perfect absorber. [23-25]
16. Making good use of losses: colouring metal. [26]
17. Press coverage.
18. Light-Harvesting metamaterial thermal detecrorst & bolometers. [27]
19. Tailored light emission from metamaterials.[28]
20. Metals not needed: Dielectric metamaterials. [29,30]
21. Graphene metamaterials. [31]
22. Conductive oxides and nitrides metamaterials; topological insulators.
23. Ultrafast switching with metamaterials. [32]
24. Improving nonlinearities with metamaterials. [33,34]
25. Nonlinear optical activity in metamaterial: 10^7 times stronger than natural media. [35-37]
26. Modulating light with light in metamaterial without nonlinearity.[38]
27. Phase Change Metamaterials & Optical memory. [39,40]
28. Quantum Metamaterials. [41]
29. Metamaterials and LC devices. [42]
30. EO & MO modulation with metamaterials. [43,44]
31. Control of Spontaneous Emission with MMs & "Lasing Spaser". [45,46]
32. Free-electron driven metamaterial light sources. [47,48]

33. Reconfigurable Metamaterials.
34. Reconfigurable Metamaterials: nanoscale forces.
35. THz MEMS Reconfigurable Photonic Metamaterials. [18]
36. Liquid Metal (Hydraulic) Random Access Metamaterial.
37. Size matters.
38. Joule reconfigurable metamaterial. [49]
39. Lorentz-Laplace reconfigurable metamaterials.[50]
40. Coulomb reconfigurable metamaterials. [51]
41. Reconfiguring metamaterials with light = giant nonlinearity. [52,53]
42. Where future "killer application" may come from?
43. Conclusions.[54]

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