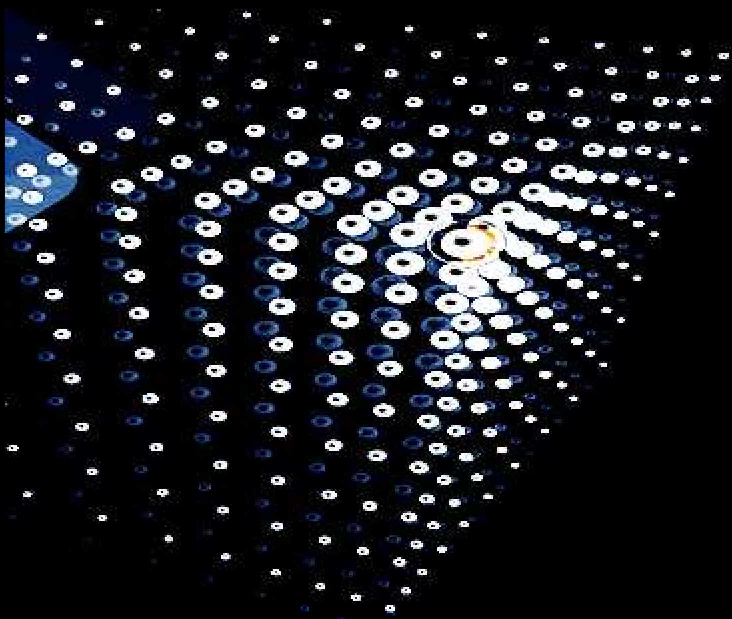


Transforming Metamaterials

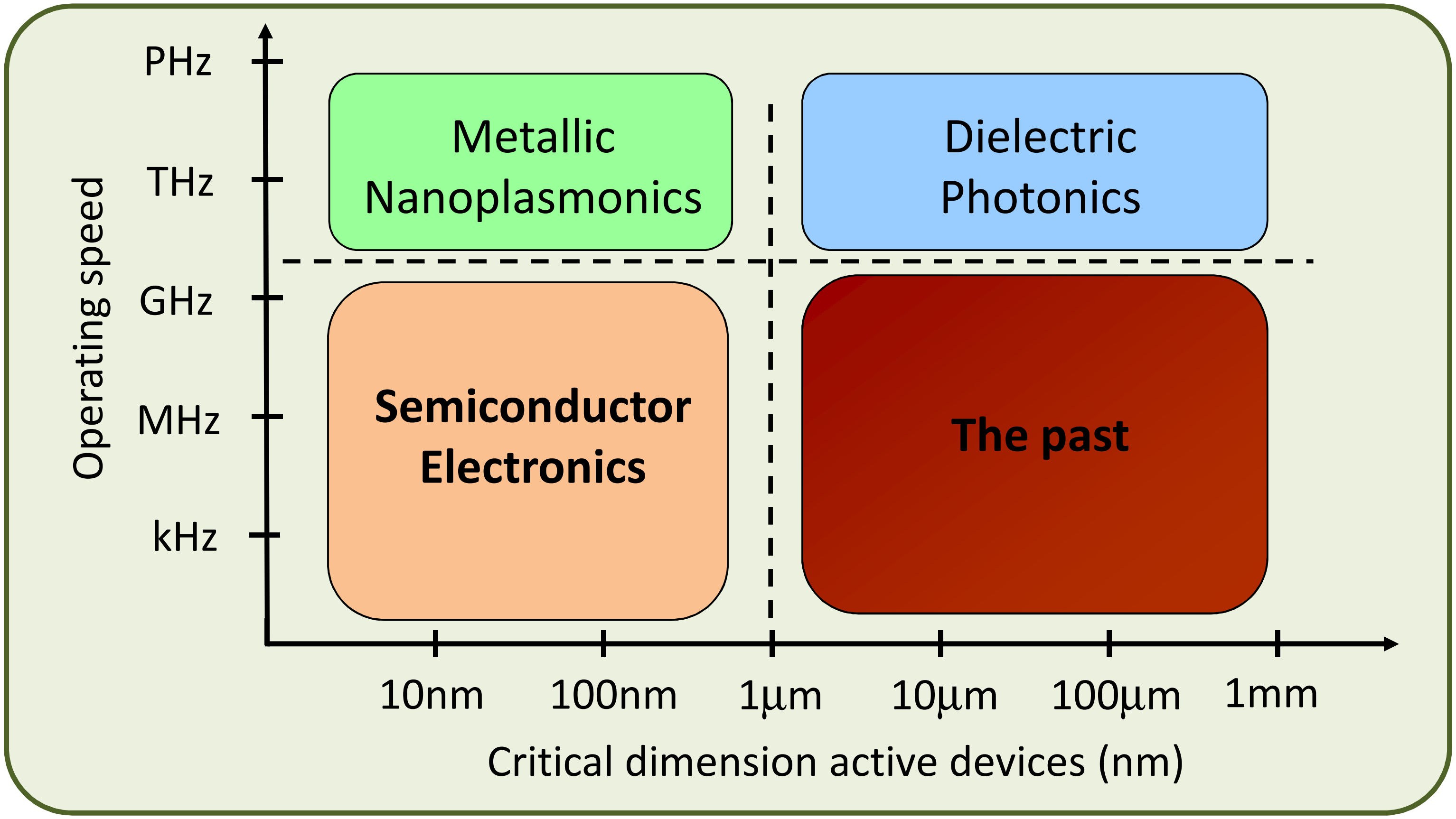
Vladimir M. Shalaev
Purdue University

Outline

- ❖ Electrical Metamaterials (Plasmonics): A Route to Nanophotonics
- ❖ New Plasmonic Materials
- ❖ Negative-Index Metamaterials
- ❖ Chiral and Stereo- Metamaterials
- ❖ Active and Loss-Free Metamaterials
- ❖ Metamaterials for Sensing
- ❖ Tunable, Ultrafast, and Nonlinear Metamaterials
- ❖ Quantum Optics with Metamaterials
- ❖ Transformation Optics: Cloaking, TO-SPP, Fish-Eye & Eaton Lenses
- ❖ Metamaterial "Multiverse"

Electrical Metamaterials (Plasmonics): A Route to Nanophotonics

Why Plasmonics/Electric ε-MMs ?

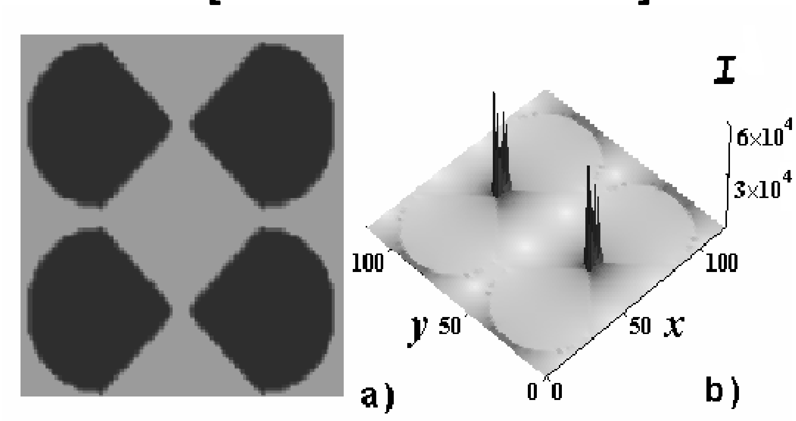


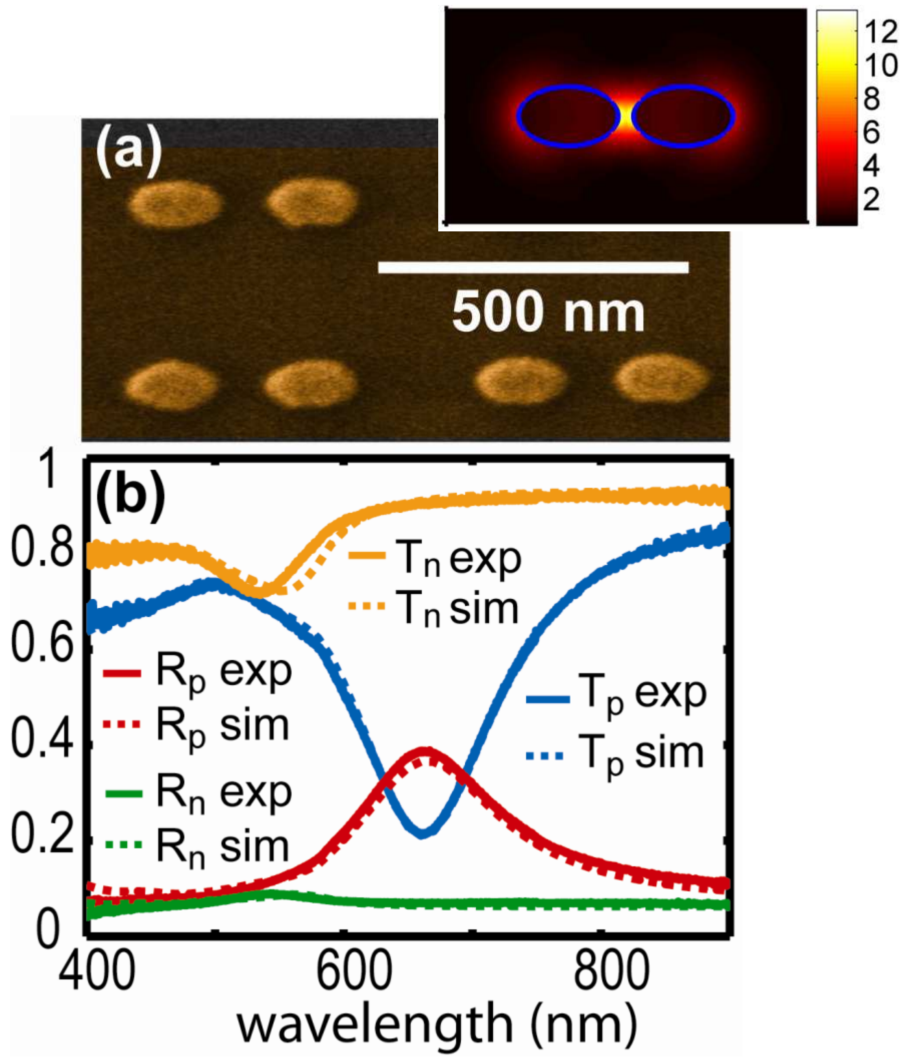
- Plasmonics will enable an improved synergy between electronic and photonic devices
  - Plasmonics naturally interfaces with similar size electronic components
  - Plasmonics naturally interfaces with similar operating speed photonic networks

Brongersma, Shalaev, Science (2010)

Optical Antennae: Focusing Light to Nanoscale

[Bow-tie antennas]





from LC-contour to nanophotonic circuits (Engheta – 'metatronics')

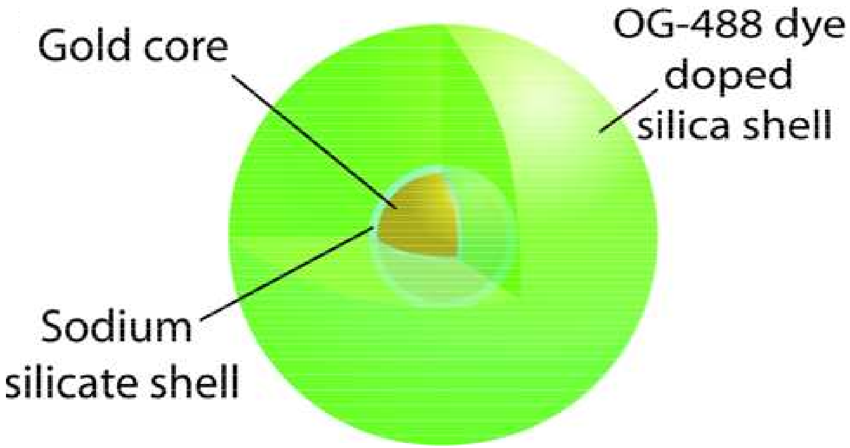
Other Applications:

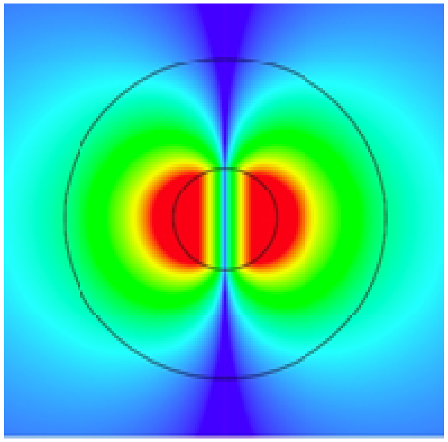
Sensors

Other nanoantenna work: van Hulst, Polman, Brongersma, Capasso,…

Optical Nanolaser Enabled by SPASER

Related prior theory:
Stockman (spaser)





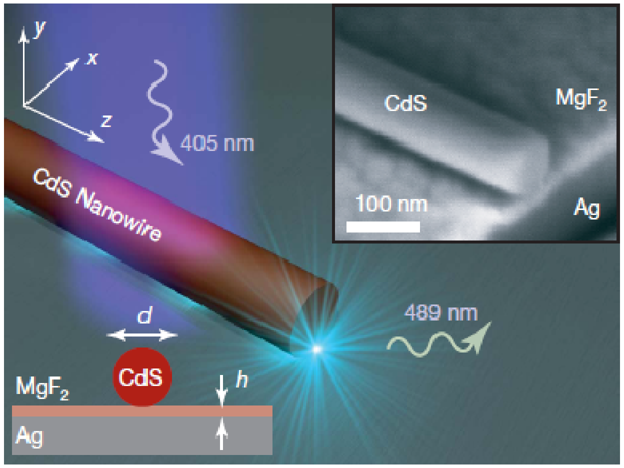
Noginov, Shalaev, Wiesner groups, Nature (2009)

NSU-Purdue-Cornell; *Nature (2009)*

Optical MOSFET
(Stockman)

Zhang's group: Plasmon laser
(Nature, 2009)

Room-T Plasmon Laser
(Nature Materials, 2010)

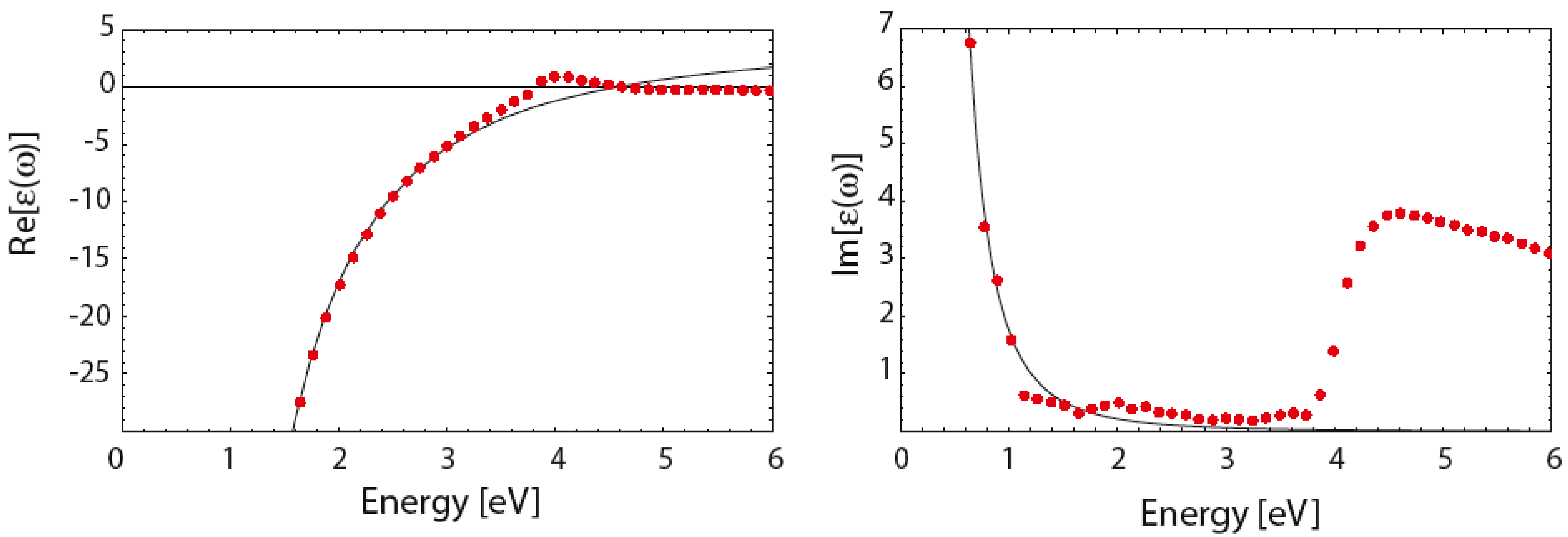


Toward Better Materials & Fabrication

Challenges

Conventional plasmonics: *Gold and Silver*

- Large losses in near-IR and visible ranges
- Interband transitions
- Surface roughness, grain boundaries, etc…



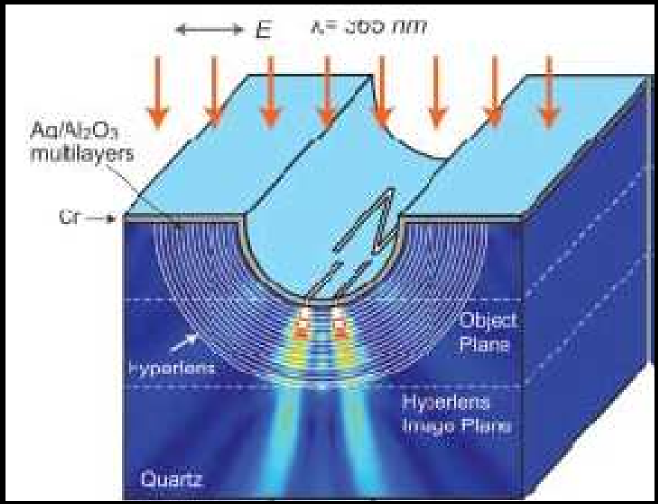
Real and Imaginary ε(ω) for Silver (Ag)

Johnson and Christy (dots) (1972)
Stefan Maier, Plasmonic Fundamentals and Applications p. 17 (Drude model fit) (2007)

Challenges

Conventional plasmonics: *Gold and Silver*

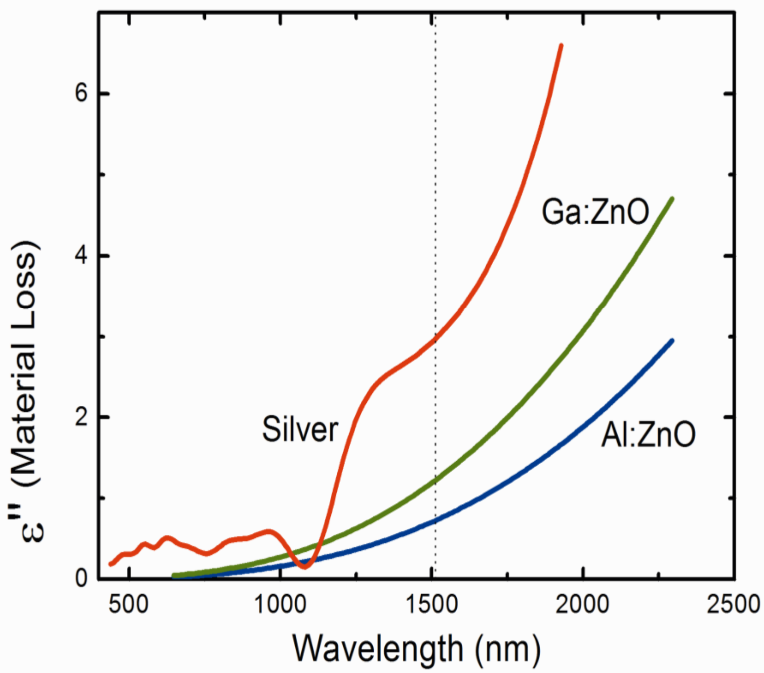
- Large losses in near-IR and visible ranges
- Emerging new fields such as Transformational Optics have different requirements
- Effective permittivity nearly zero: e.g. optical cloaks, hyperlens etc.
- Real permittivity of metals must be comparable to that of dielectrics



Z. Liu, et al., Science, 2007

Alternative Plasmonic Materials

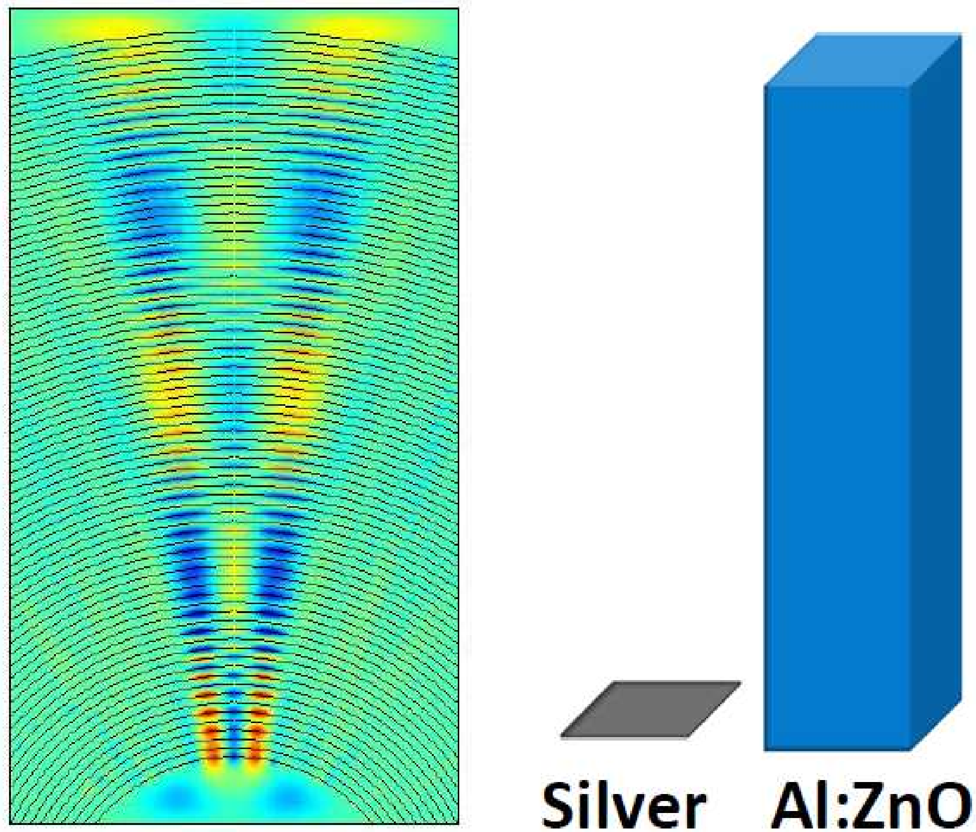
Transparent Conductive Oxides



P. R. West et. al, Lasers & Photon. Rev 4, 795 (2010)
(Boltasseva group)

There are Other Materials!

Figure of Merit of Hyperlens @ 1.55 µm



Performance of HMM devices:
(A. Hoffman, Nature Materials 6(2007) 946–950)

$FOM=Re\{k_\perp\}/Im\{k_\perp\}$

G. Naik and A. Boltasseva, Phys. Status Solidi RRL 4, 295–297 (2010)

HMM Performance: Figure of merit for TiN

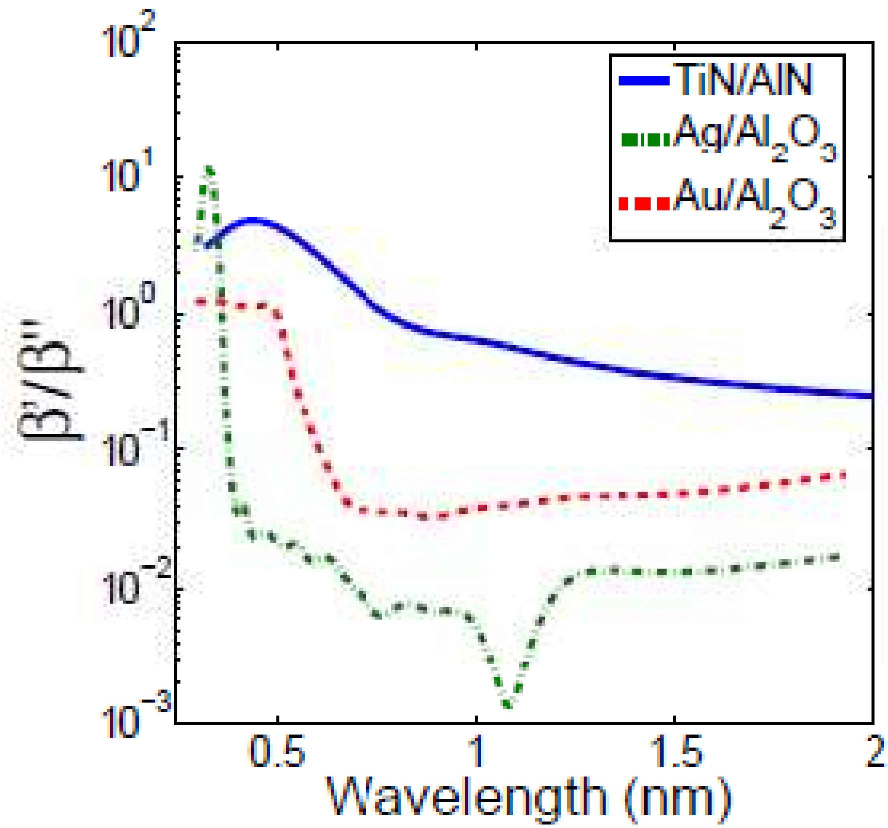
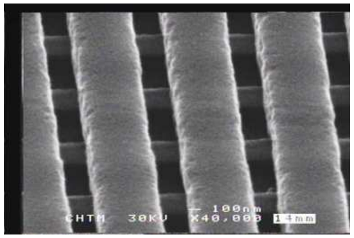


Figure-of-merit of HMMs formed by alternating, sub-wavelength layers of TiN/AlN, Ag/alumina and Au/alumina

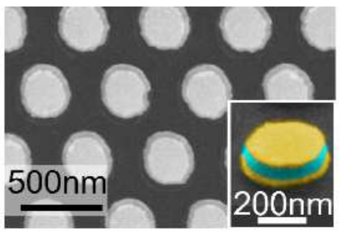
G. Naik and A. Boltasseva, arXiv:1011. 4896v1 (2010)

Progress in Large-Scale & 3D Fabrication

[Interference Lithography]

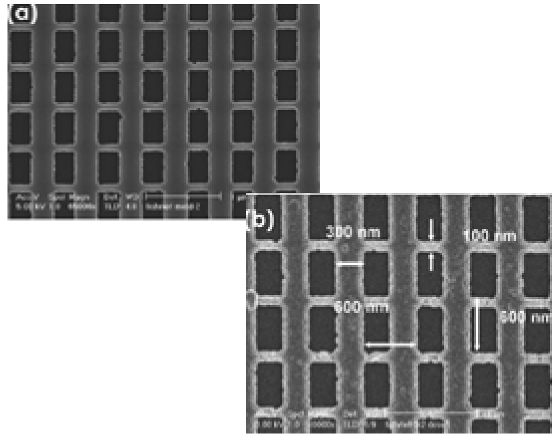


Z. Ku & SRJ Brueck, Opt. Exp. **15**, 4515 (2007)



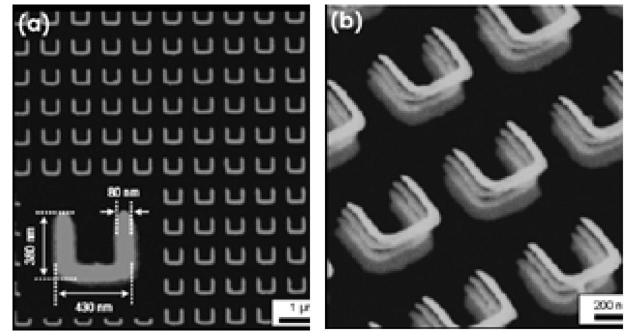
Nils Feth et. al, Opt. Exp. **15**, 501 (2007) (Wegener group)

[Nanoimprint Lithography]



W. Wu et. al, Appl. Phys. A **87**, 143 (2007)

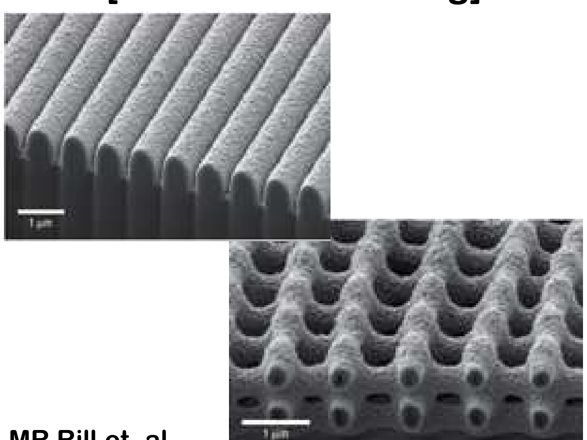
[Building layer-by-layer]



Na Liu et. al, Nat. Mater. **7**, 31 (2007)
(Giessen group)

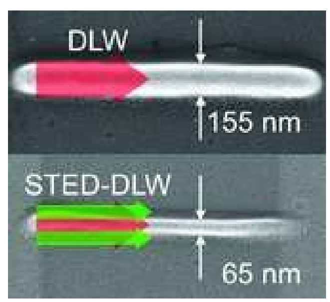
3D

[Direct Laser Writing]



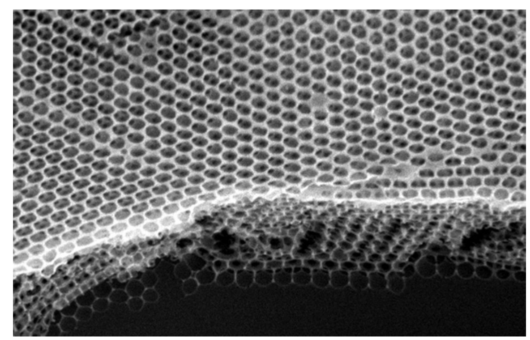
MR Rill et. al,
Nat. Mater. **5**,743 (2008) (Wegener group)

[STED-Direct Laser Writing]



J. Fischer et. al, Adv. Mater. **22**, 3578 (2010)
(Wegener group)

[Self-assembly]

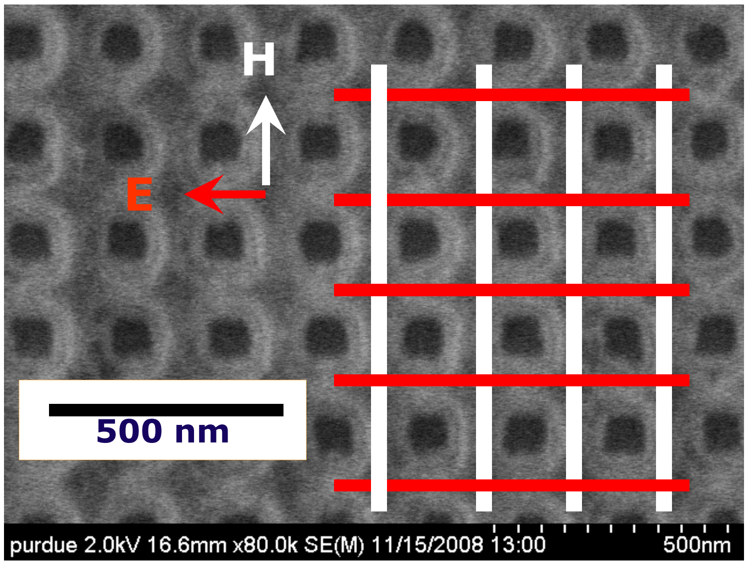


JF Galisteo et. al, J. Opt. A **7**, 244 (2005)

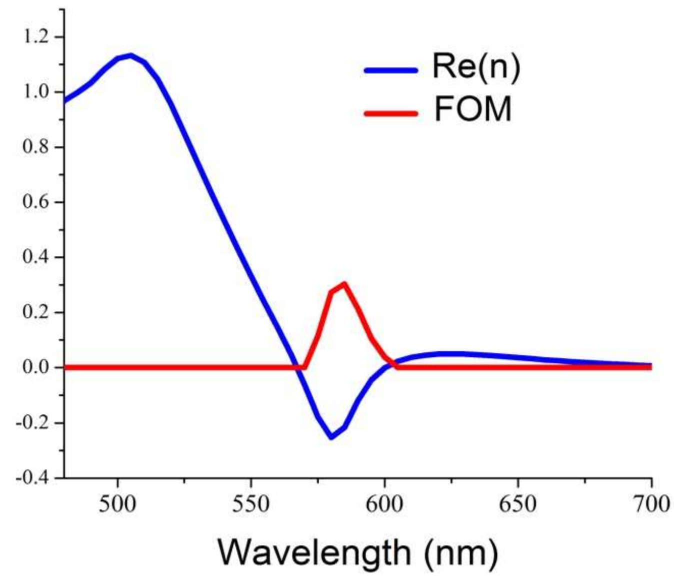
Optical Negative-Index Metamaterials

Negative Index for Yellow Light

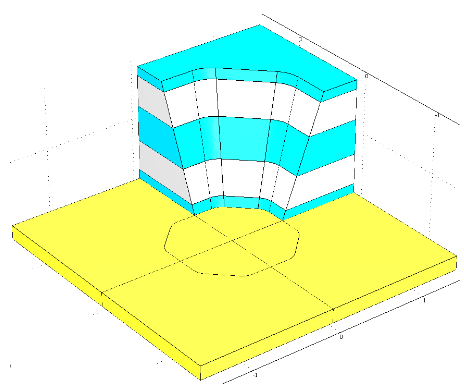
Periodicity, E: 220 nm; H: 220 nm



n’=-0.25, FOM=0.3, at 580 nm



FOM = -n’/n”



Stacking:

8 nm of Al_2O_3

43 nm of Ag

45 nm of Al_2O_3

43 nm of Ag

8 nm of Al_2O_3

Xiao et al, OL (2009)

Negative Refractive Index in Optics

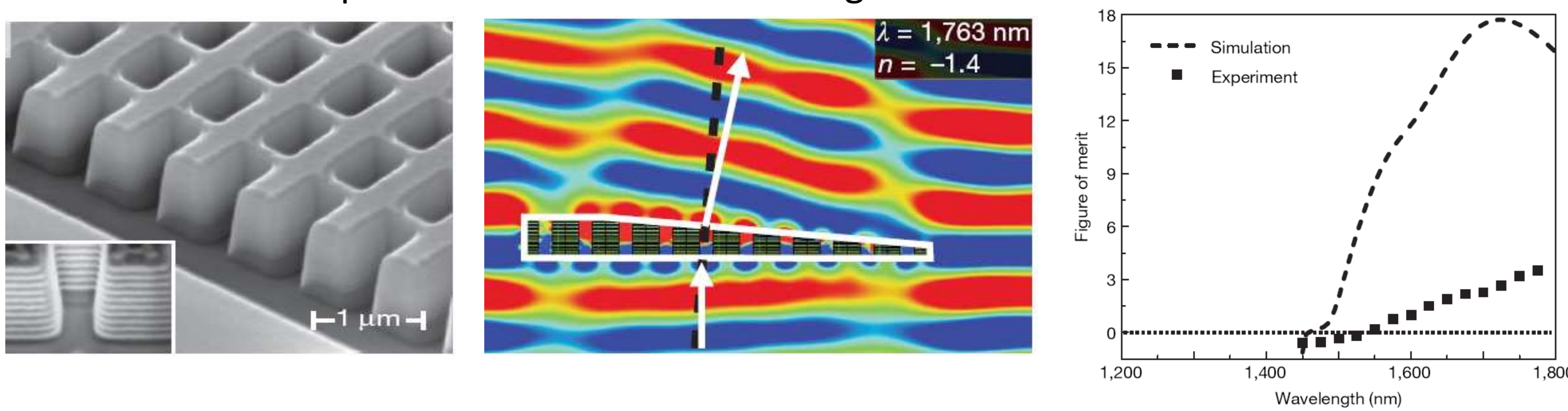
Year and Research group	*1st time posted and publication*	*Refractive index, n´*	*Wavelength, λ*	*Figure of Merit F=|n´|/n″*	*Structure used*
2005					
Purdue	April 13 (2005) arXiv:physics/0504091 Opt. Lett. (2005)	–0.3	1.5 μm	0.1	Paired nanorods
UNM & Columbia	April 28 (2005) arXiv:physics/0504208 Phys. Rev. Lett. (2005)	–2	2.0 μm	0.5	Nano-fishnet with round voids
2006					
UNM & Columbia	J. of OSA B (2006)	–4	1.8 μm	2.0	Nano-fishnet with round voids
Karlsruhe & ISU	OL. (2006)	–1	1.4 μm	3.0	Nano-fishnet
Karlsruhe & ISU	OL (2006)	–0.6	780 nm	0.5	Nano-fishnet
Purdue	MRS Bulletin (2008)	-0.8 -0.6	725nm 710nm	1.1 0.6	Nano-fishnet
Purdue	OL (2009)	-0.25	580nm	0.3	Nano-fishnet

CalTech (Atwater): negative refraction in the visible for MIM waveguide SPPs (2007)

Negative-Index Metamaterials (NIMs)

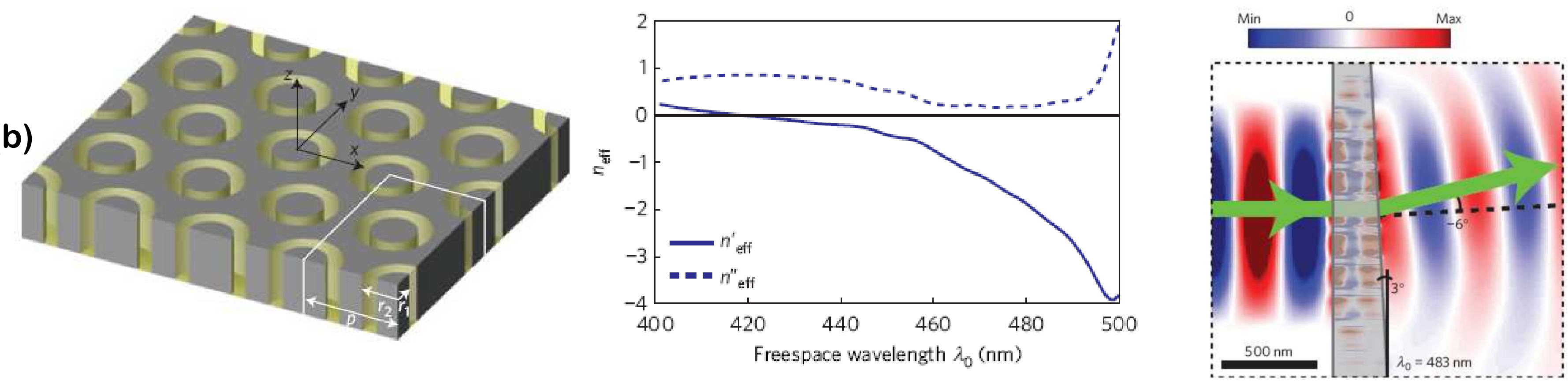
- Three-dimensional optical metamaterial with a negative refractive index

(a)



- A single-layer wide-angle negative-index metamaterial at visible frequencies

(b)



(a) Zhang group, Nature. 455, 376 (2008)
(b) S. P. Burgos, et al, Nature materials. (2010) (Polman-Atwater groups)

Chiral and Stereo-Metamaterials

Chiral Metamaterials

- Coupling effect between E-field and M-field (Chirality parameter[κ])

$$\begin{pmatrix} D \\ B \end{pmatrix} = \begin{pmatrix} \varepsilon_0 \varepsilon & -\frac{i\kappa}{c} \\ \frac{i\kappa}{c} & \mu_0 \mu \end{pmatrix} \begin{pmatrix} E \\ H \end{pmatrix}$$

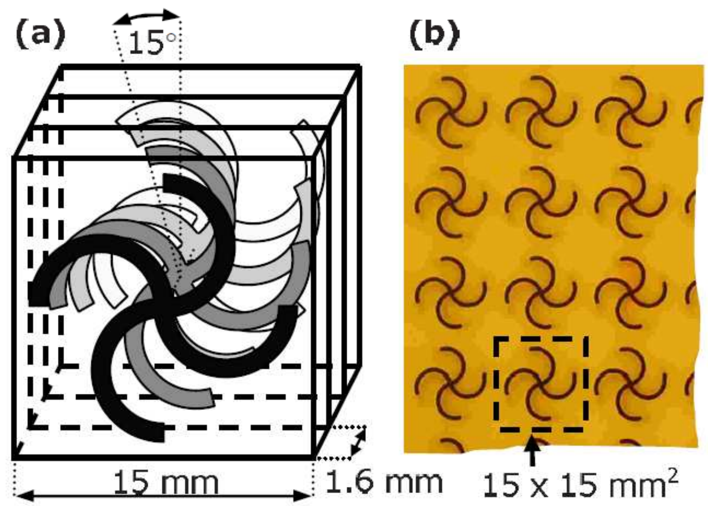
- Right circularly polarized (RCP) / Left circularly polarized (LCP)

$$k_{\pm} = k_0(n \pm \kappa)$$
$$n_{\pm} = n \pm \kappa$$

<Negative index refraction>

- without negative permittivity (ϵ) /negative permeability (μ)
- Chirality parameter (κ) > $\sqrt{\epsilon\mu}$
- Refractive index for the LCP ⇒ negative

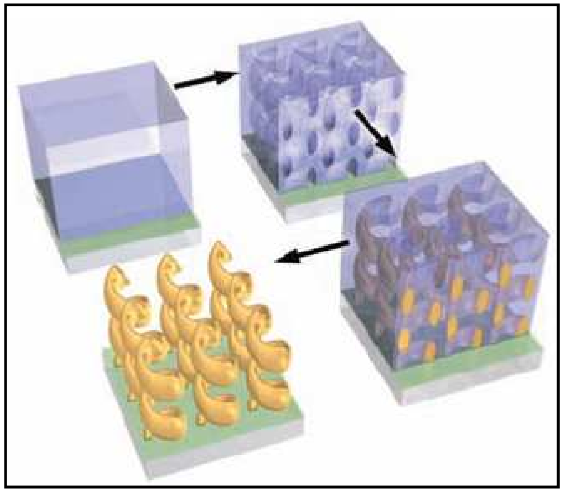
$$k_{-} < 0, \quad n_{-} < 0,$$

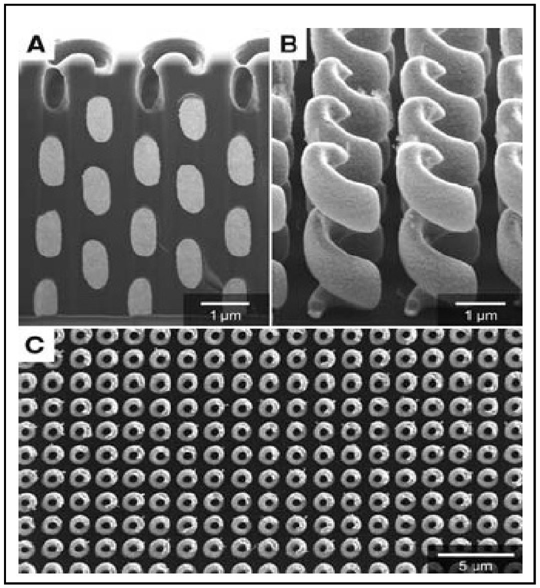


E. Plum, et al, Phys. Rev. (2009) / Zheludev’s group

3-D Chiral Metamaterials

[Fabrication process]



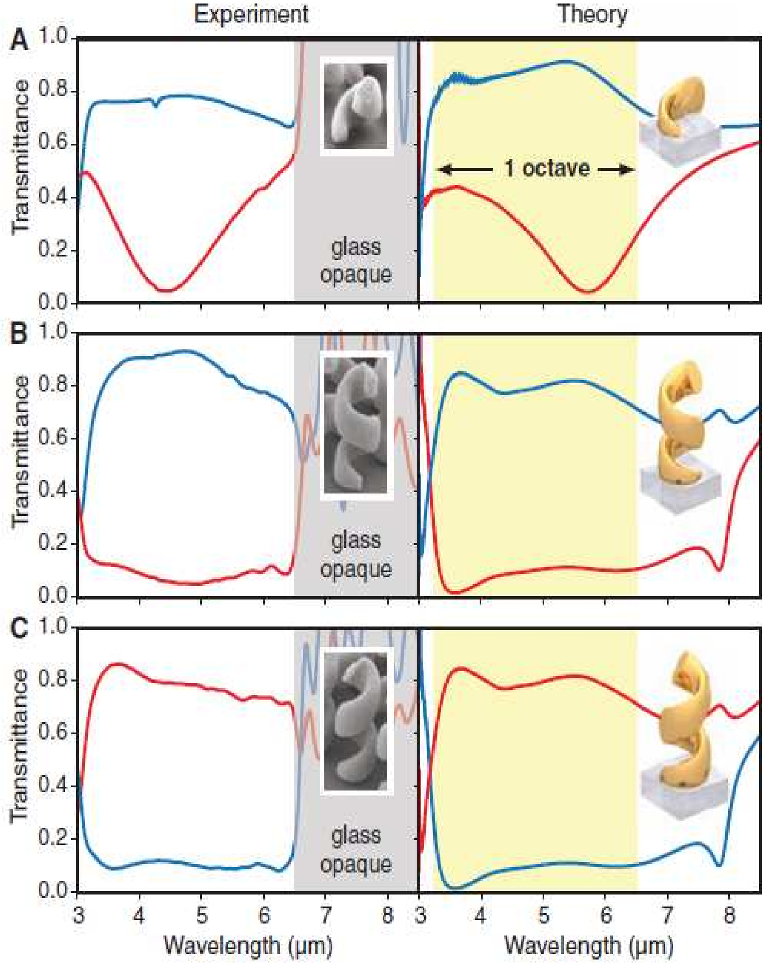


[SEM images]

A Cross view

B Till angle view

C Top view

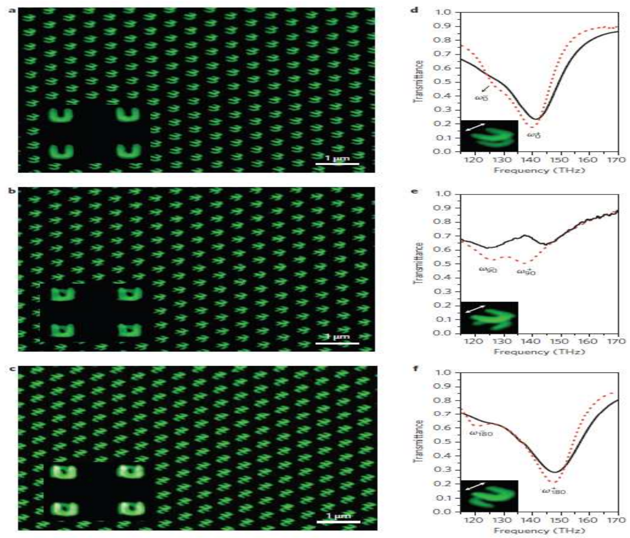


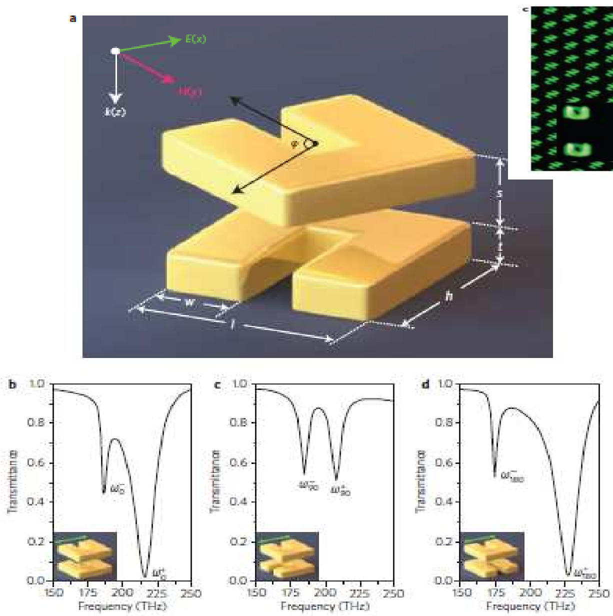
— LCP, — RCL

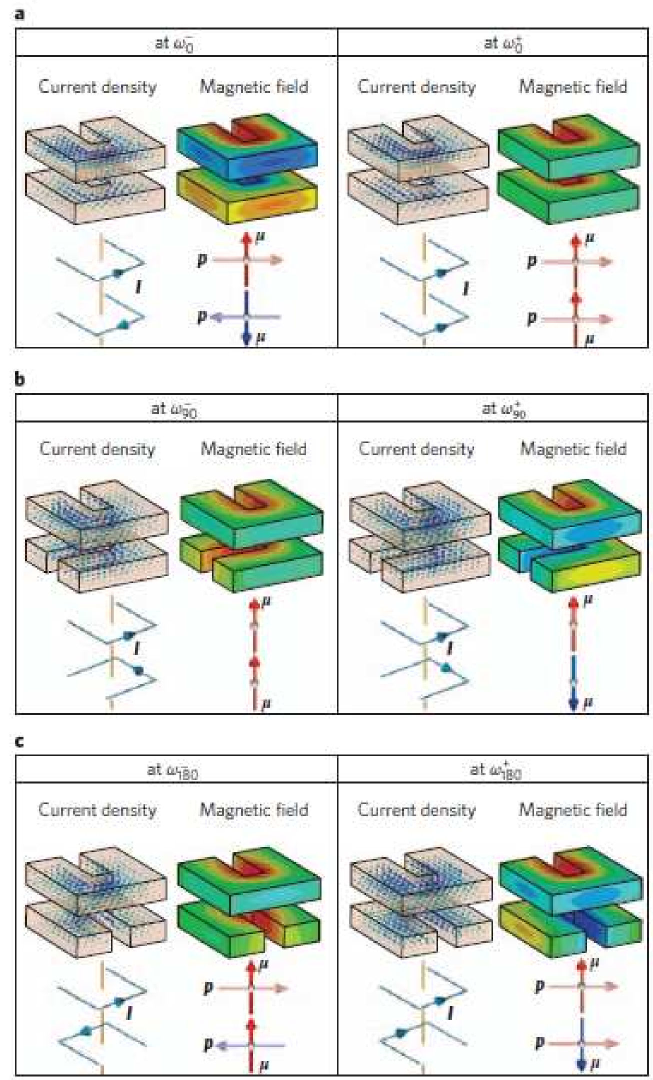
J. K. Gansel, et al, Science (2009) / Wegener group

Stereometamaterials

- Metamaterials with the same constituents but different spatial arrangements





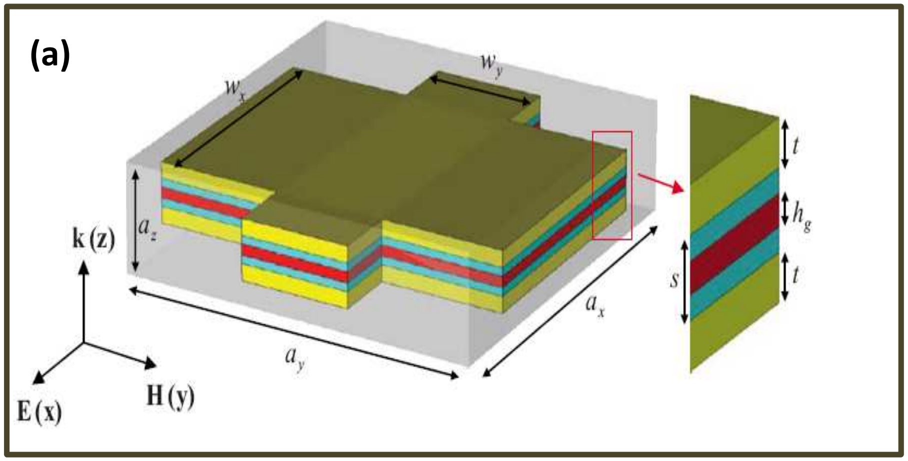


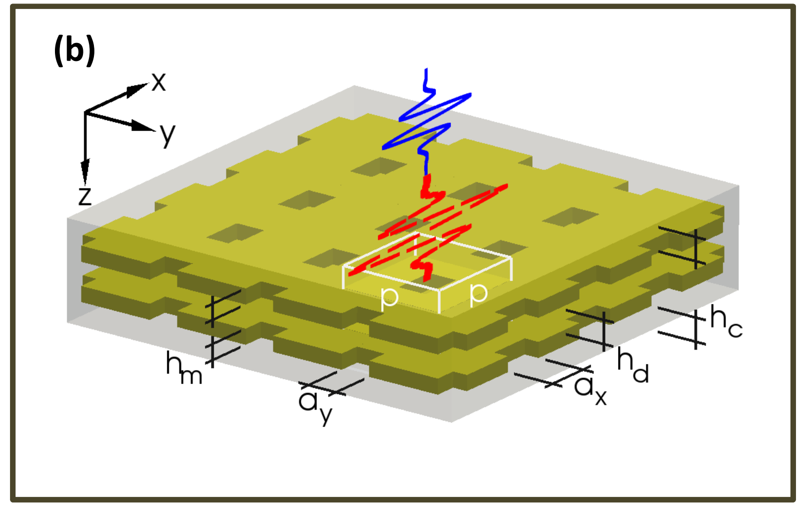
Numerical current and magnetic field distributions

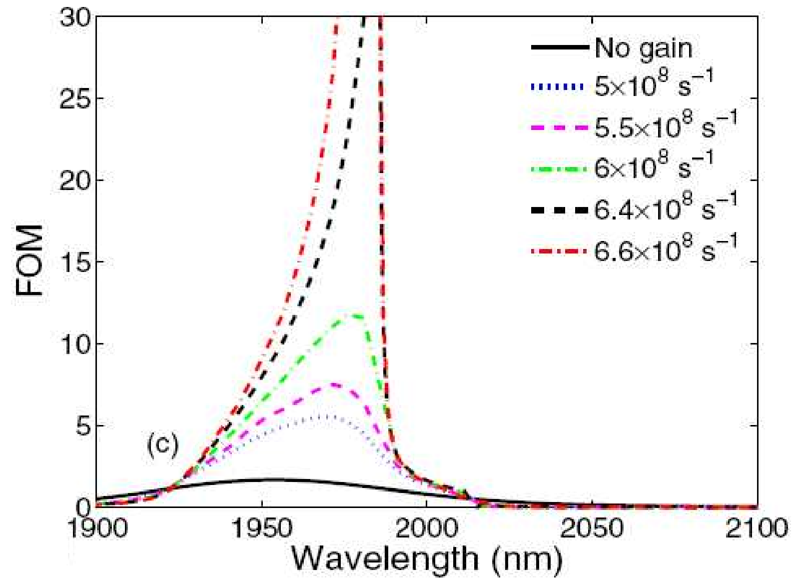
Na Liu, et al, Nature Photonics (2009) / H. Giessen's group

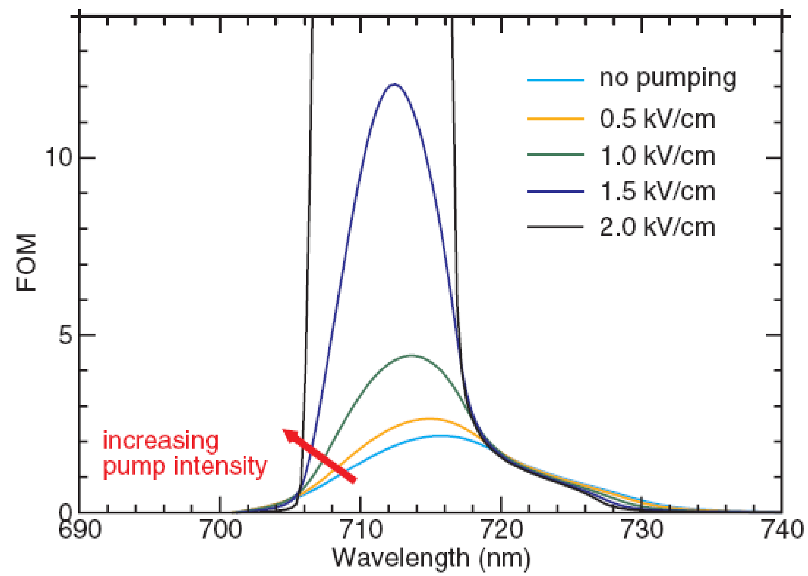
Active Negative-Index Metamaterials

Active Metamaterials (3D-FDTD Simulations)







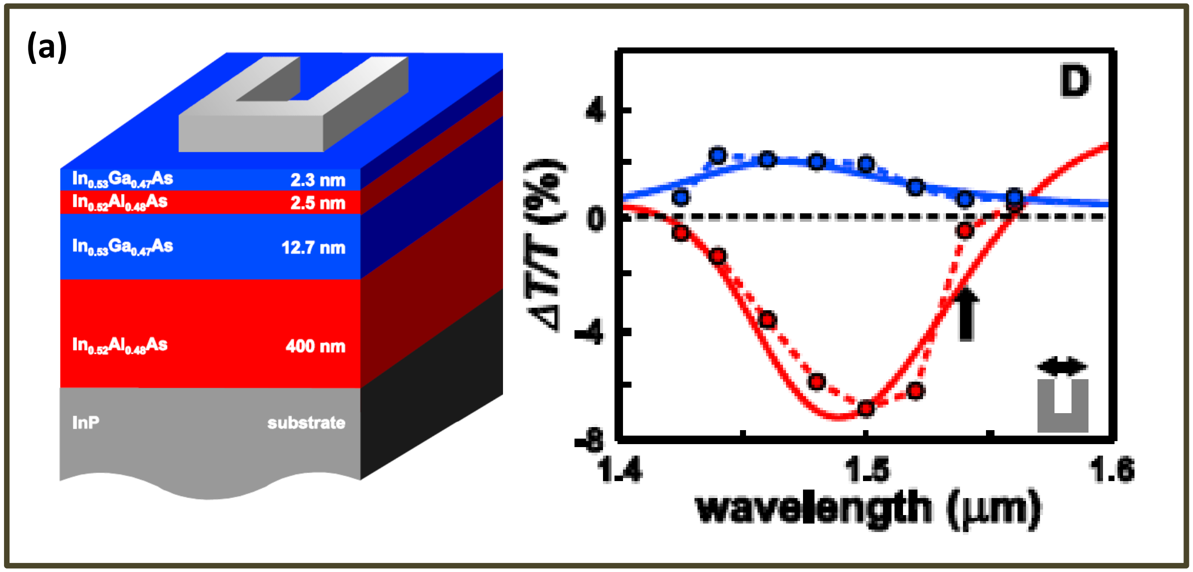


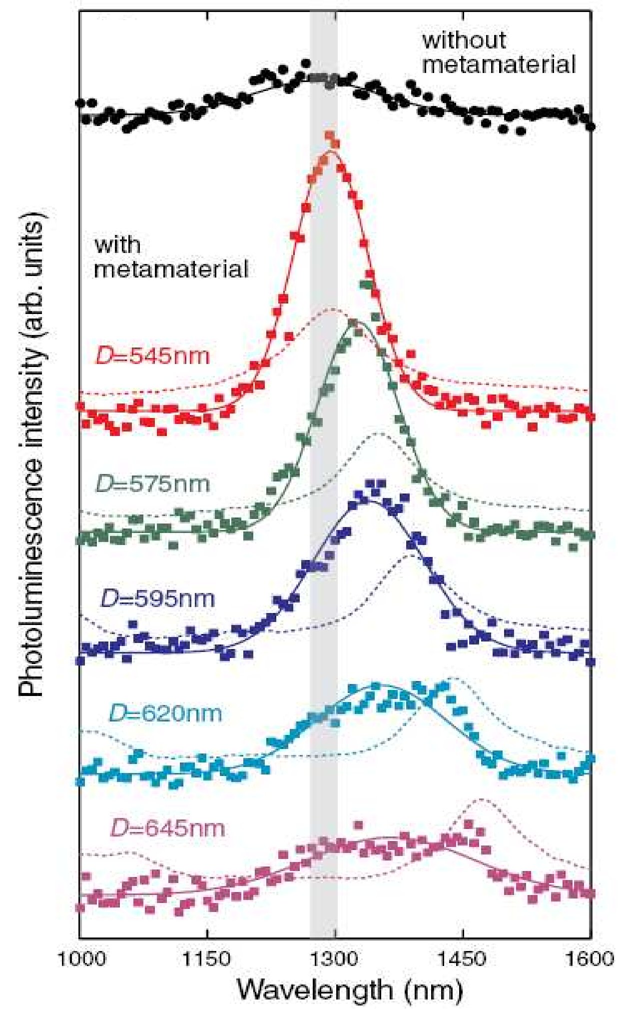
FOM =-n'/n"

(a) Soukoulis group, PRB. 82, 121102(R), (2010)
(b) Ortwin Hess group, PRL. 105 , 127401, (2010)

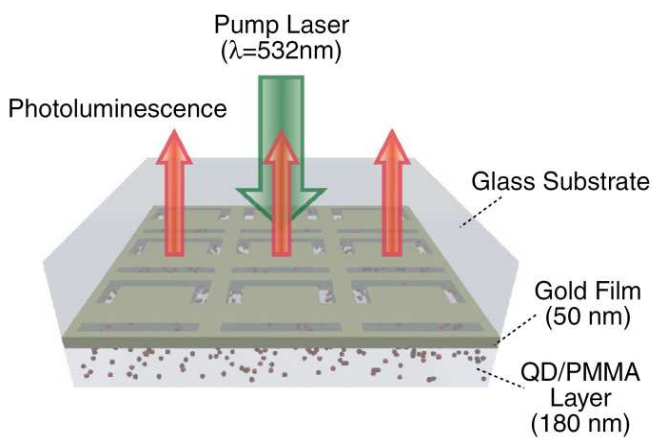
Active Metamaterials (Experiments)

- Arrays of Ag split-ring resonators coupled to InGaAs single-quantum-well gain





- Multifold Enhancement of Quantum Dot Luminescence in Plasmonic Metamaterials

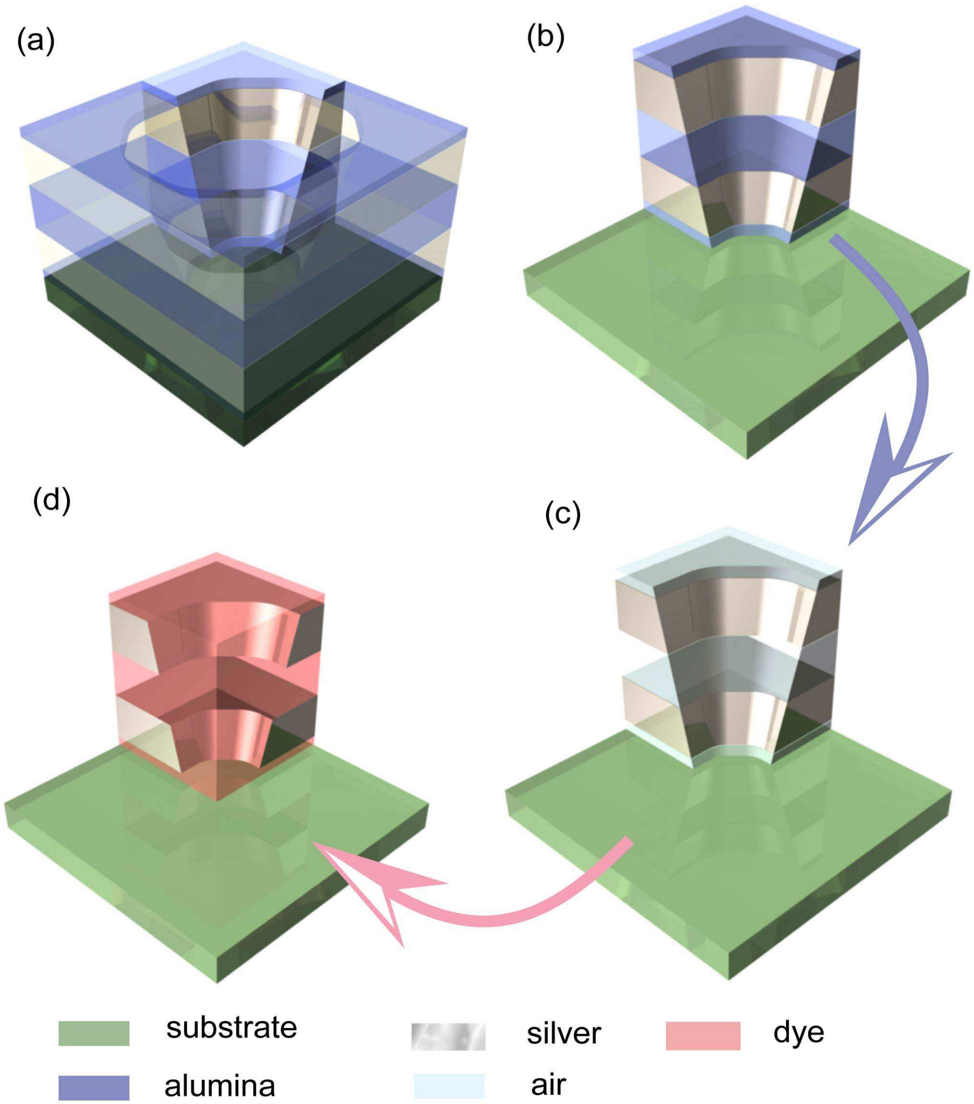


(a) Wegener group, OE. 18, 24140, (2010)
(b) Zheludev group, PRL. 105, 227403, (2010)

Structure and Fabrication Process

a) Unit cell of fishnet with 50 nm alumina as spacer

b) A quarter of fishnet with an alumina spacer

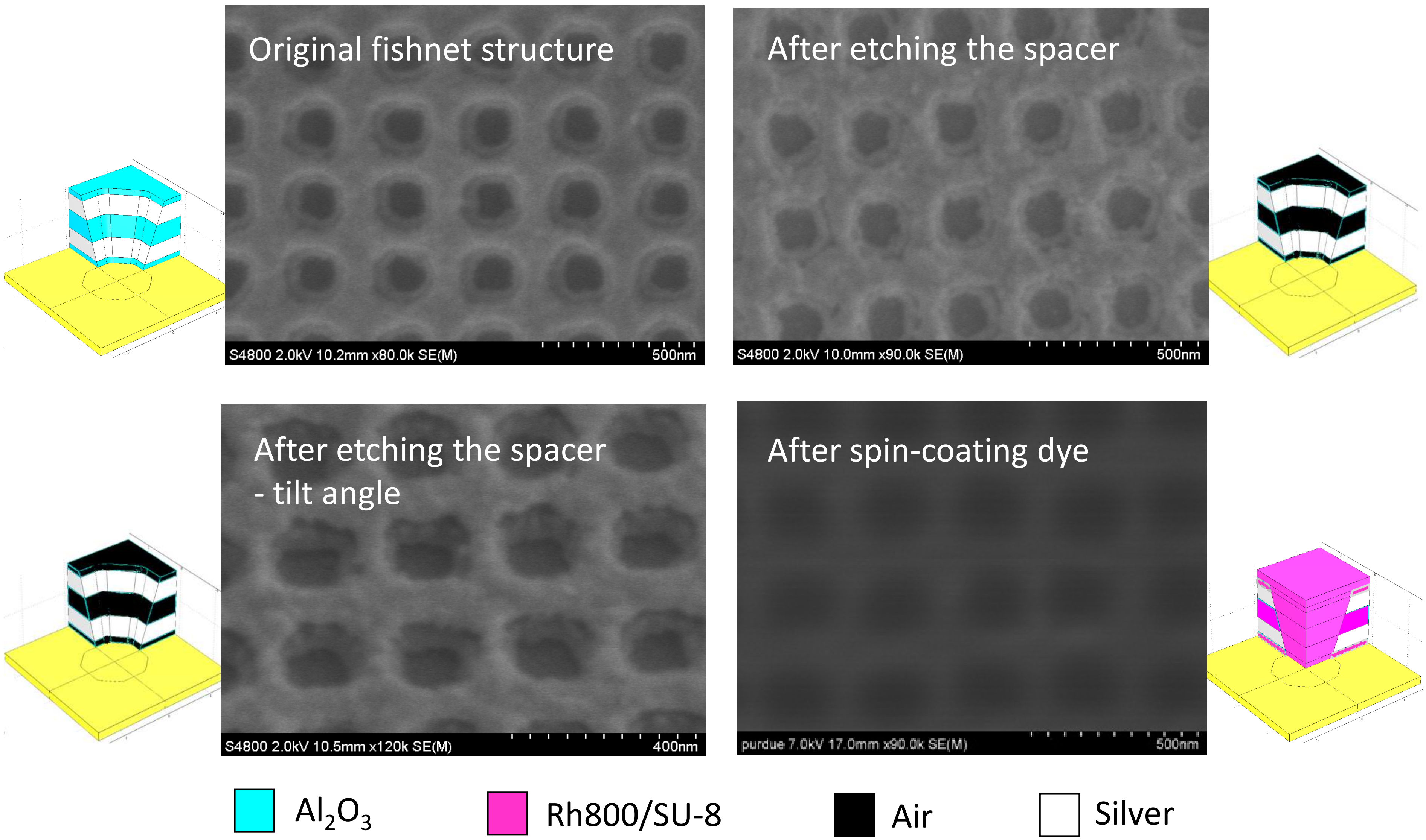


c) After etching alumina

d) After coating with Rh800/epoxy; structure has dye/epoxy in spacer region and atop

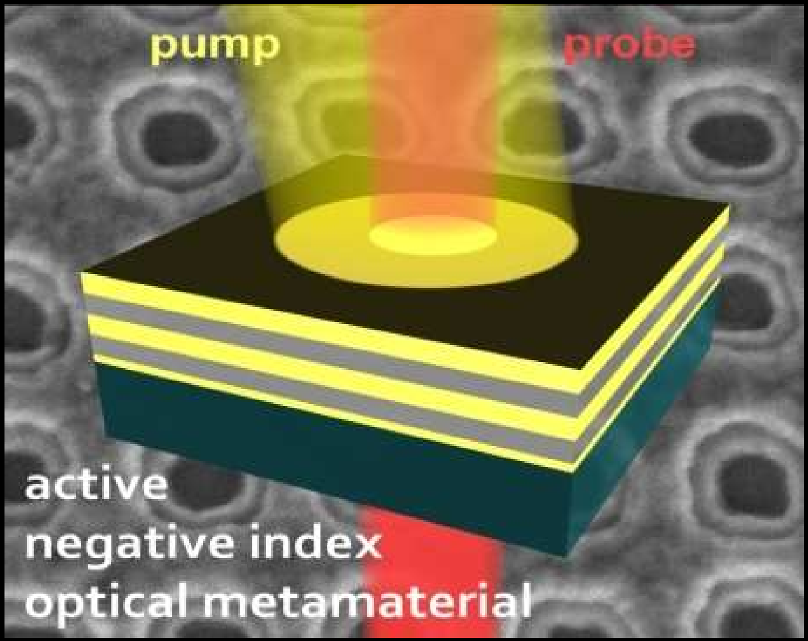
S. Xiao, et al, Nature (2010)

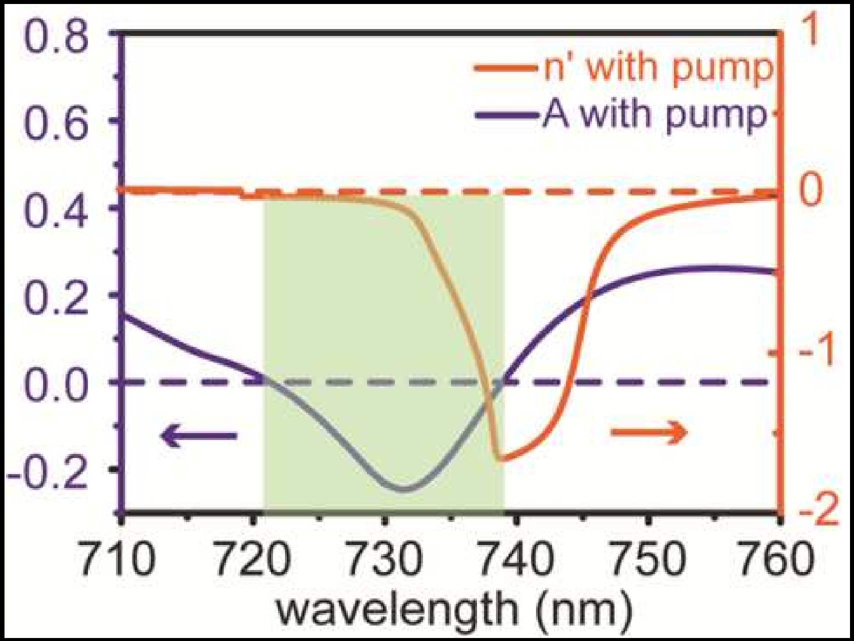
FESEM Images



Loss Free *NIM*

- **Optical NIM with Negative Absorptance**



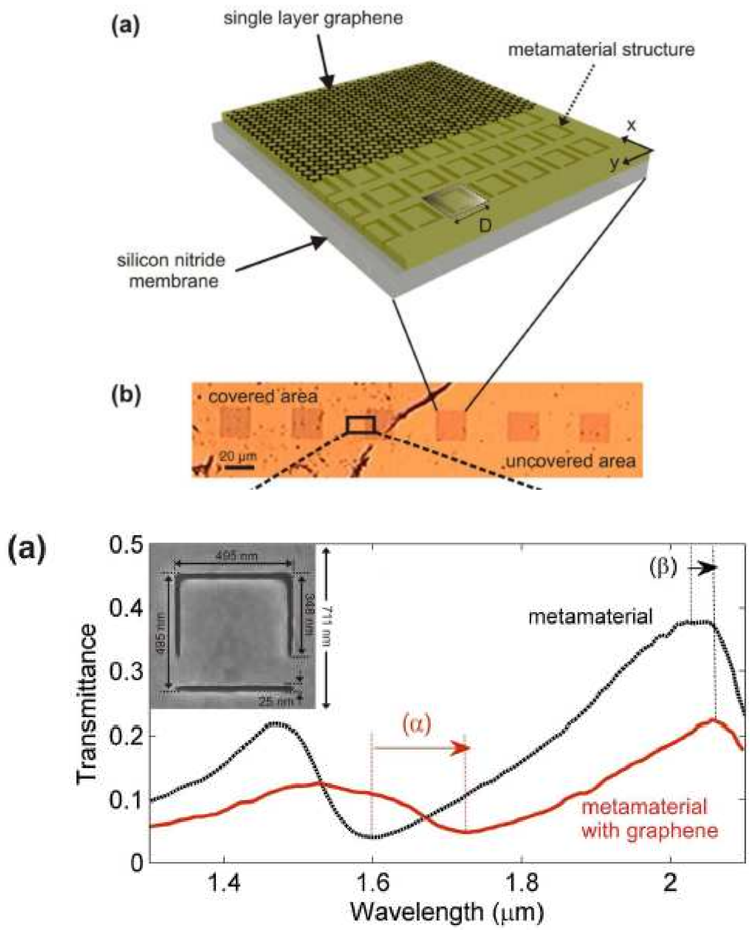


- wavelength range for negative n': 720 nm - 760 nm
- wavelength for negative absorptance: 720 nm - 740 nm

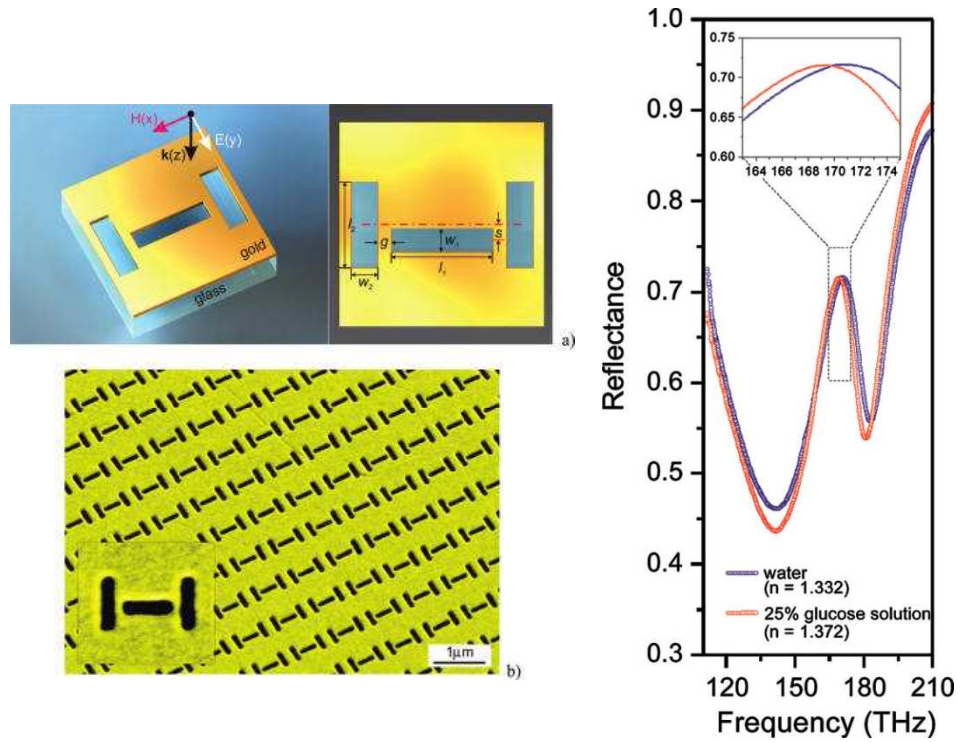
S. Xiao, et al, Nature (2010)

Metamaterials for Sensing

Metamaterials for Sensing



Graphene+metamaterial for sensing

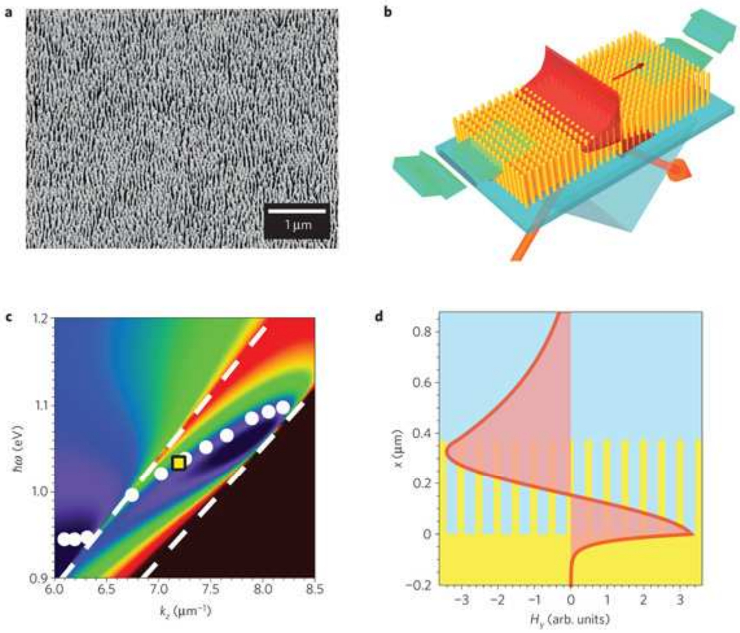


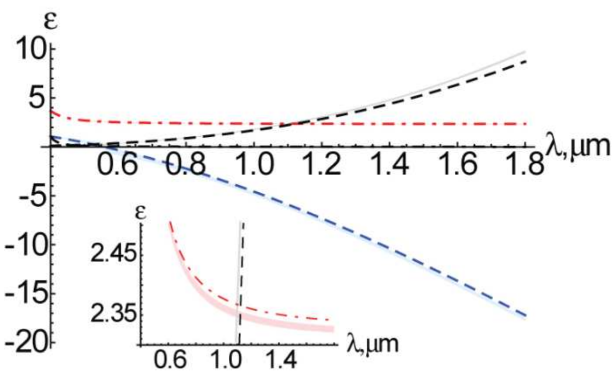
EIT metamaterial for sensing

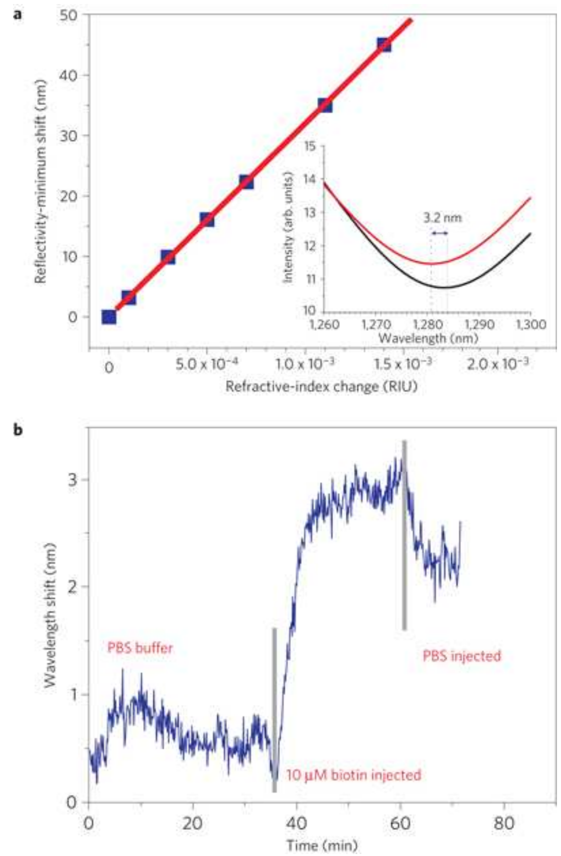
Papasimakis, et al, OE (2010) (Zheludev group)

N. Liu, et al, Nano. Lett.. (2010) (Gissnen group)

Hyperbolic Metamaterials for Biosensing







More than <u>100 times</u> sensitive than other SPR based sensors

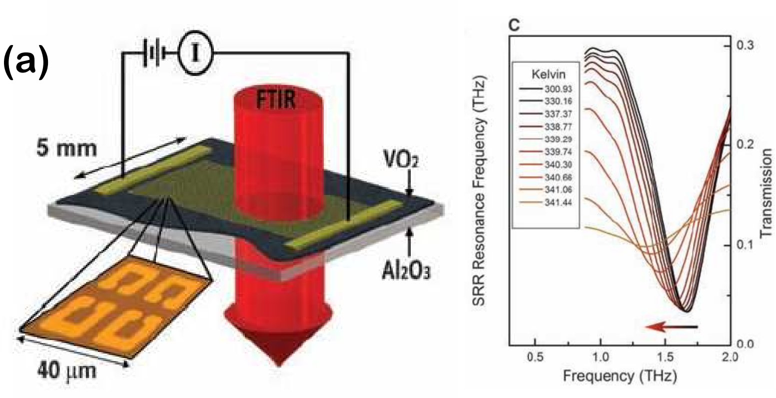
A. V. Kabashin, et al, Nature Mat. (2009) (Zayats group with Podolskiy)

Tunable, Ultrafast, & Nonlinear Metamaterials

Tunable MMs with Phase Change Components

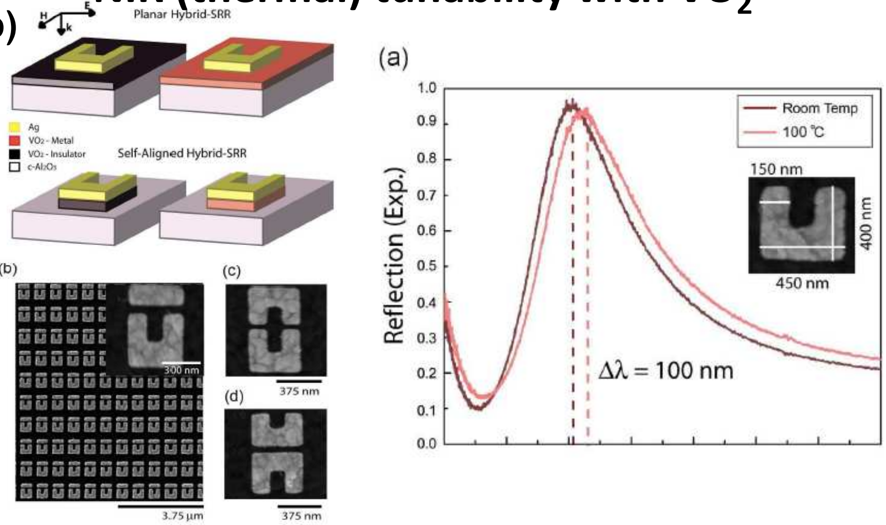
Electrically controllable memory with VO_2

(a)



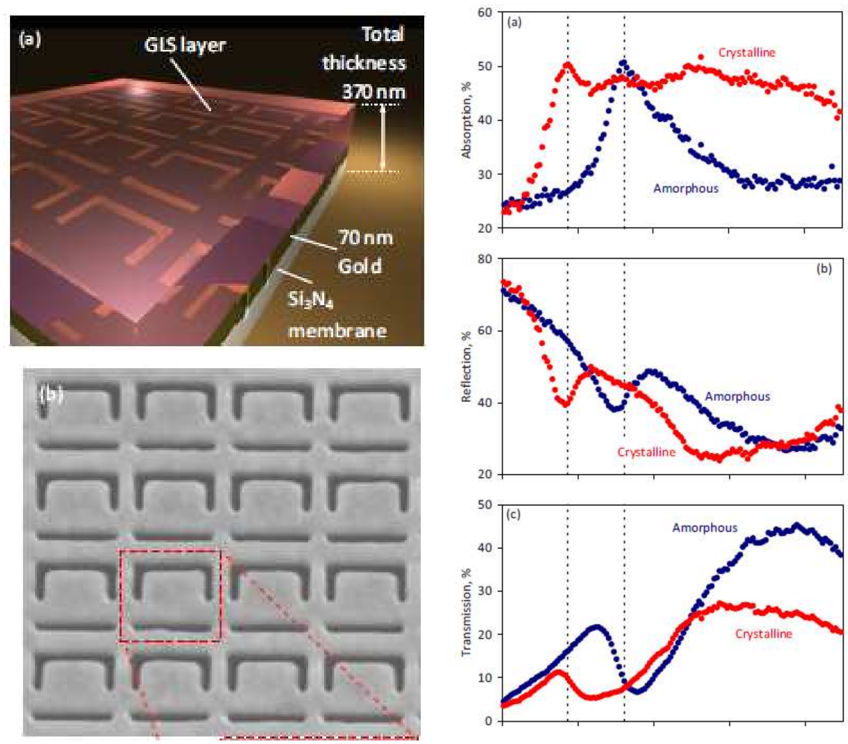
NIR (thermal) tunability with VO_2

(b)



(c)

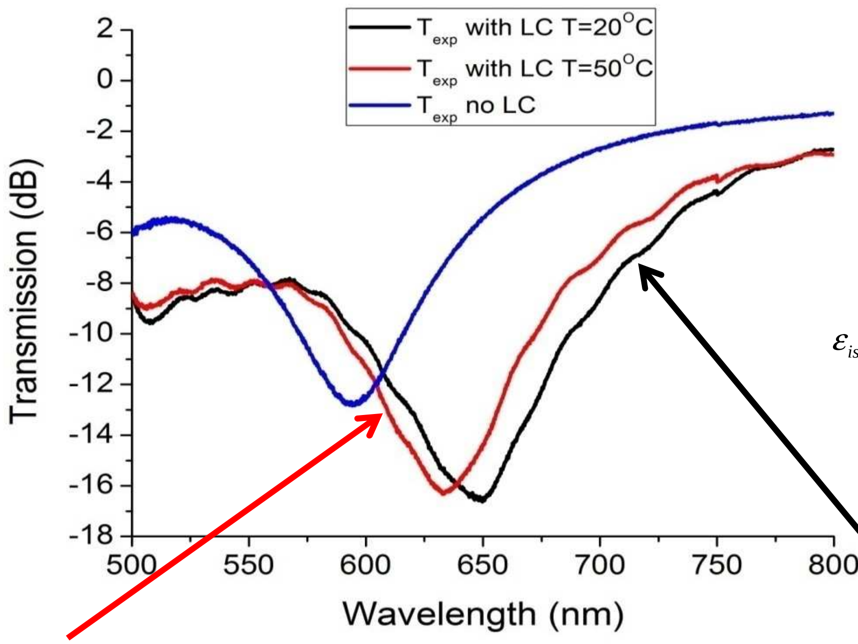
Tunability with ChG



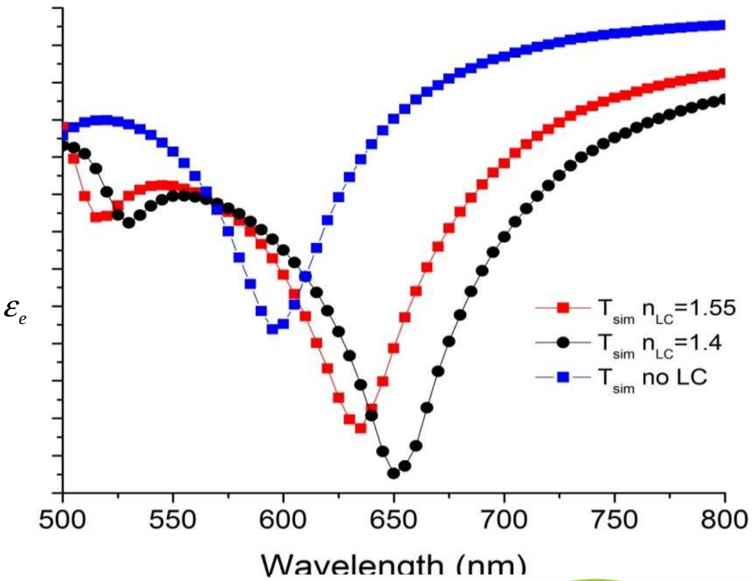
THz range – Willie Padilla

(a) T. Driscol, et al, Science, (2009) (Smith and Basov)
(b) M. J. Dicken, et al, OE (2009) (Atwater group)
(c) Sámson, et al, APL, (2010) (Zheludev group)

Tunable Metamaterials



$$\varepsilon_{iso} = \frac{2}{3}\varepsilon_o + \frac{1}{2}\varepsilon_e$$



(Isotropic)

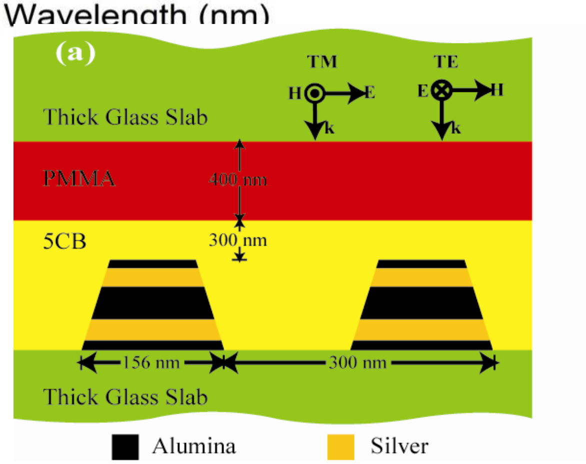
$$n_{iso}^2 = \frac{2}{3}n_o^2 + \frac{1}{2}n_e^2$$

Phase transition
Δn=0.17

$T>T_e$

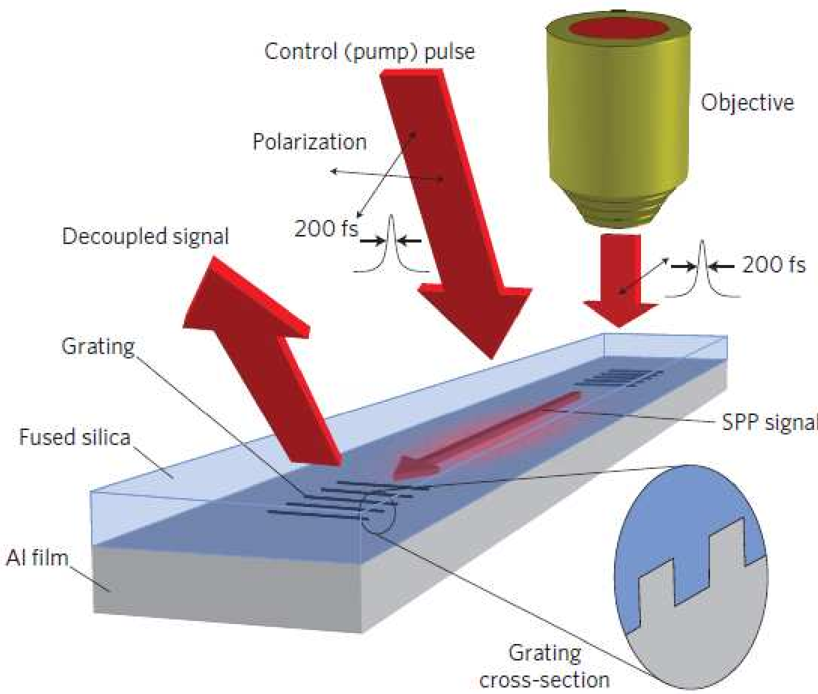
(Nematic)

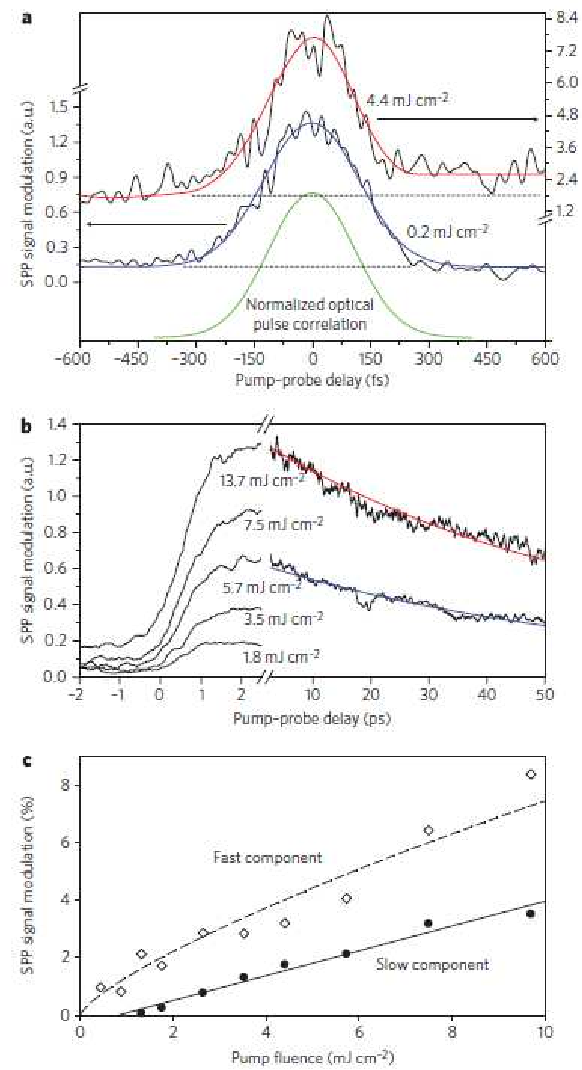
$$n_{eff} = n_e$$



S. Xiao et al, APL (2009)

Ultrafast Active Plasmonics





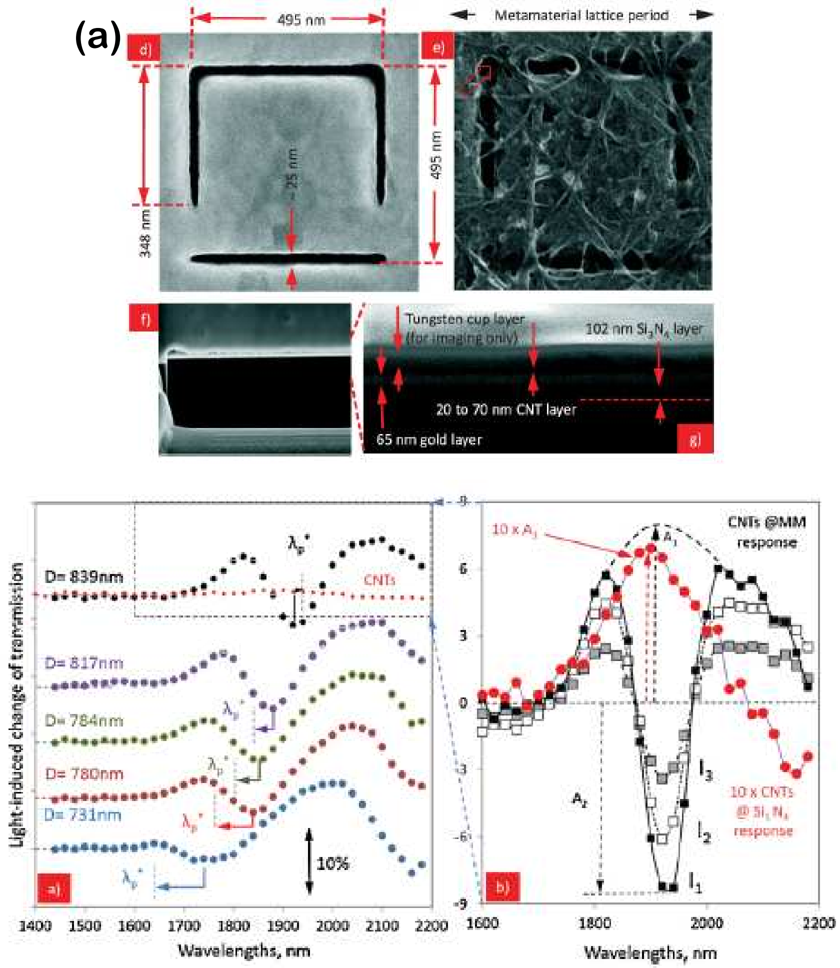
- SPP propagation influenced by optical pump
- Sub-ps control on SPPs

K. F. MacDonald, et al, Nature Photon. (2008) (Zheludev group and Stockman)

Nonlinear Materials + Metamaterials

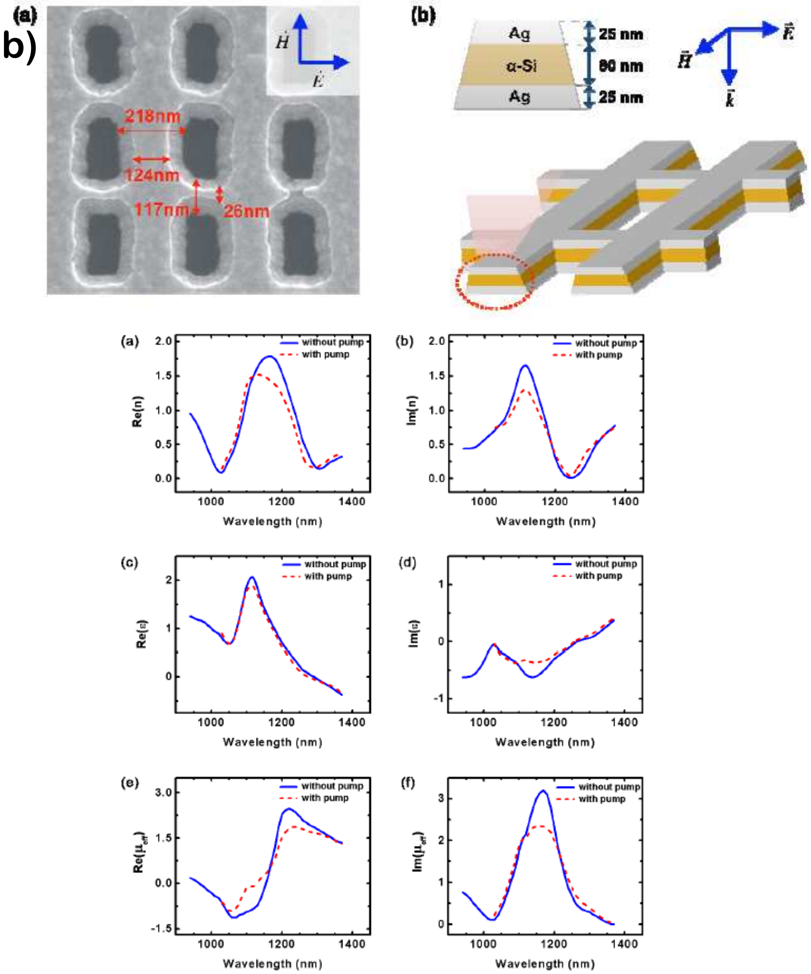
Carbon nanotubes + MM

(a)



α-Si+ MM

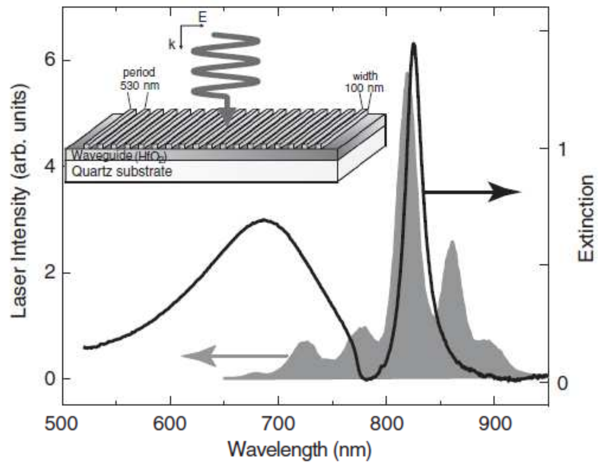
(b)

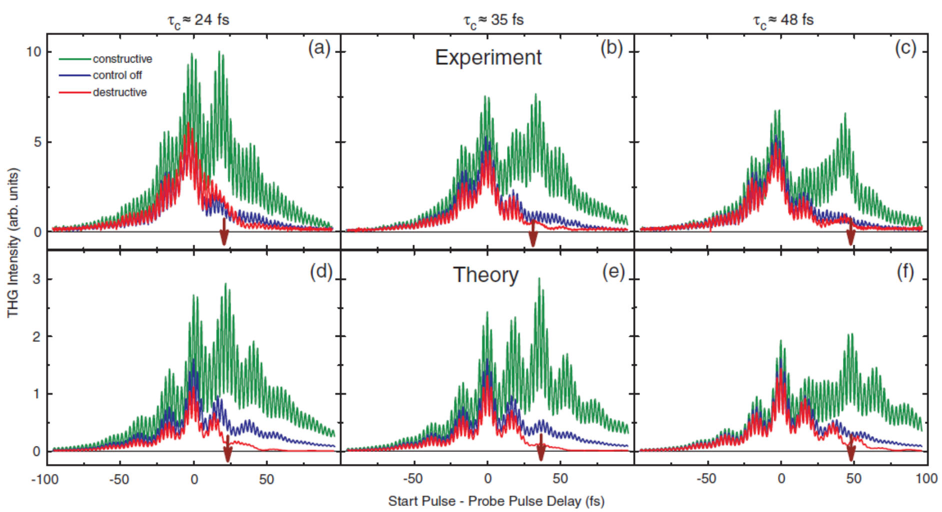


(a) Papasimakis, et al, PRL (2010) (Zheludev group)

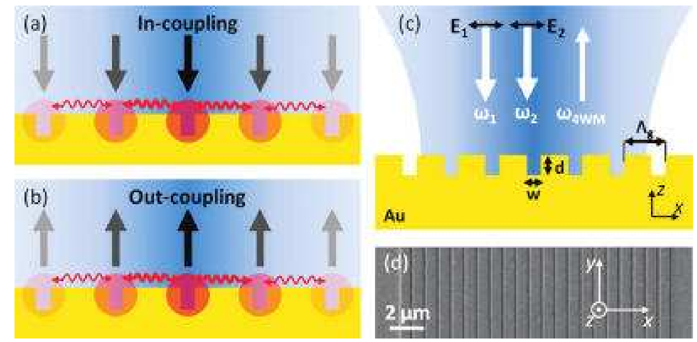
(b) D. J. Cho, et al, OE (2009) (Bratkovsky-Zhang-Shen groups)

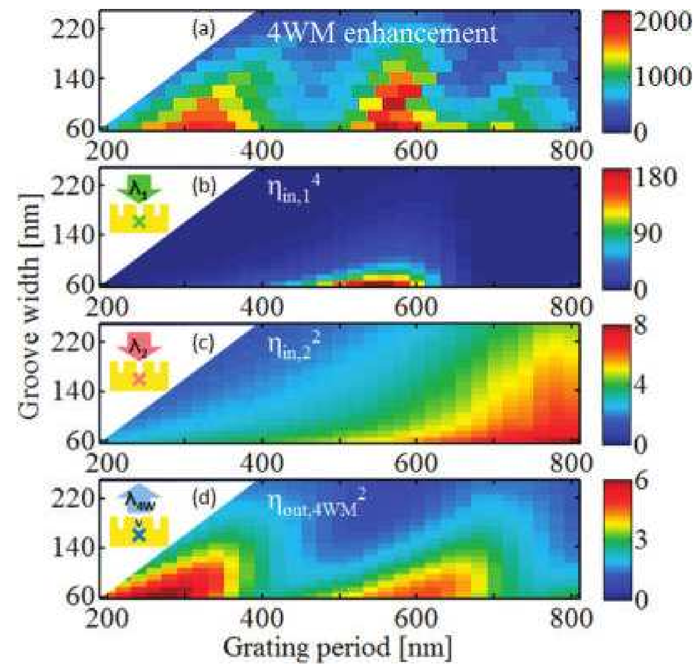
Four-Wave Mixing in Metamaterials





T. Utikal, et al, PRL (2010) (Giessen group)





P. Genevet, et. al., NL (2010) (Capasso group)

Quantum Optics with Metamaterials:
Engineering Photonic Density of States with Metamaterials

Z. Jacob, J.-Y. Kim, G. V. Naik,
A. Boltasseva, E. E. Narimanov and V. M. Shalaev

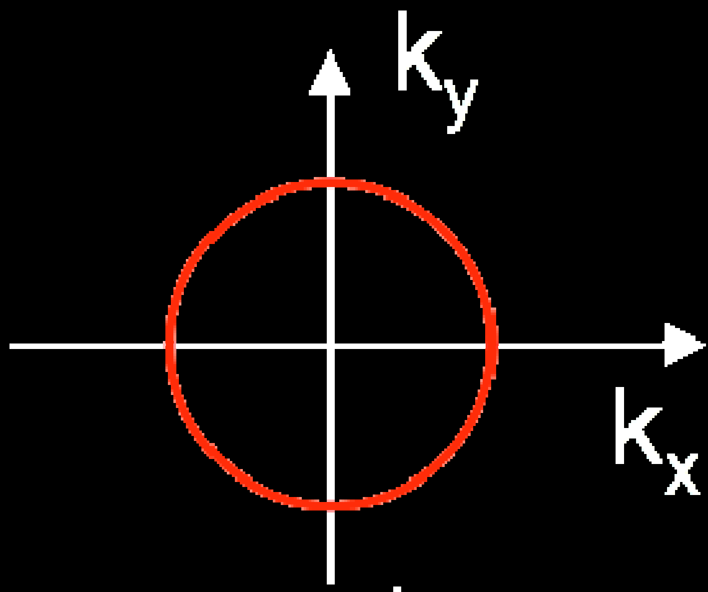
(Applied Physics B Centennial Volume July , 2010)

Other interesting work on Quantum Optics in MMs:
Nordlander, J.G. de Abajo, Leonhard, O'Brien, Capasso,…

Hyperbolic Dispersion

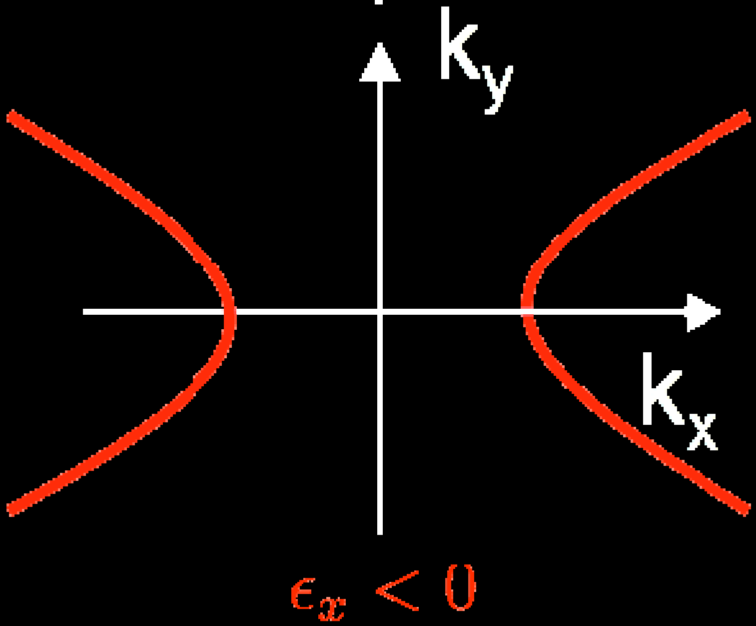
"Regular" dielectric

$$\frac{k_x^2}{\epsilon_y} + \frac{k_y^2}{\epsilon_x} = \frac{\omega^2}{c^2}$$



"Strongly Anisotropic" media

$$\frac{k_x^2}{\epsilon_y} + \frac{k_y^2}{\epsilon_x} = \frac{\omega^2}{c^2}$$

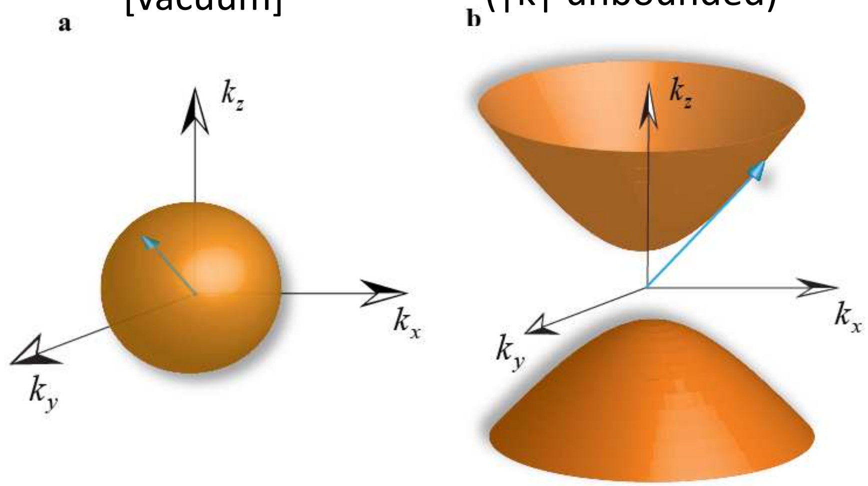


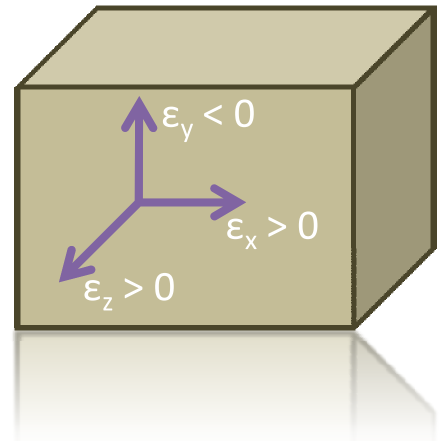
Special case of "Indefinite Media", D.Smith et al, 2003

PDOS in Hyperbolic Metamaterial?

[vacuum]

[metamaterial]
(|k| unbounded)

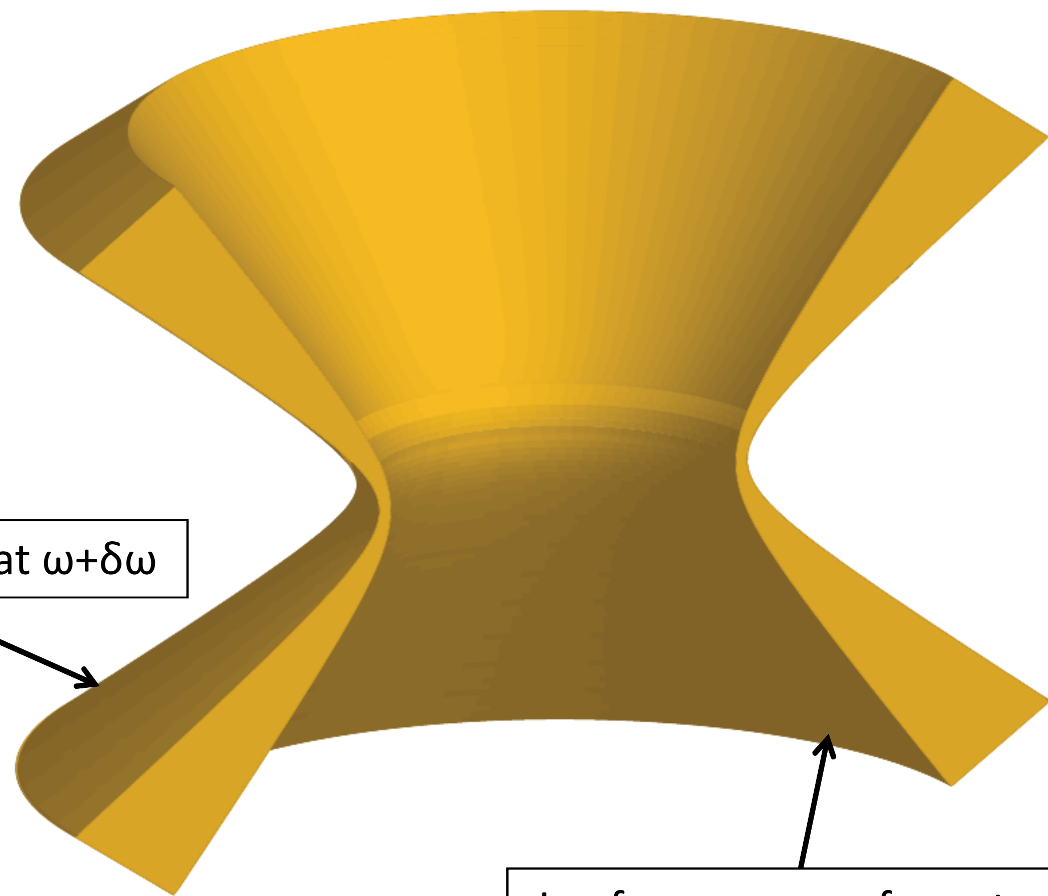




Singularity in density of states!!!!

- **Hyperbolic dispersion supports high spatial wavevectors compared to vacuum**
- **Large contribution to DOS from the "high k" states (think beyond imaging!)**

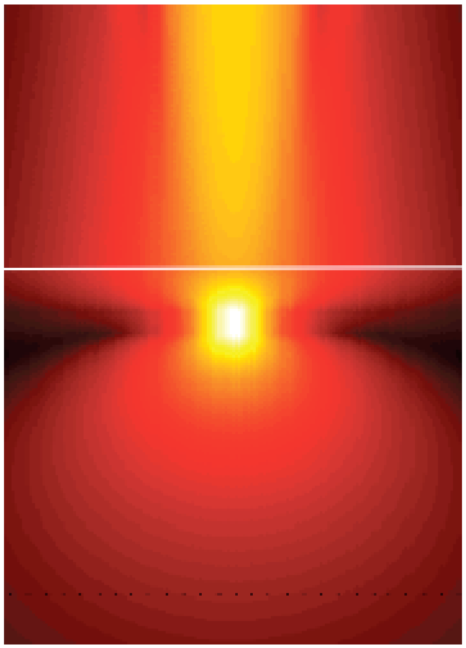
Photonic Density of States (PDOS)

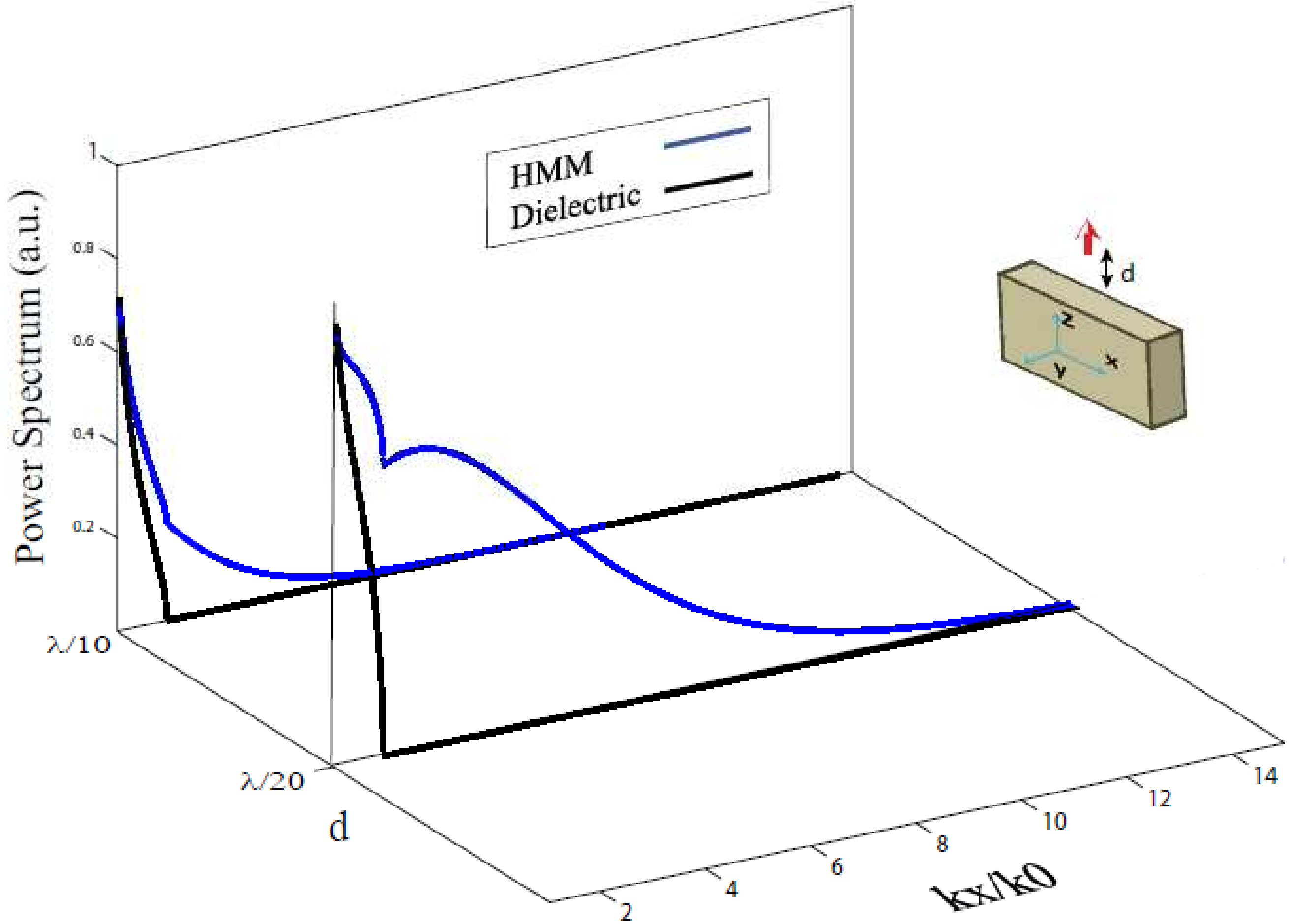


$$\mathrm{DOS} = \infty, \ \forall\omega \ !$$

Broadband Purcell effect: Radiative decay engineering with metamaterials
- Z. Jaco<u>b</u>, I. Smolyaninov, E. Narimanov (*on Arxiv*)

Emission Power Spectrum





Calculation Methods: $\Gamma = \dfrac{P}{\hbar\omega}$: Ford and Weber (1984)

QED: Hughes group (2009)

Experiment: Z. Jacob ,et al, Appl. Phys. B (2010)

Transformation Optics:
Optical Cloaking,
Trapped Rainbow,
& Maxwell Fish-eye and Eaton Lenses

V. M. Shalaev, Transforming Light, Science, Oct. 17, 2008

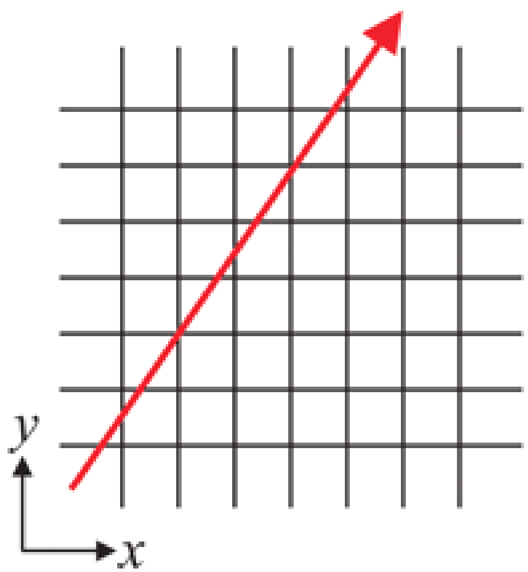
Designing Space for Light with Transformation Optics

Fermat:

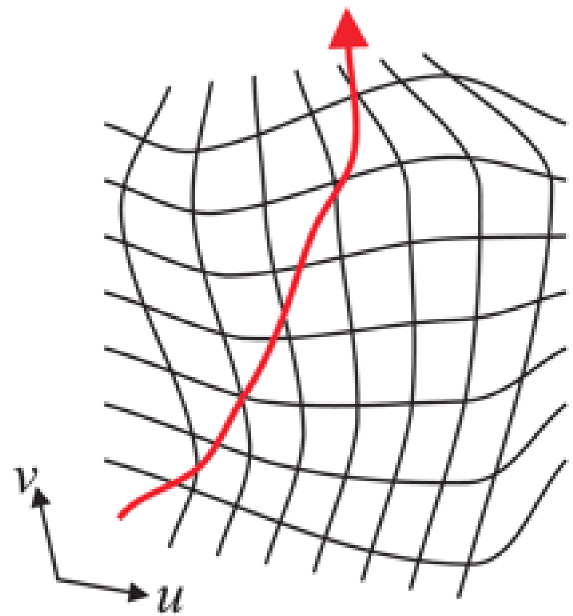
$$\delta\int n\,dl = 0$$

$$n = \sqrt{\varepsilon(r)\mu(r)}$$

"curving" optical space



Straight field line
in Cartesian coordinate

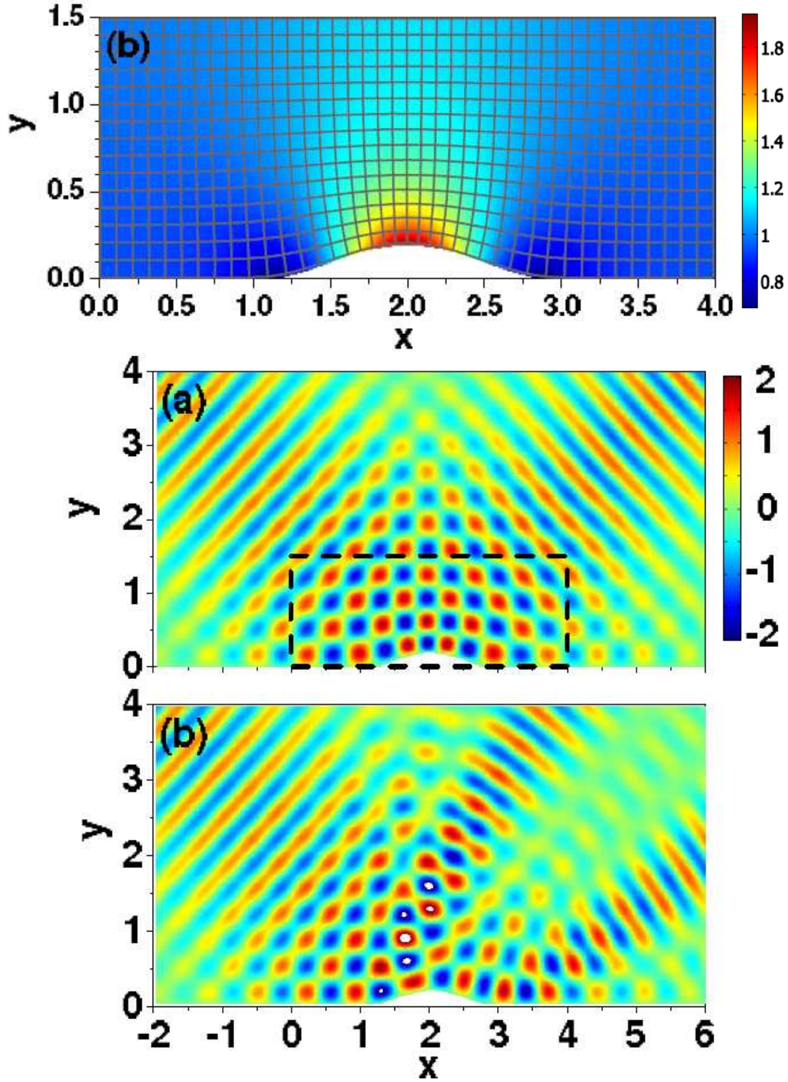


Distorted field line
in distorted coordinate

- Spatial profile of ε & μ tensors determines the distortion of coordinates
- Seeking for profile of ε & μ to make light avoid particular region in space — optical cloaking

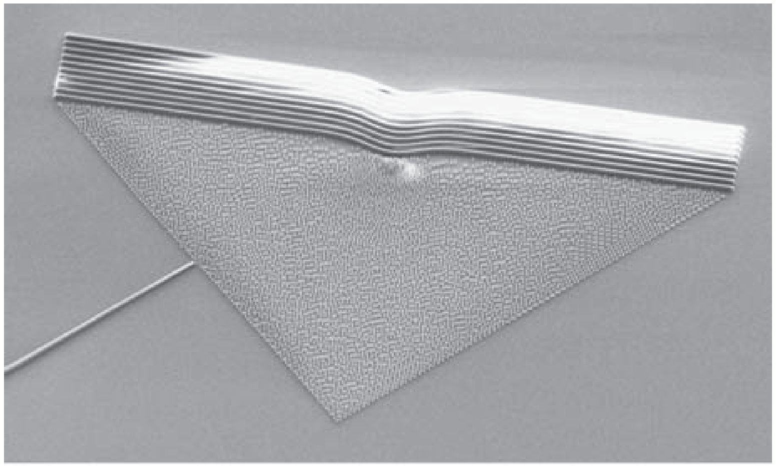
Pendry et al., Science, 2006
Leonhard, Science, 2006
Greenleaf et al (2003)
L. S. Dolin, Izv. VUZ, 1961

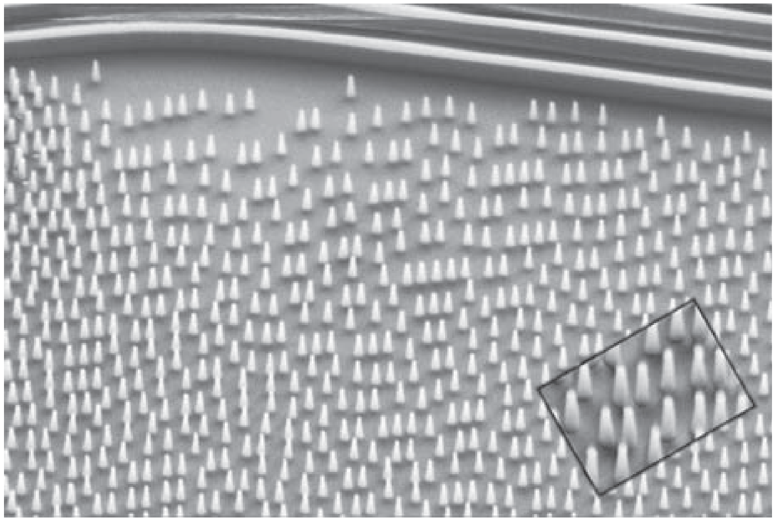
Invisible Carpet (ground-plane cloak)



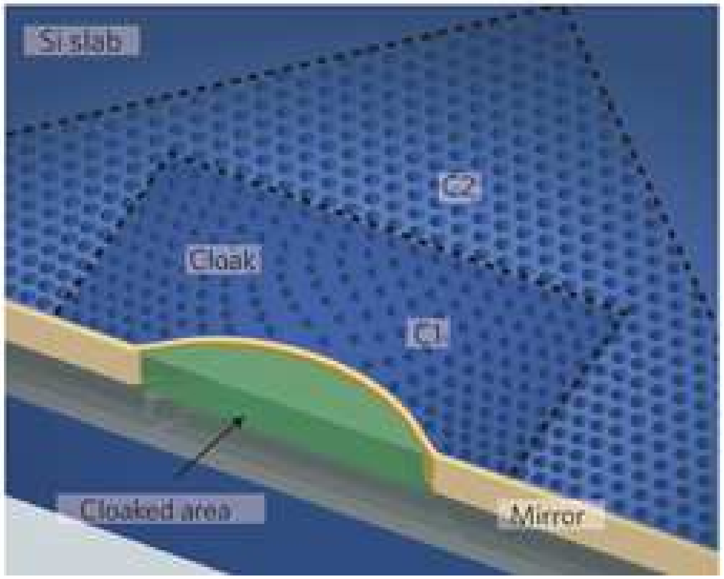
picture from discovery.com

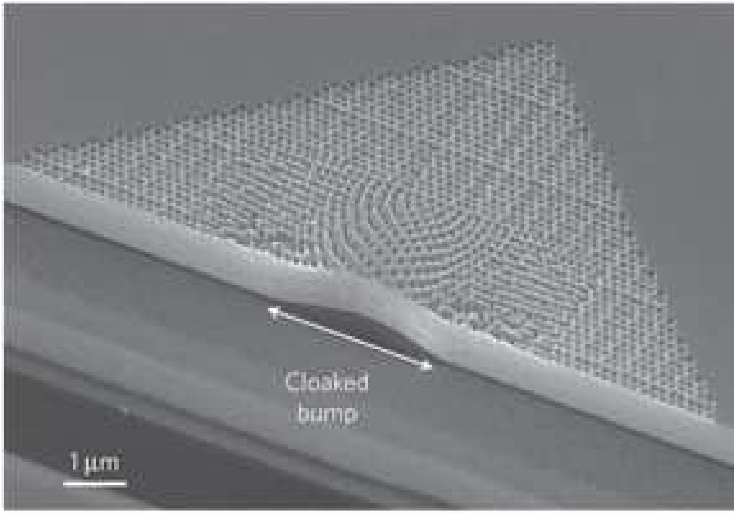
J. Li and J. B. Pendry , Phys. Rev. Lett., 2008



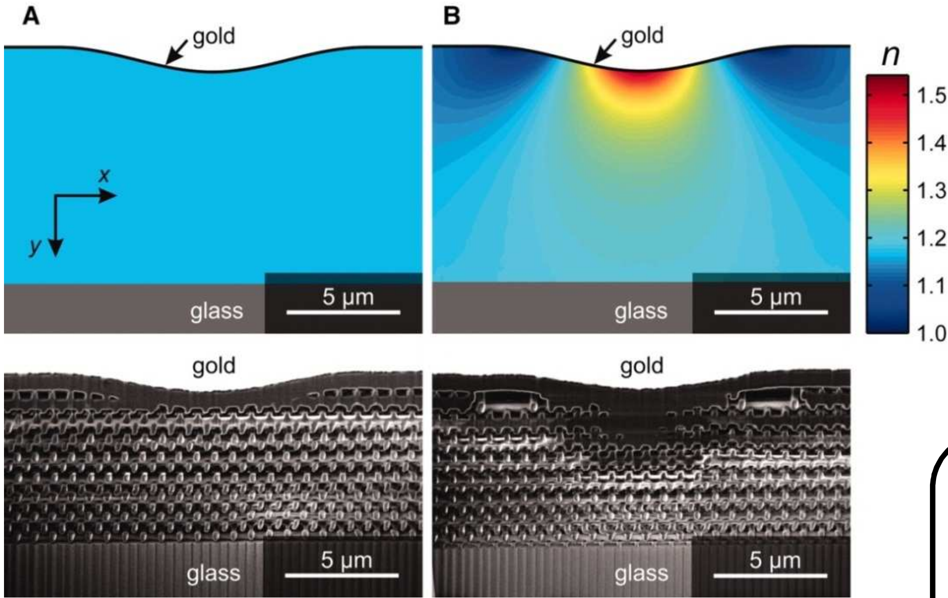


L. H. Gabrielli, *et al.*, *Nat. Photonics* **3**, p.461, Aug 2009.
(M. Lipson group)

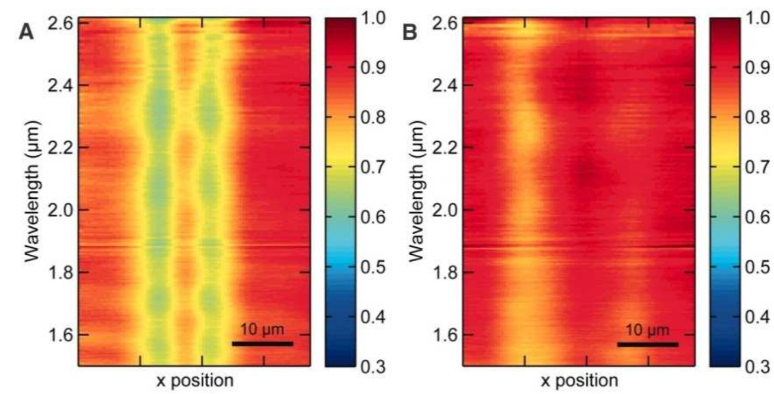




J. Valentine, *et al.*, *Nat. Mater.* **8**, p.568, Jul 2009.
(X. Zhang group)



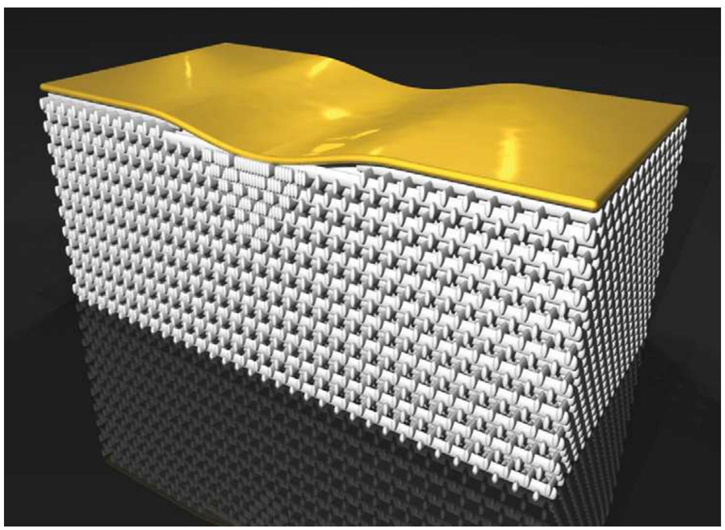
Target refractive index (*n*) distributions (top) and oblique-view electron micrographs of fabricated structures after FIB milling (bottom). (**A**) A bump without a cloak. (**B**) A bump with a cloak.



Optical characterization of the 3D structures with **unpolarized** light in bright-field mode.

(A) A bump without a cloak. The bump is immediately visible.

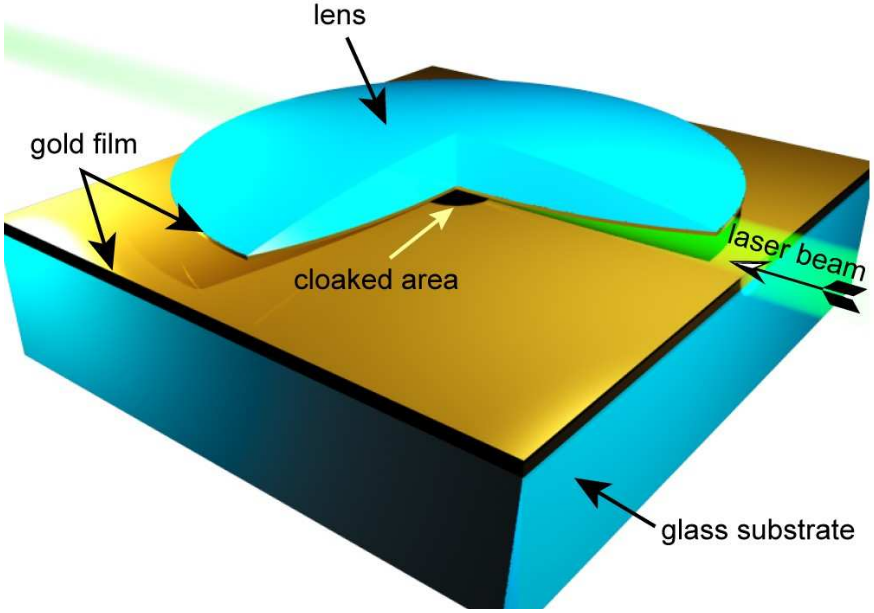
(B) (**B**) Result for a bump with a cloak that approaches the expectation for an ideal cloak (constant intensity).



Blueprint of the 3D carpet-cloak structure

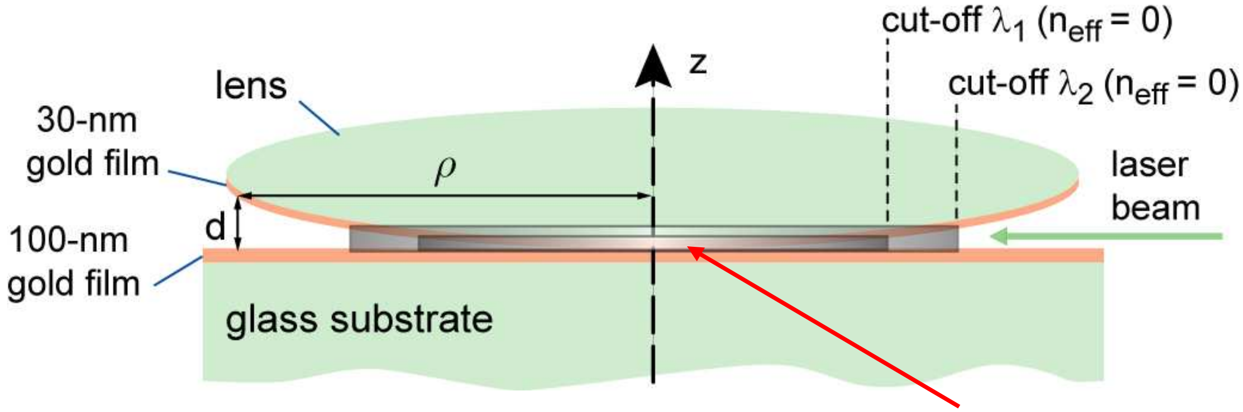
T. Ergin, et al., Science 328, p. 337, Apr 16 2010. (M. Wegener group)

Broadband Optical Cloak in Tapered Waveguide



$$\left(\omega/c\right)^2 = k_\rho^2 + \left(m/\rho\right)^2 + \left[\pi l/d(\rho)\right]^2$$
$$= k_\rho^2 + k_\phi^2(\rho - b)^{-2}$$

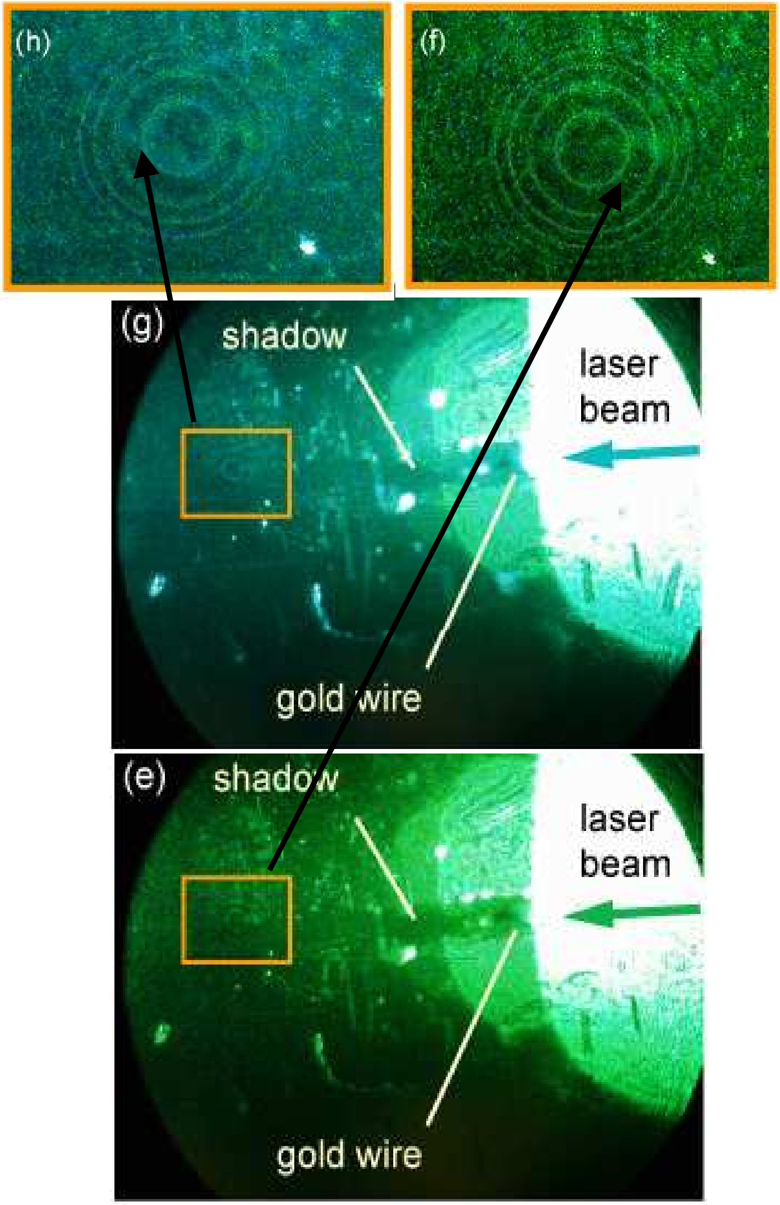
Z. Jacob and E. E. Narimanov, *OE*, 2008.



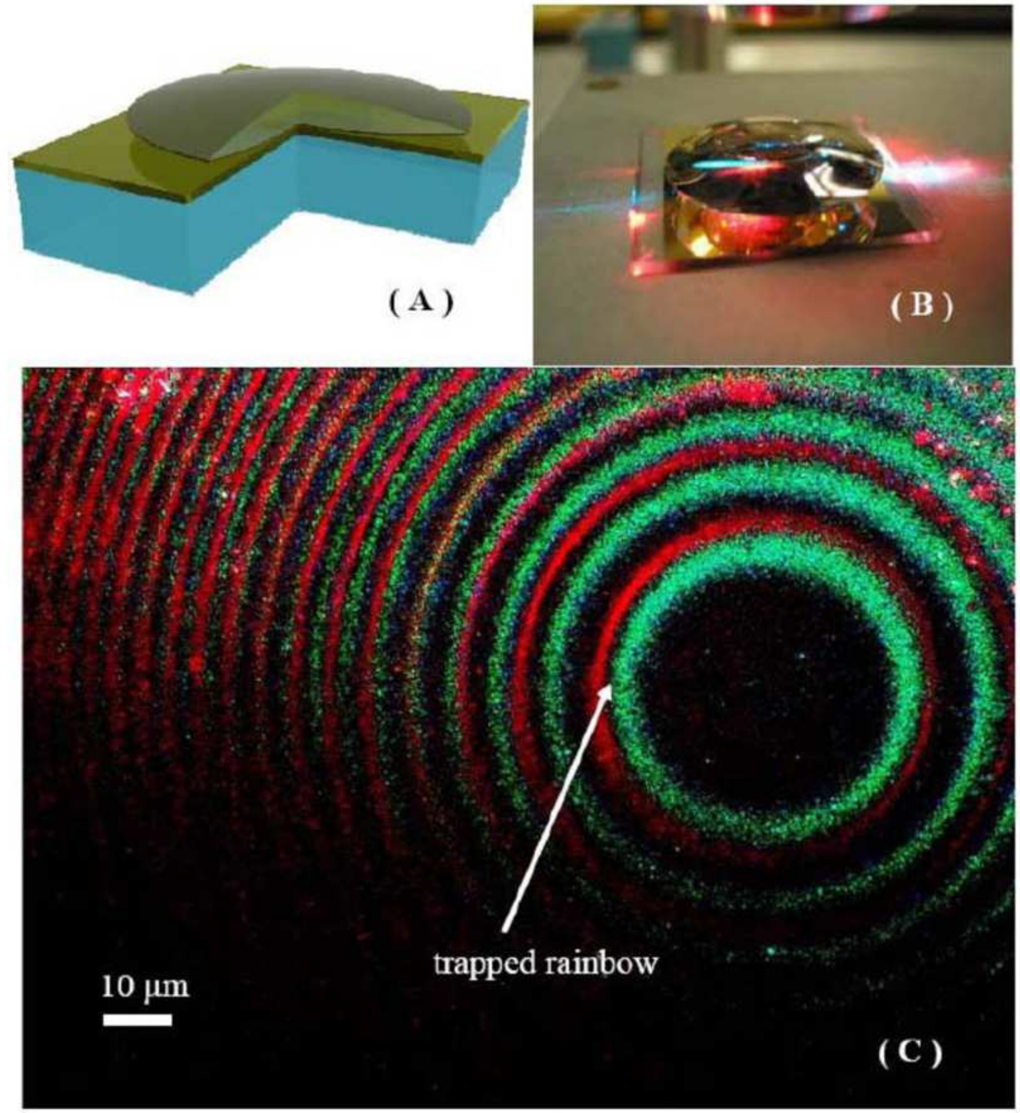
Cloaked area

I. I. Smolyaninov, et al, *PRL*, 2009.

Optical Cloak & Trapped Rainbow

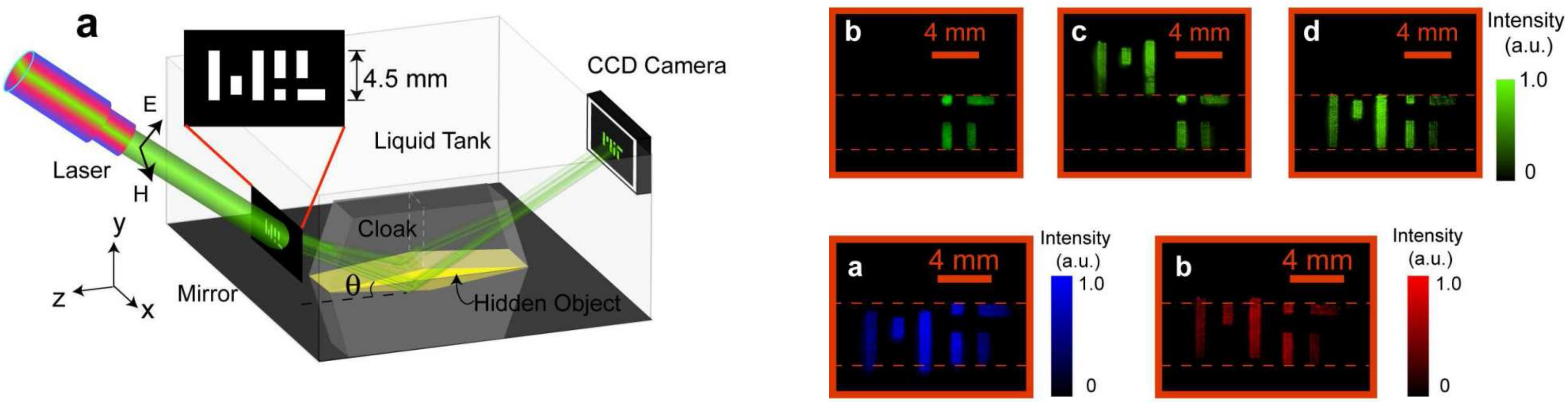


I. I. Smolyaninov, et al, *PRL,* 2009.

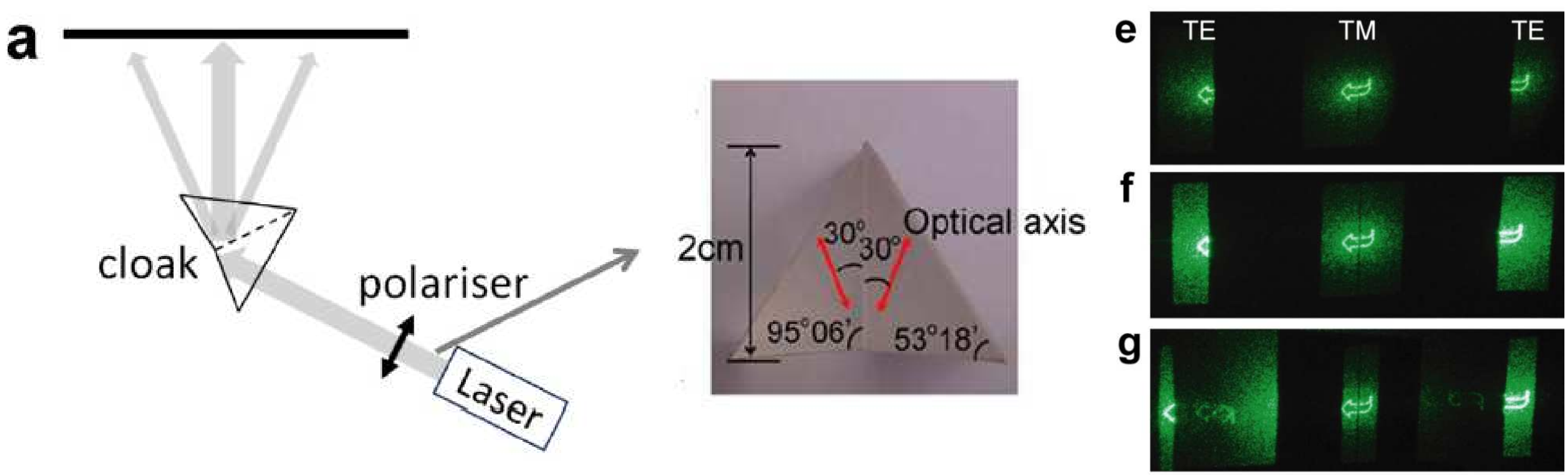


V. N. Smolyaninova, et al, *APL*, May 24 2010.

Macroscopic Cloaking Based on Calcite

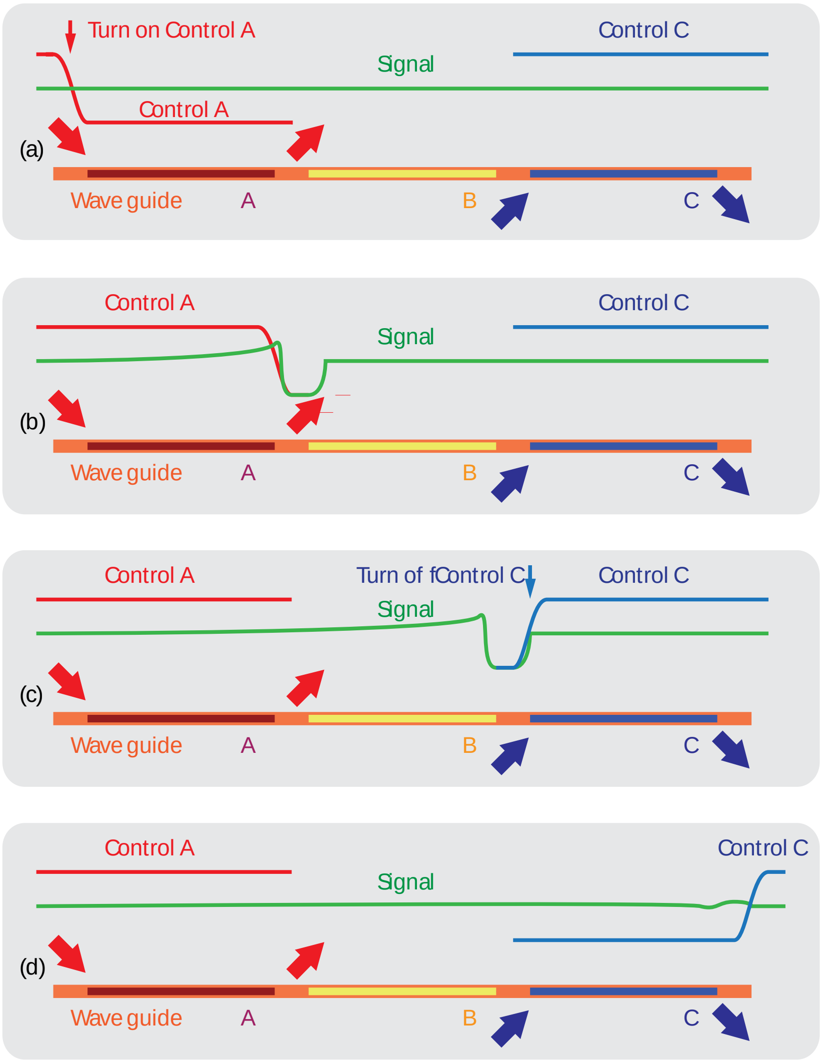


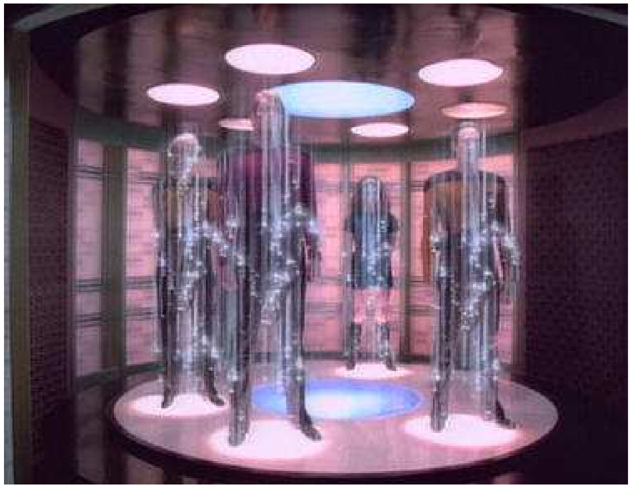
B. Zhang, et al, arXiv:1012.2238 (Singapore-MIT)



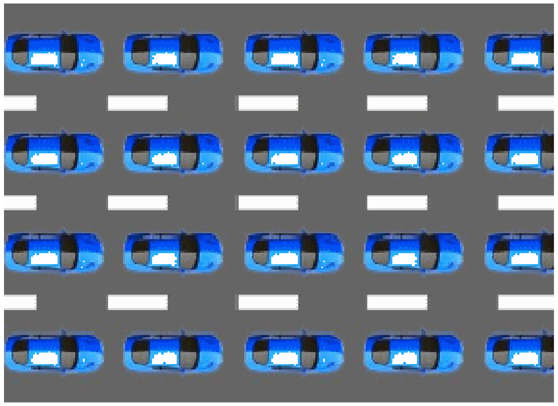
X. Chen, et al, arXiv:1012.2783 (Brimingham, DTU, Imperial)

Space-time Cloak – History Editor



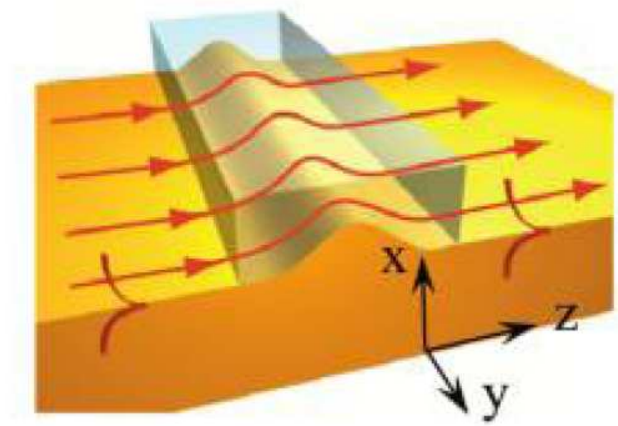


Star Trek transporter

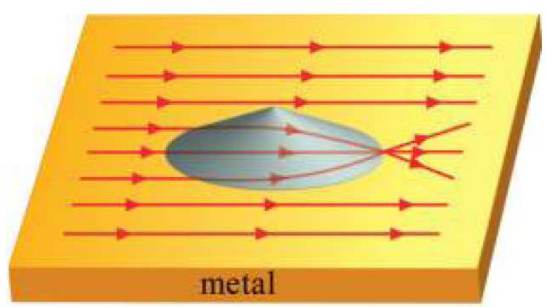


M. W. McCall and et al., *Journal of Optics*, 2011.

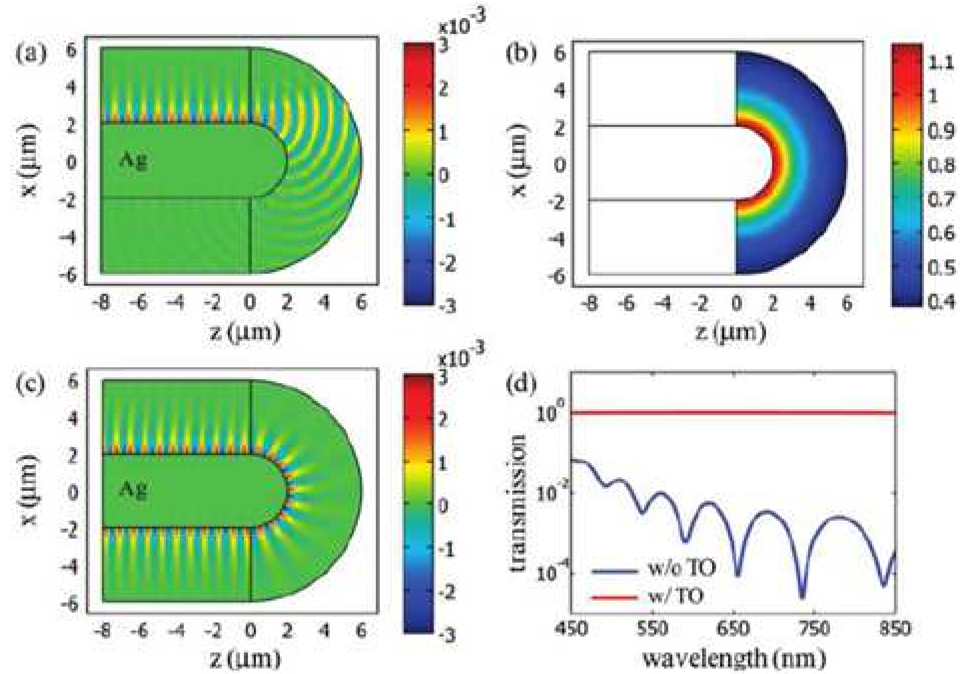
Plasmonics Gets Transformed



SPP overcoming protrusion



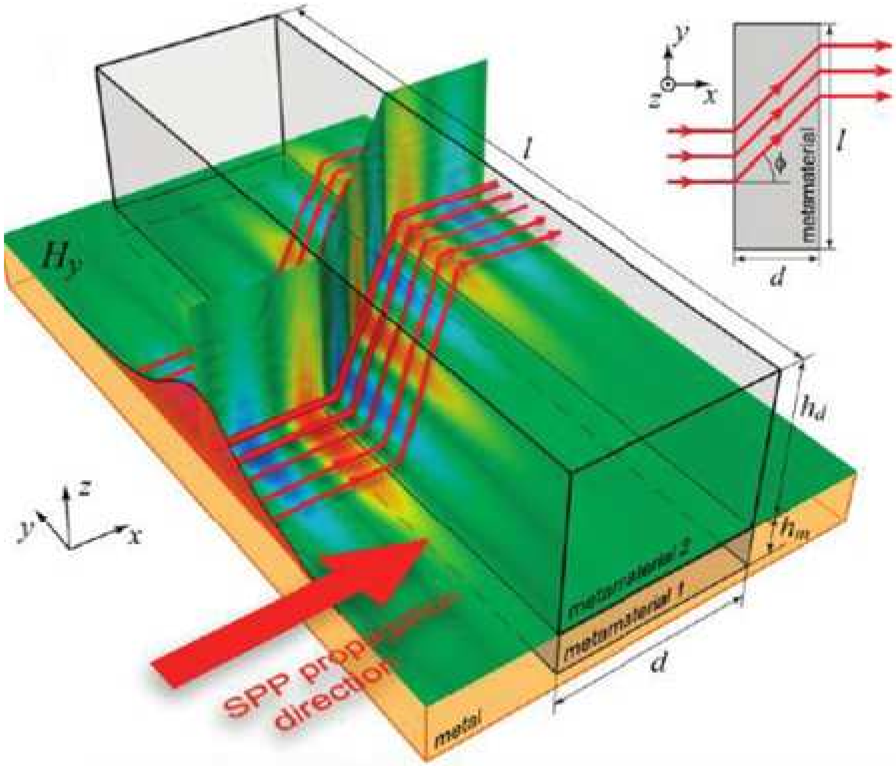
Plasmonic Luneburg lens



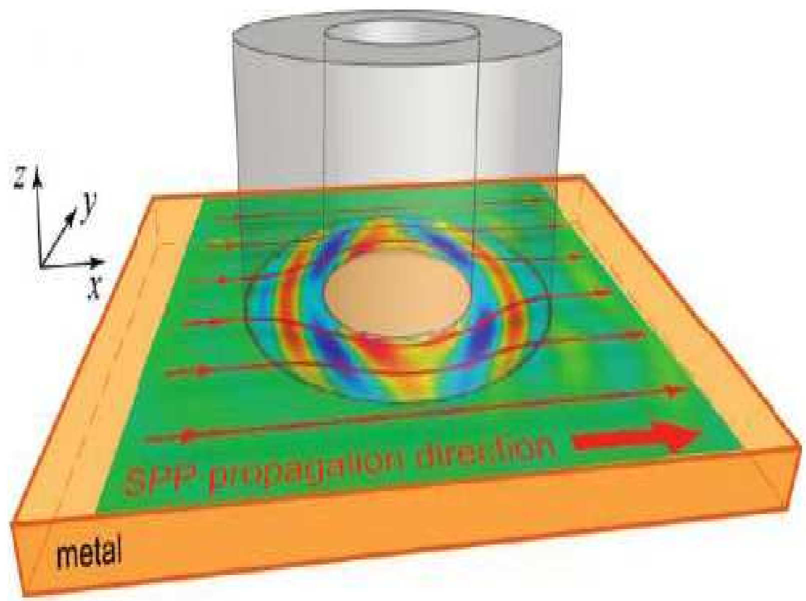
Plasmonic 180° waveguide bend

X. Zhang, et al, Nano lett. 2010

Plasmonics Gets Transformed



SPP beam shifter



Cylindrical cloak for SPPs

F . J. García-Vidal, et al, Nano lett.2010

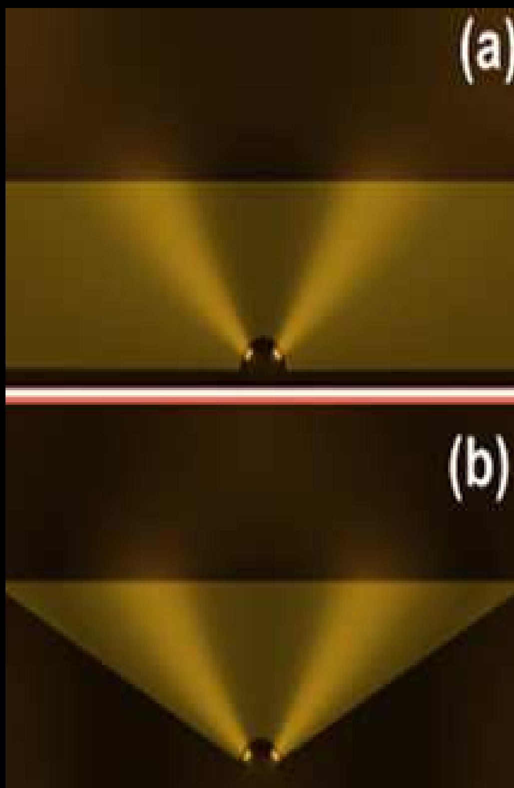
Engineering Meta-Space for Light

Kildishev, VMS *(OL, 2008)*; Shalaev, *Science 322, 384 (2008)*

Fermat: $\delta \int n\,dl = 0$

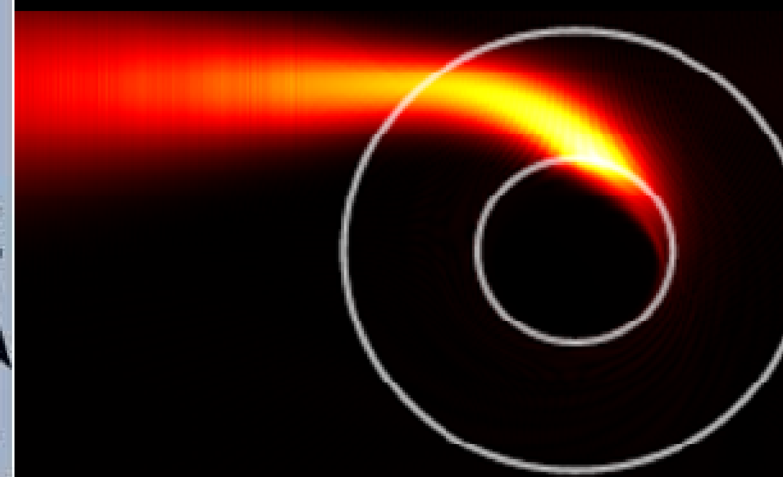
$n = \sqrt{\varepsilon(r)\mu(r)}$

curving optical space



Planar hyperlens
(Kildishev and VMS)
(Schurig et al; Zhang group)

Light concentrator
(also, Schurig et al)



Optical Black Hole
(Zhang group;
Narimanov,Kildishev)

Maxwell Fisheye and Eaton Lenses Emulated by Microdroplets

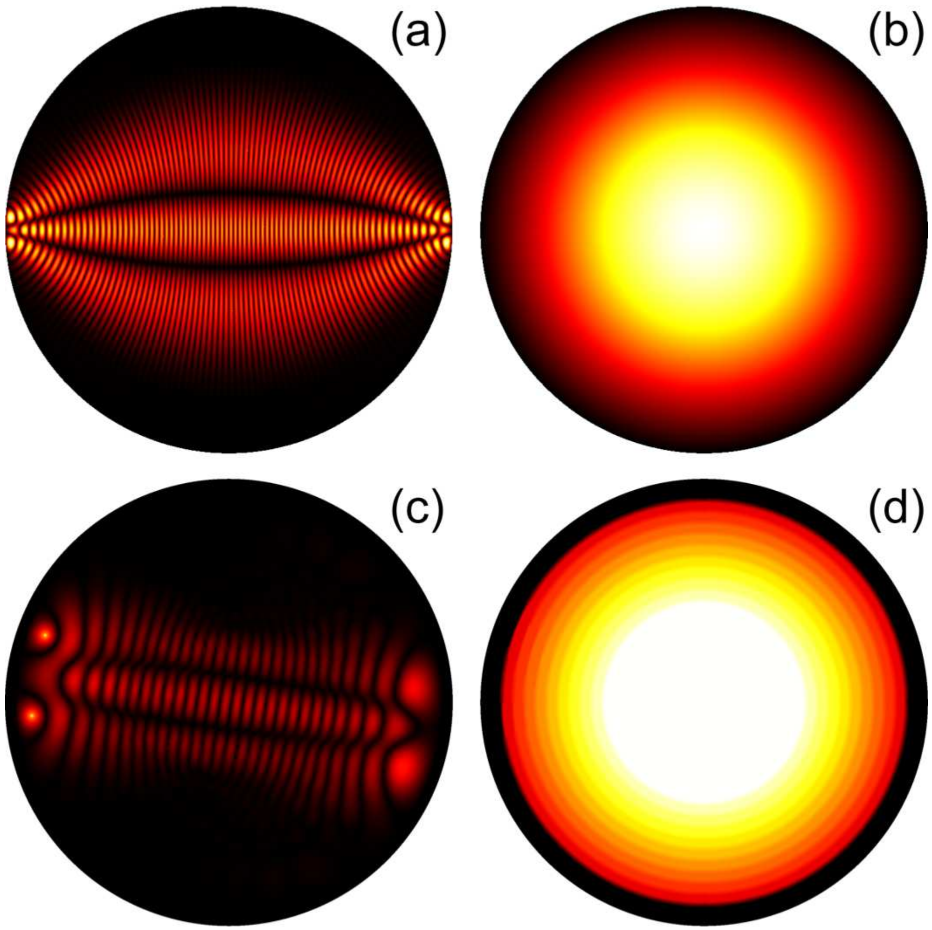
V.N. Smolyaninova, I.I. Smolayninov, A.V. Kildishev
and V.M. Shalaev

(Optics Letters 2010)

Other relevant work by Leonhard , et al.

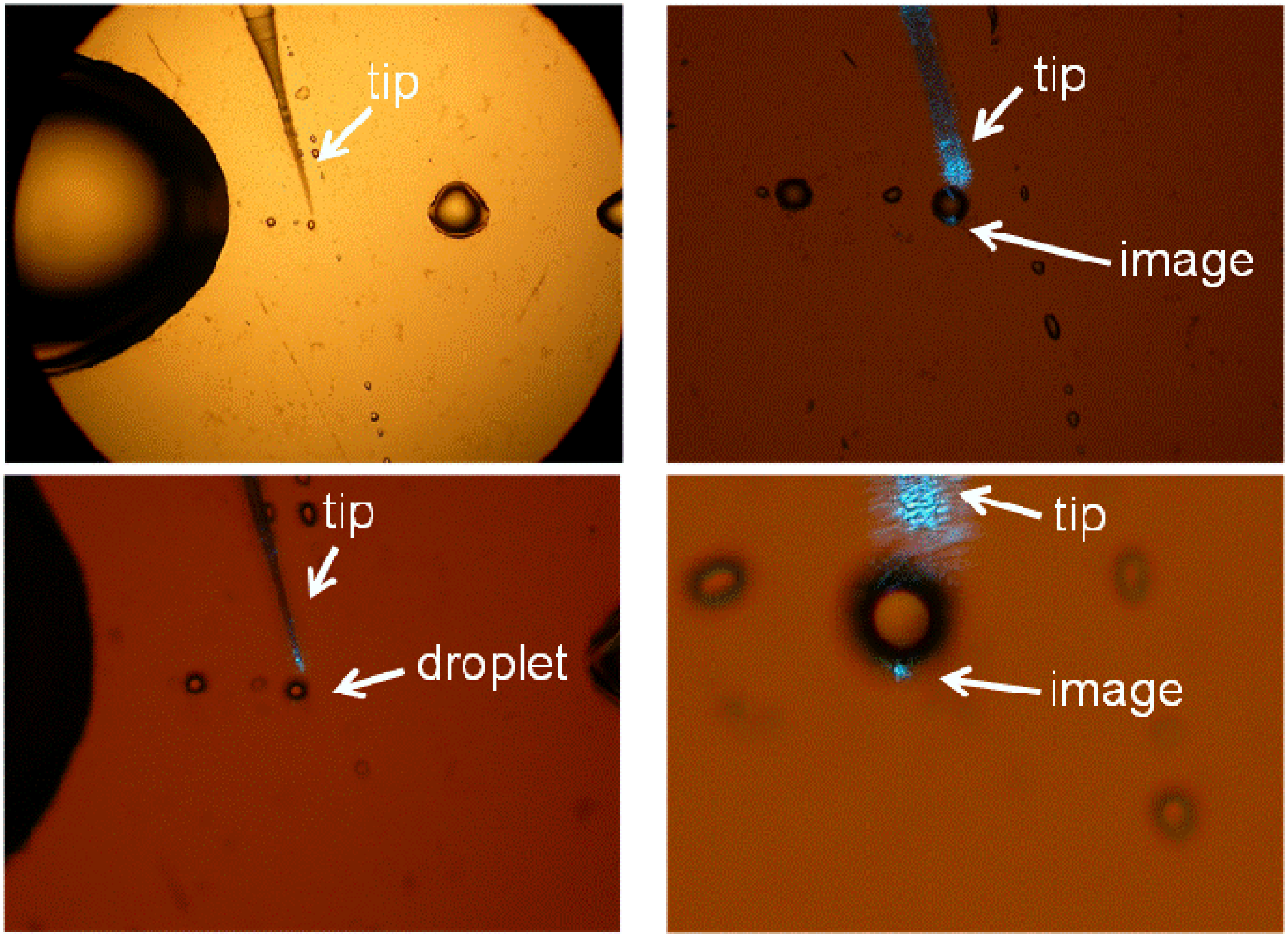
Simulations of Fish Eye and Eaton Lenses

Fish eye and Eaton lenses



refractive index

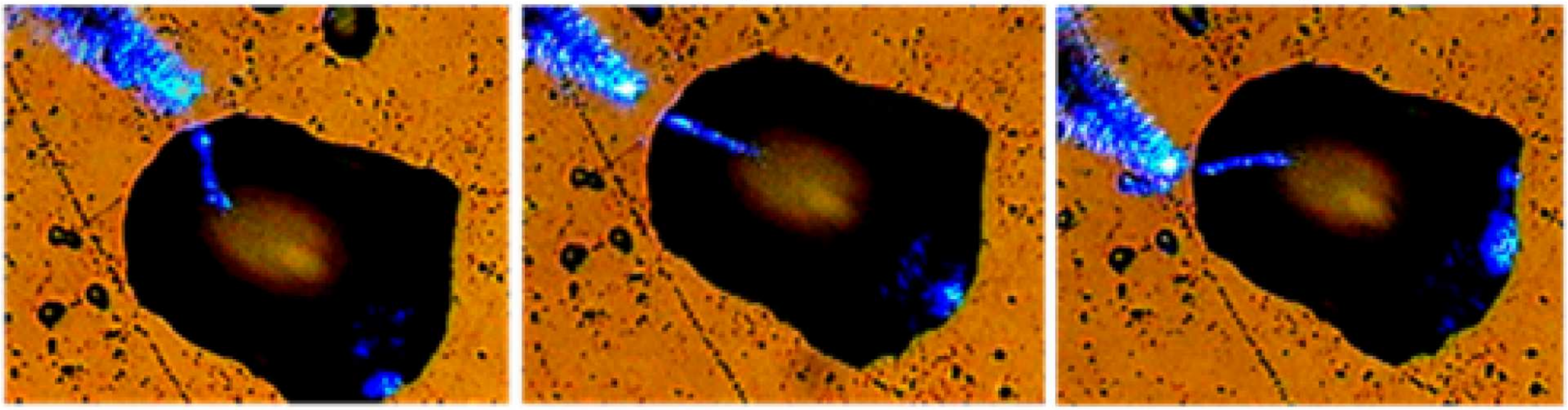
Fish Eye / Eaton Lens Based on a Droplet



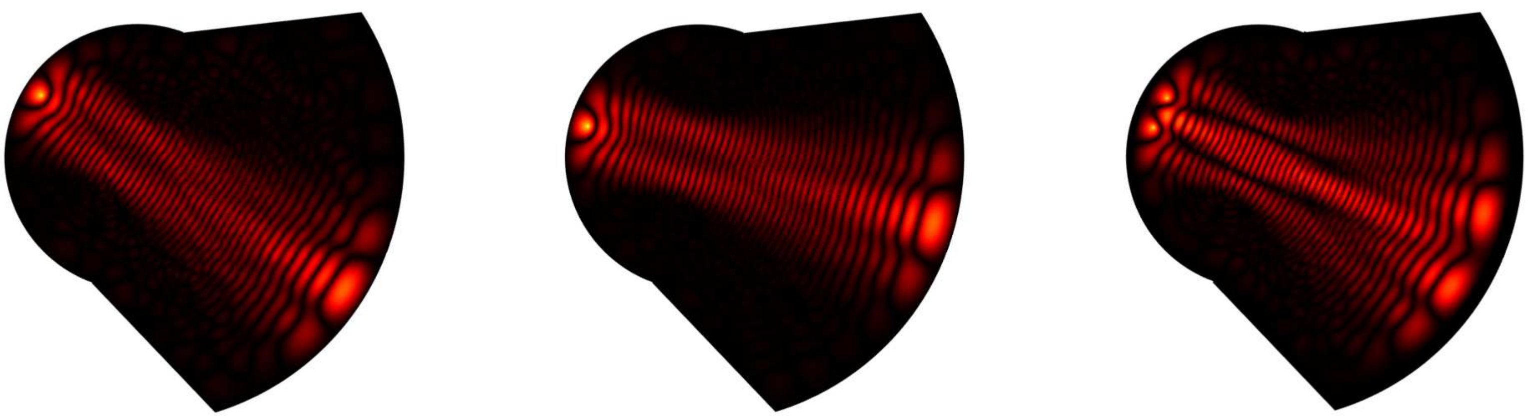
i22

Magnification with an Eaton Lens

Moving source close to the 'equator' as a proof of magnification



Magnification with Eaton lens



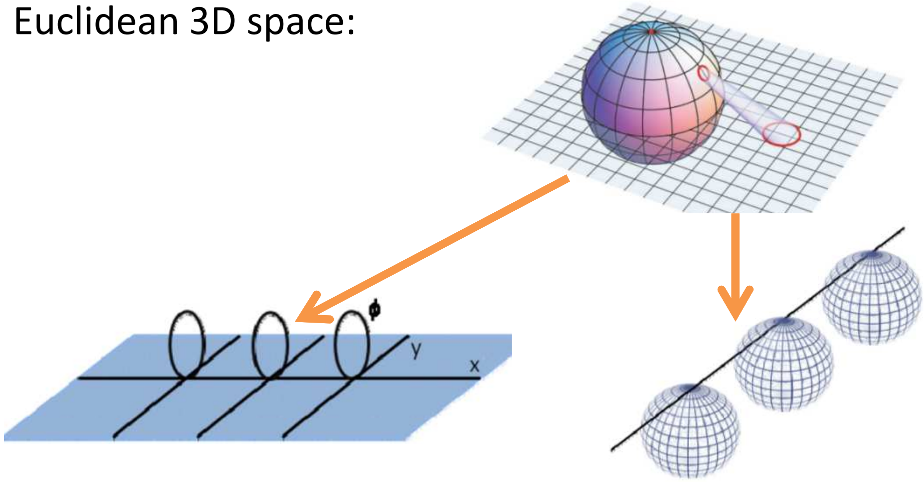
Slide 57

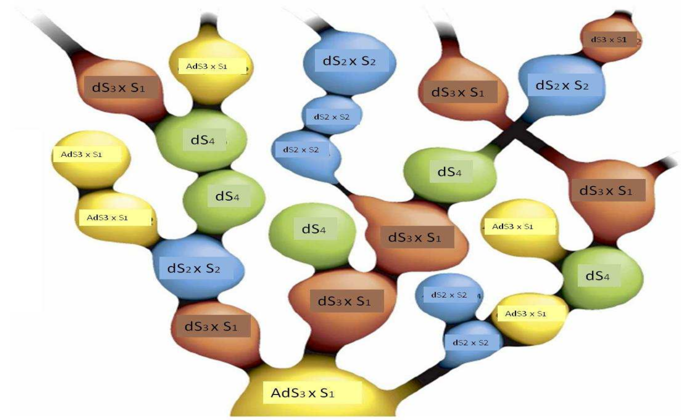
i22 We have created glycerin droplets with shapes, which are very close to the shape of the “deformed droplet” used in the numerical simulations. Image magnification of the “deformed droplet” has been tested by moving the near field microscope tip along the droplet edge, as shown in the top row. Image magnification appears to be close to the M=2 value predicted by our simulations

igor.smolyaninov, 06/02/2010

Metamaterial "Multiverse" (Smolyaninov)

Using transformation optics we can create "optical spaces" having non-trivial topology, which cannot normally fit into Euclidean 3D space:





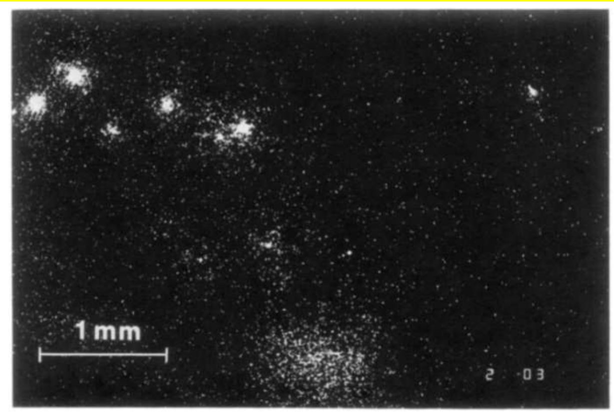
Modern cosmology describes Universe as collection of spaces connected by black holes and wormholes. These spaces may have different topology and different number of dimensions.

Even metric signature of the "optical space" may differ from the (+ - - -) signature of the Minkowski space. In hyperbolic materials (Smolyaninov, Narimanov – PRL, 2010):

$$\frac{\partial^2\varphi}{c^2\partial t^2}=\frac{\partial^2\varphi}{\varepsilon_1\partial z^2}+\frac{1}{\varepsilon_2}\left(\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}\right) \qquad \begin{matrix}\varepsilon_1<0\\ \varepsilon_2>0\end{matrix}$$

$$\left(\frac{\partial^2}{\partial x_1^{\ 2}}+\frac{\partial^2}{\partial x_2^2}-\frac{\partial^2}{\partial x_3^2}-\frac{\partial^2}{\partial x_4^2}\right)\varphi=0$$

2T K-G



Flashes of light are observed during metric signature transitions : toy Big Bang physics

Smolyaninov, J. of Optics (2011)

Purdue "meta-strike force"

Published 2009