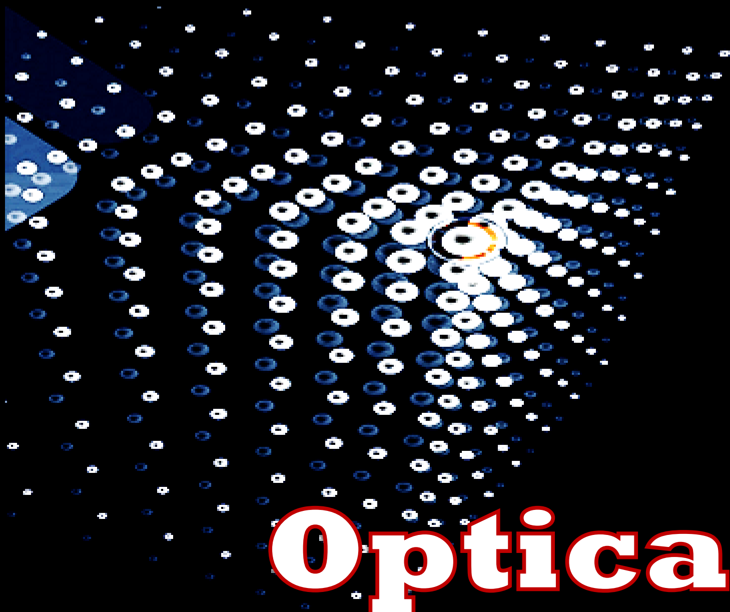


Optical Metamaterials

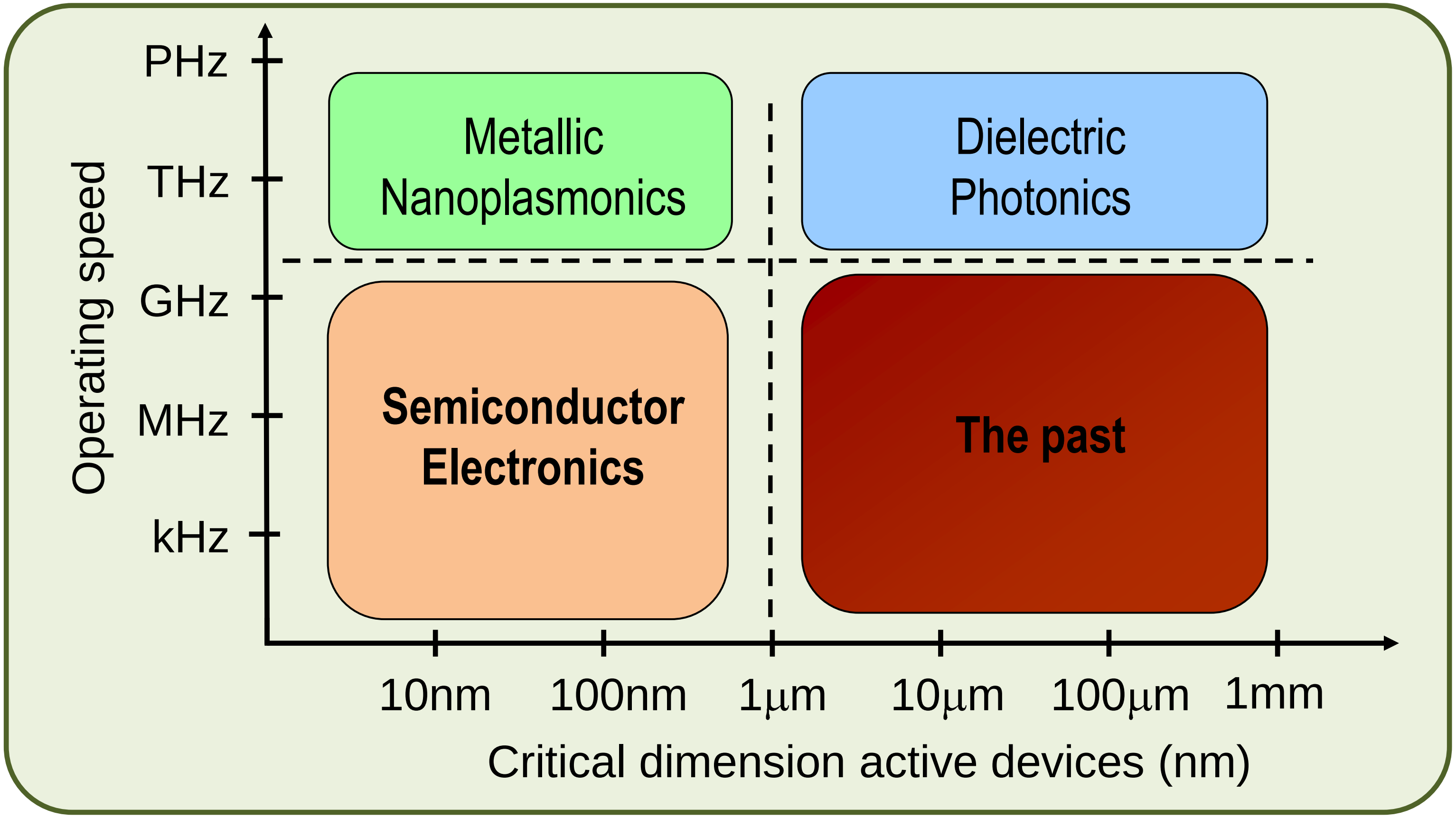
Vladimir M. Shalaev
Purdue University

Outline

- ❖ Electrical Metamaterials (Plasmonics): A Route to Nanophotonics
- ❖ Optical Metamagnetics
- ❖ Negative-Index Metamaterials
- ❖ Active and Loss-Free Metamaterials
- ❖ New Plasmonic Materials
- ❖ Chiral Metamaterials
- ❖ Metamaterials for Sensing
- ❖ Nonlinear, Tunable, and Ultrafast Metamaterials
- ❖ Quantum Optics with Metamaterials
- ❖ Transformation Optics , Cloaking, and "Multiverse"
- ❖ Generalized Snell's Law and Light Bending with Nanoantennas

Electrical Metamaterials (Plasmonics): a route to nanophotonics

Why nanophotonics needs plasmonic/electric ε-MMs ?



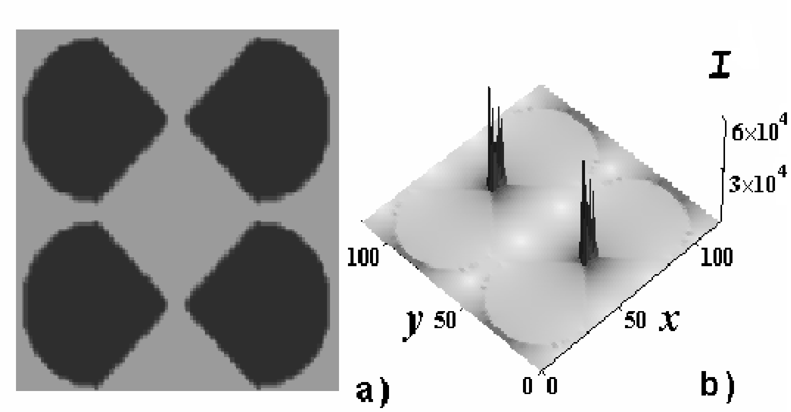
- Plasmonics will enable an improved synergy between electronic and photonic devices
  - Plasmonics naturally interfaces with similar size electronic components
  - Plasmonics naturally interfaces with similar operating speed photonic networks

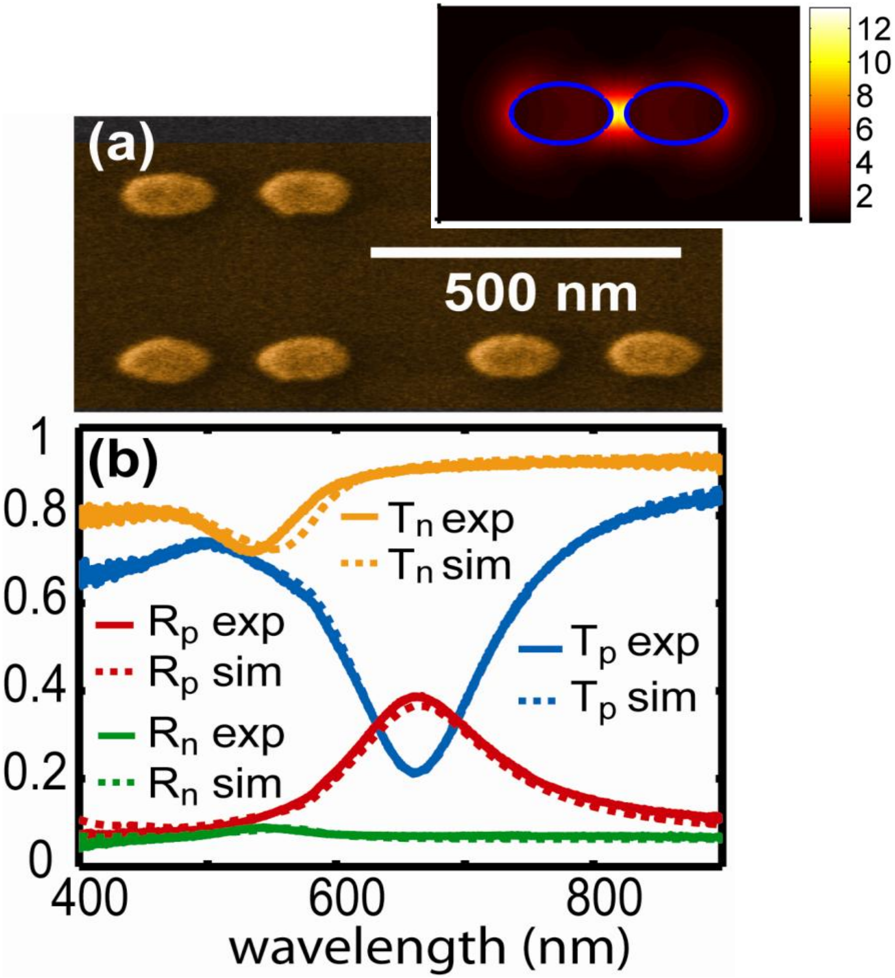
Brongersma, Shalaev, Science (2010)

Optical Antennae: Focusing Light to Nanoscale

OE (2009); NJP (2008); Metamaterials (2008); APL (2008)

[Bow-tie antennas]





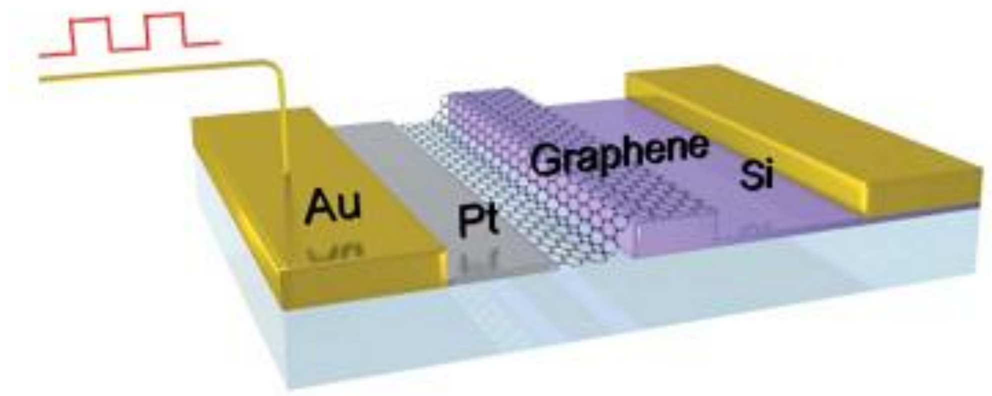
from LC-contour to nanophotonic circuits (Engheta – 'metatronics')

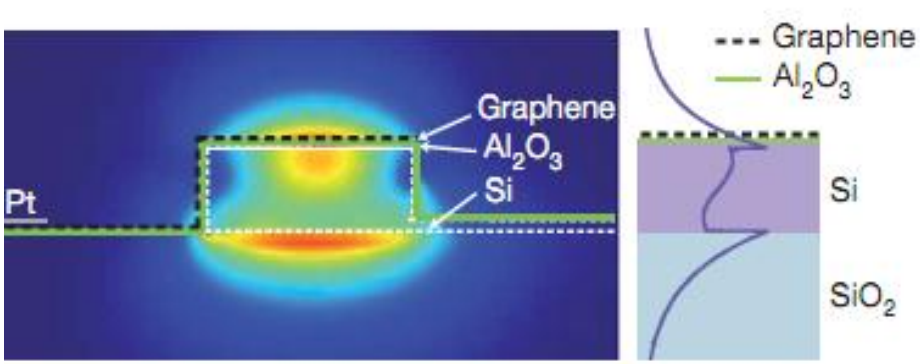
<u>Other Applications:</u>
Sensors

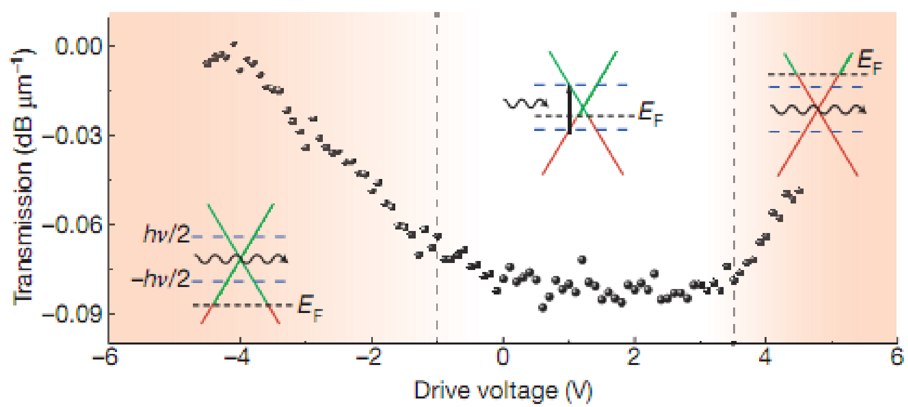
Other nanoantenna work: van Hulst; Polman; Brongersma; Capasso; Sandoghdar…

Graphene-Based Optical Modulator

Guided light is electrically modulated in a broad spectral range of 1.35-1.6 m by controlling the interband transitions in graphene.

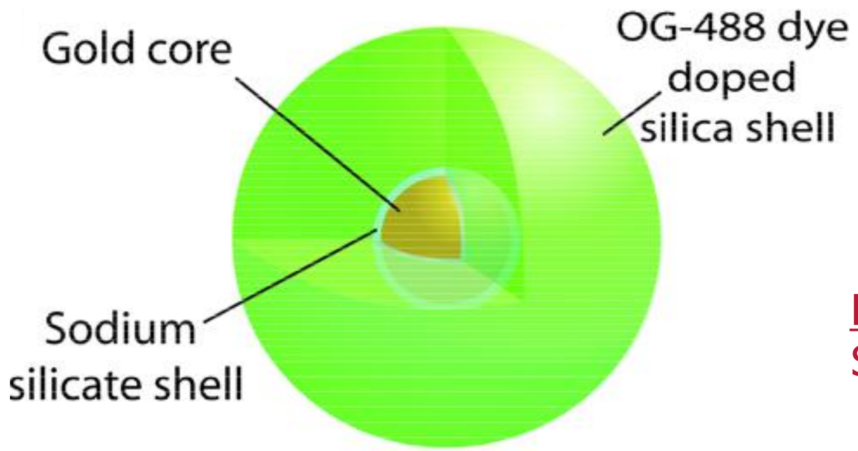






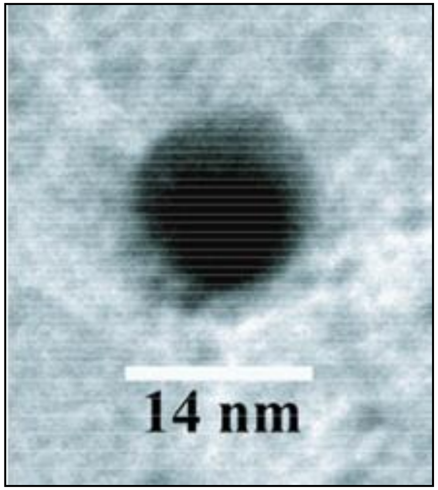
Optical Nanolaser Enabled by SPASER
NSU-Purdue-Cornell; *Nature* (2009)

Hybrid Nanoparticle

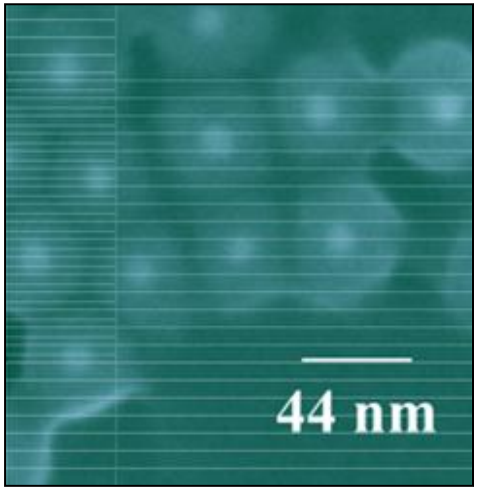


Related prio theory:
Stockman (spaser)

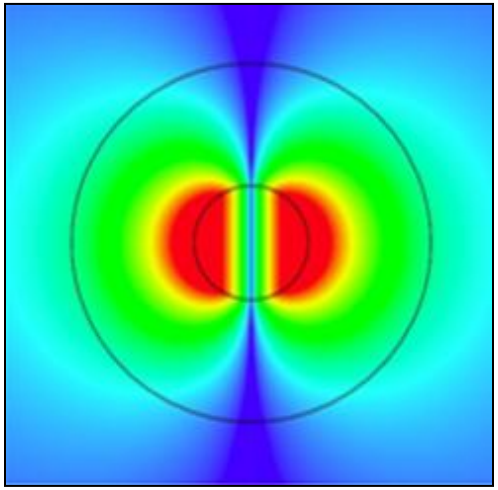
[Au core]



[Au/silica/dye NPs]

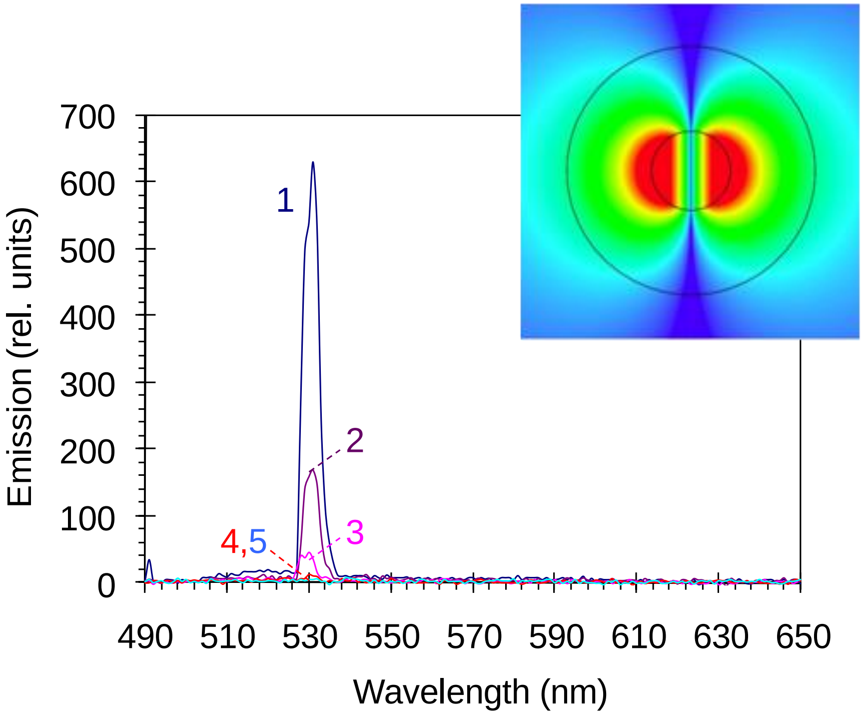


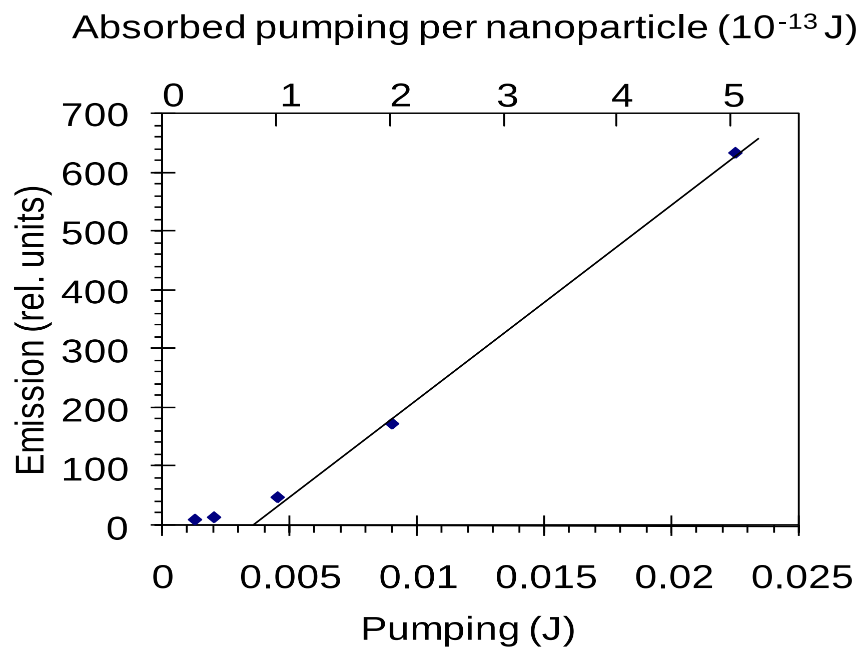
[SPASER mode]



World's Smallest Nanolaser (NSU-Purdue-Cornell)

Noginov,… Shalaev, et al, Nature (2009)



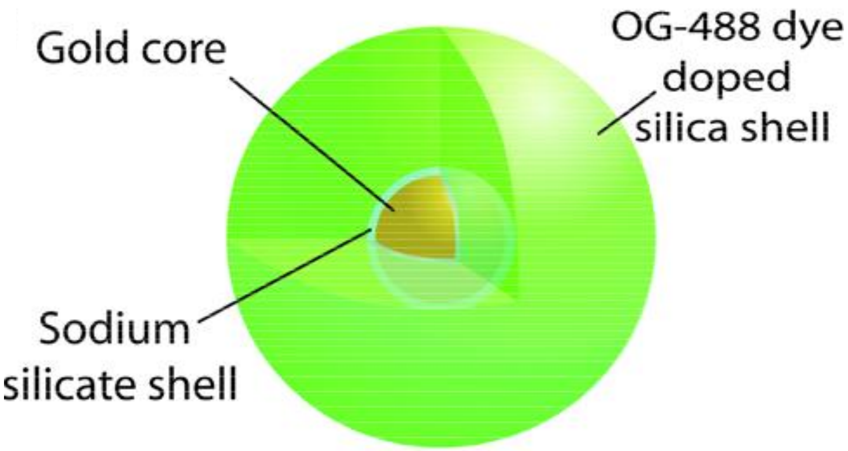


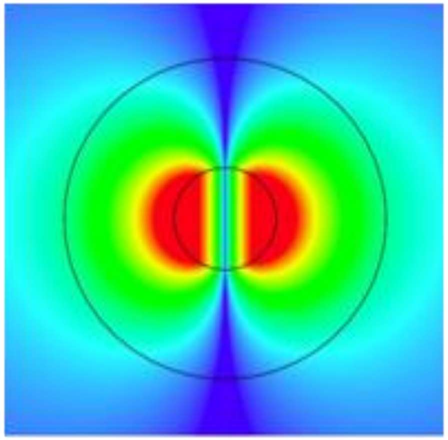
Stimulated emission spectra at different pumps by OPO pulses at λ=488 nm

Optical MOSFET

also: Zhang's group nanolaser Nature (2009)

Optical Nanolaser Enabled by SPASER





Related prior theory:
Stockman (SPASER)

Noginov, Shalaev, Wiesner groups, Nature (2009)

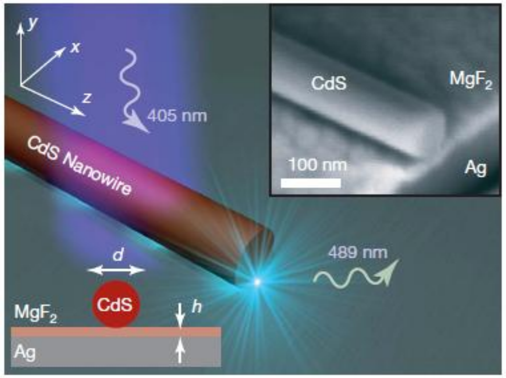
Optical MOSFET
(Stockman)

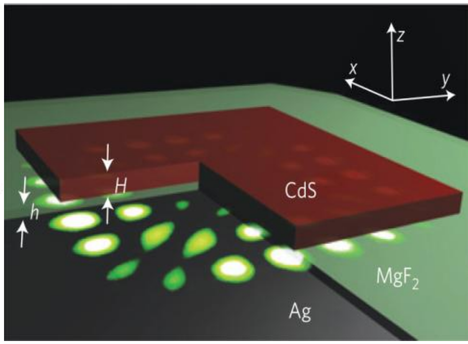
Zhang group: Plasmon Laser (Nature,2009)
Room-T Plasmon Laser (Nat. Mat, 2010)

“Spasing Laser” – Zheludev, Stockman

M. T. Hill, et al; C. Z. Ning, et al (electr. pump)

Spotlight on Plasmon Lasers (Perspective, Science, 2011)- X. Zhang, et al

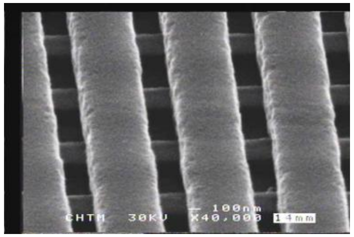




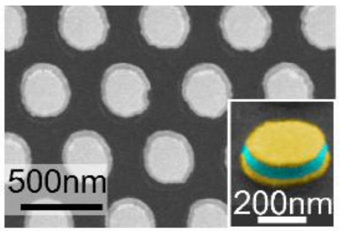
Fabrication of Metamaterials

Progress in Large-Scale & 3D Fabrication

[Interference Lithography]

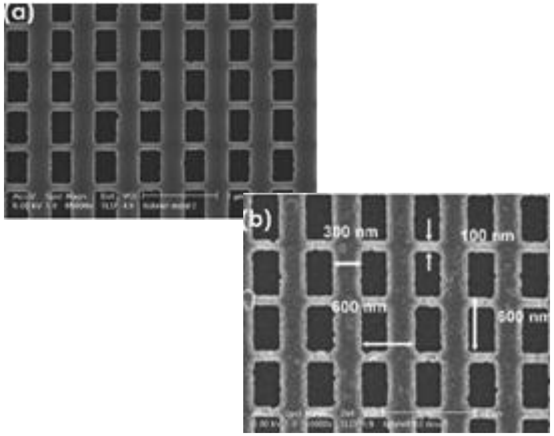


Z. Ku & SRJ Brueck, Opt. Exp. **15**, 4515 (2007)



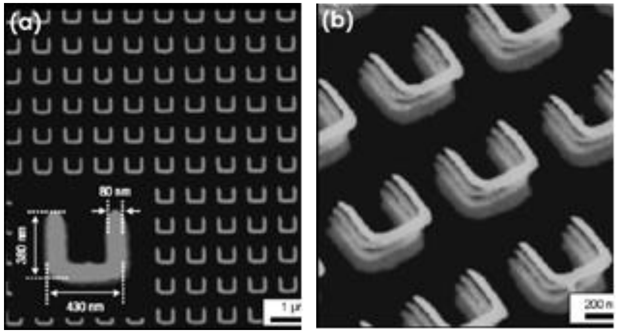
Nils Feth et. al, Opt. Exp. **15**, 501 (2007) (Wegener group)

[Nanoimprint Lithography]



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

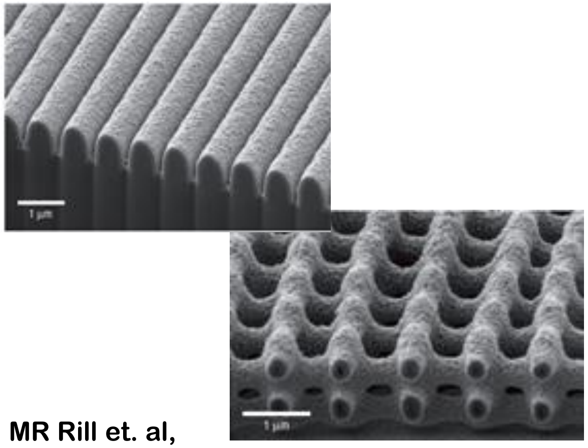
[Building layer-by-layer]



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

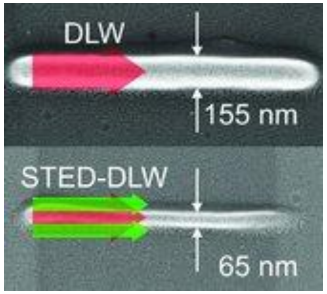
3D

[Direct Laser Writing]



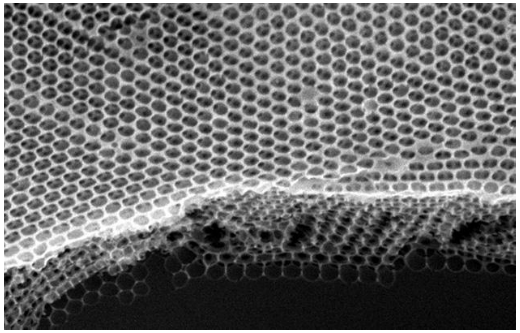
MR Rill et. al,
Nat. Mater. **5**,743 (2008) (Wegener group)

[STED-Direct Laser Writing]



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

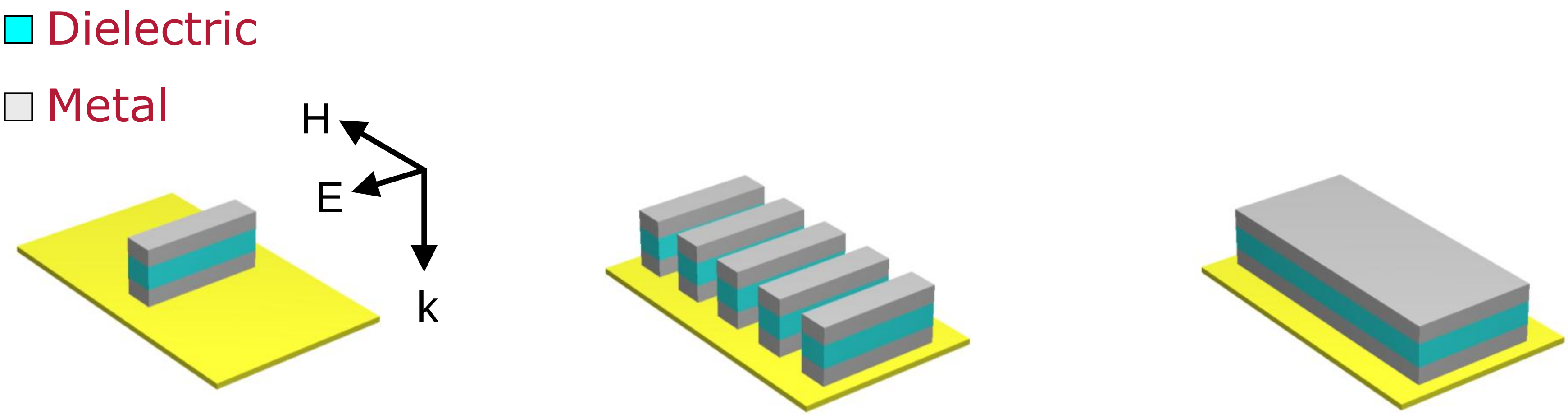
[Self-assembly]



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

Metamagnetics for optical range

Artificial Magnetic Metamaterials for Visible



Nanorod pair

Nanorod pair array

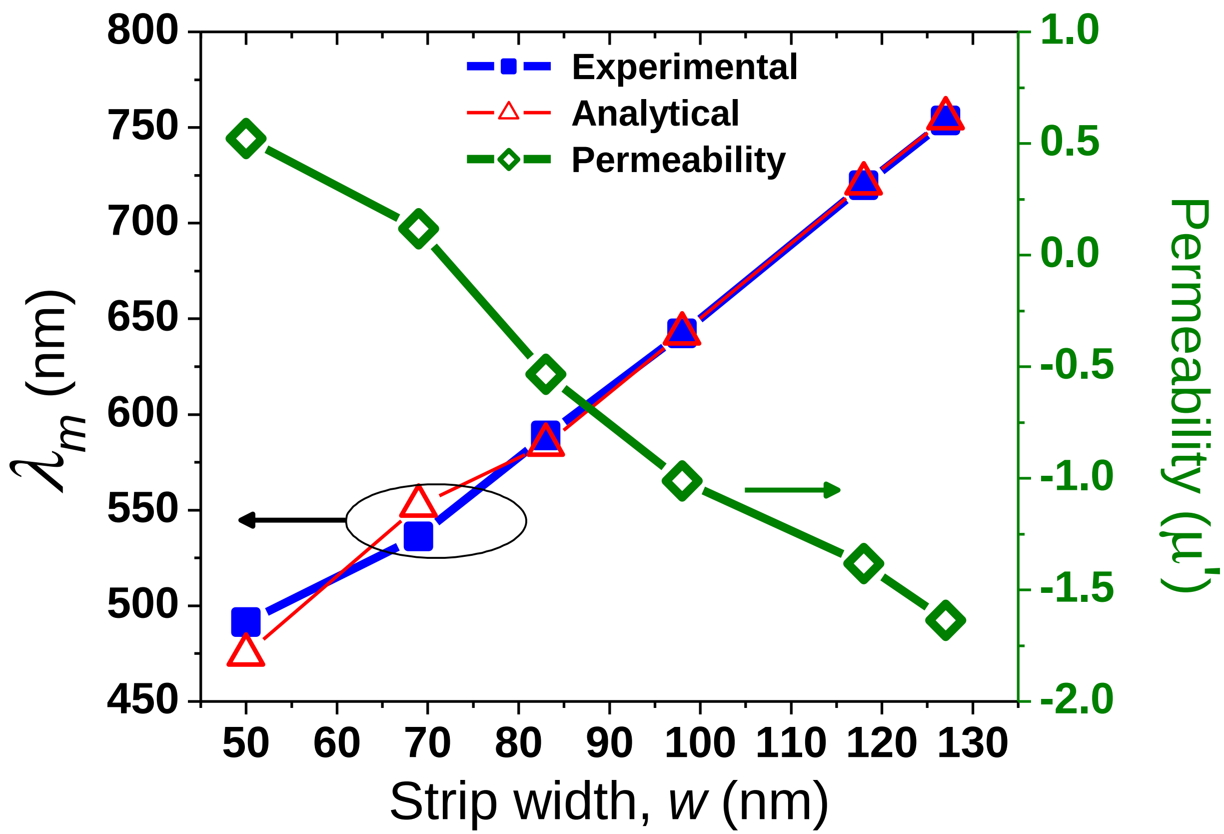
Nanostrip pair

Nanostrip pair has a much stronger magnetic response

Podolskiy, Sarychev & Shalaev, *JNOPM* (2002) - μ < 0 & n < 0
Lagar'kov, Sarychev PRB (1996) - μ > 0
Kildishev et al, *JOSA B* (2006); Shvets et al (2006) – strip pairs
Zheludev et al (2001) – pairs of rods for chirality

Visible Meta-Magnetics: from Red to Blue

Cai, et al OE (2007)



λ_m as a function of strip width "w": experiment vs. theory

Optical Negative-Index Metamaterials

Negative refractive index: A historical review

Sir Arthur Schuster

Sir Horace Lamb

… energy can be carried forward at the group velocity but in a direction that is anti-parallel to the phase velocity…

Schuster, 1904

Negative refraction and backward propagation of waves

Mandel'stam, 1945

L. I. Mandel'stam

V. G. Veselago

Left-handed materials: the electrodynamics of substances with simultaneously negative values of ε and μ

Veselago, 1968

Pendry, the one who whipped up the recent boom of NIM researches

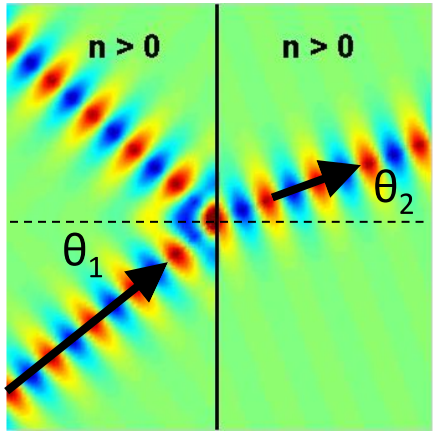
Perfect lens (2000)

EM cloaking (2006)

Sir John Pendry

Others: Sivukhin. Agranovich,…

Metamaterials with Negative Refraction

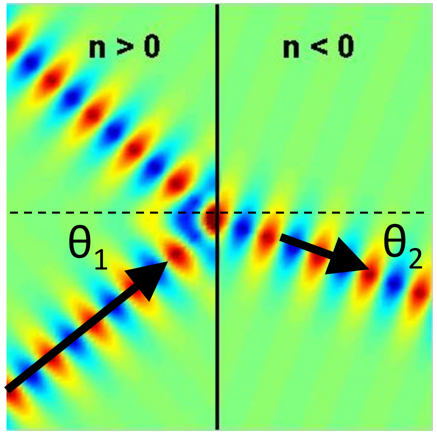


- **Refraction:** $n^2 = \varepsilon\mu$

  $n = \pm\sqrt{\varepsilon\mu}$

- **Figure of merit:** $F = |n'| / n''$

$n < 0,$ if $\varepsilon'|\mu| + \mu'|\varepsilon| < 0$



Single-negative:

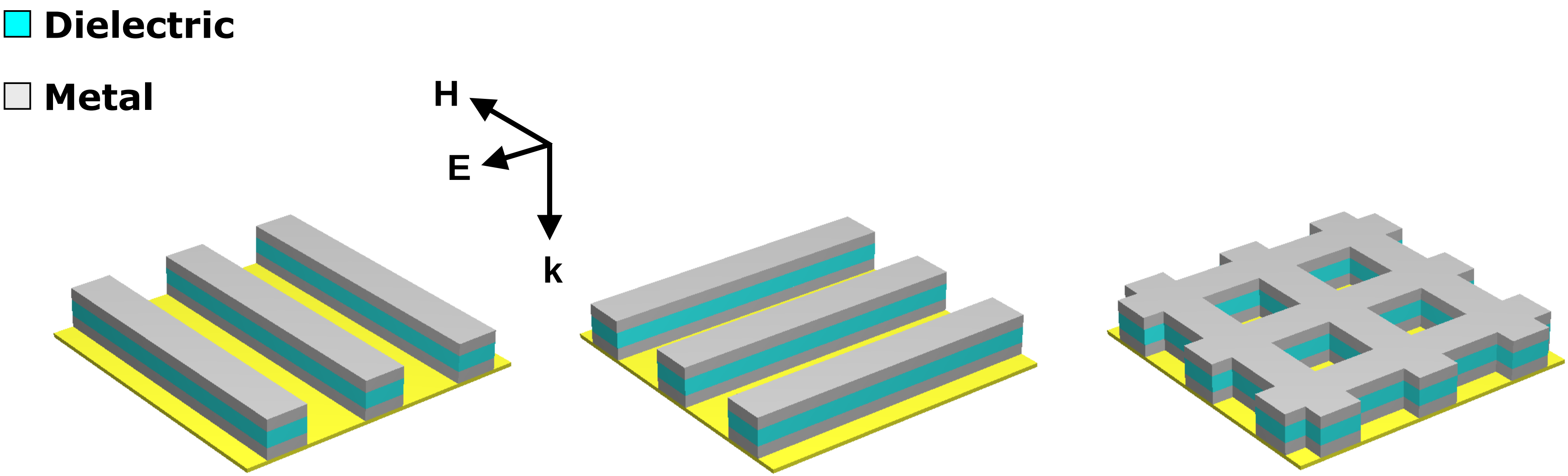
$n < 0,$ when ε′ < 0 whereas μ′ > 0 (F is low)

Double-negative:

$n < 0,$ with both ε′ < 0 and μ′ < 0 (F can be large)

Negative Permeability and Negative Permittivity

S. Zhang, et al., PRL (2005)



Nanostrip pair (TM)

$\mu < 0$ **(resonant)**

Nanostrip pair (TE)

$\varepsilon < 0$ **(non-resonant)**

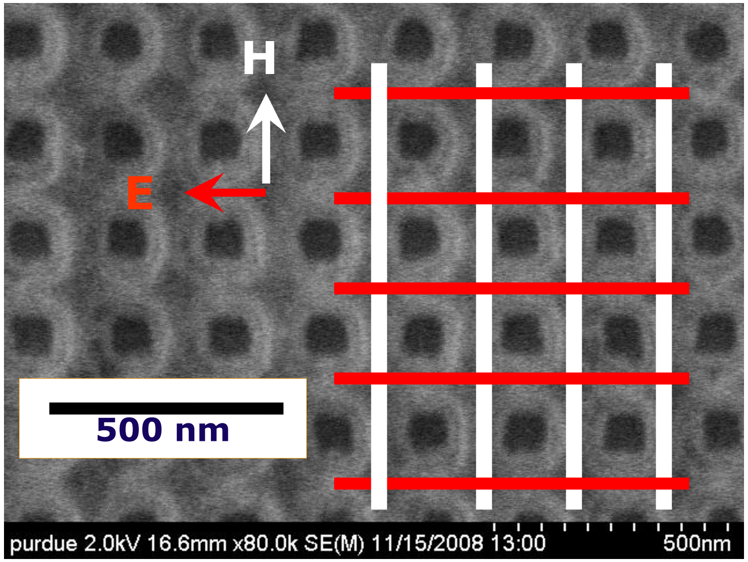
Fishnet

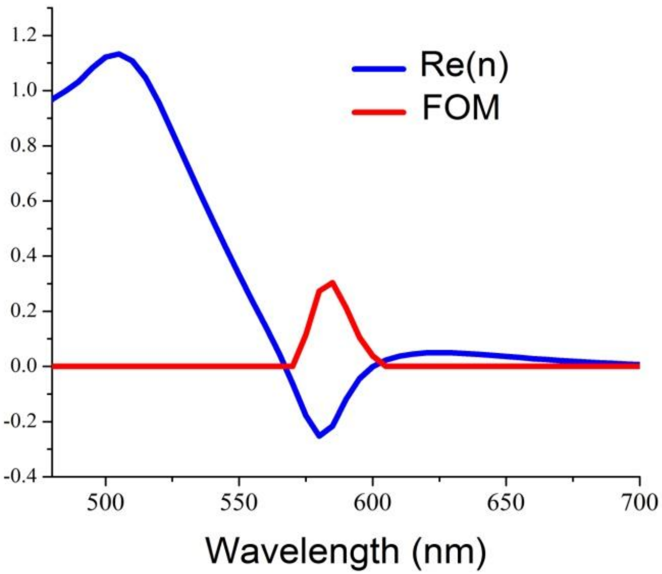
ε **and** $\mu < 0$

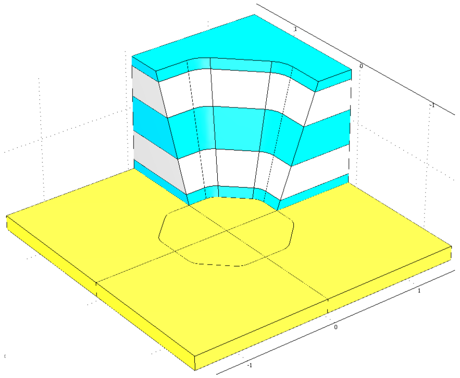
Negative Index for Yellow Light (n'=-0.25, FOM=0.3, at 580 nm)

Xiao et al, OL (2009)

Periodicity, E: 220 nm; H: 220 nm







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

Negative Refractive Index in Optics

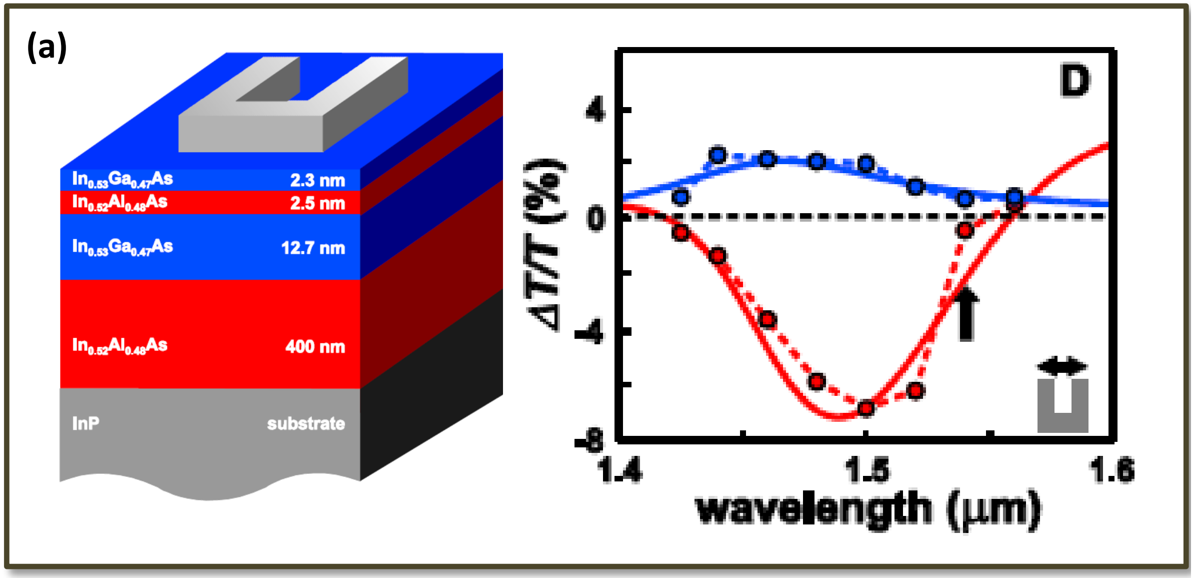
Year and Research group	*1st time posted and publication*	*Refractive index, n′*	*Wavelength, λ*	*Figure of Merit F=|n′|/n″*	*Structure used*
2005					
Purdue	**April 13 (2005)** **arXiv:physics/0504091** **Opt. Lett. (2005)**	**−0.3**	**1.5 μm**	**0.1**	**Paired nanorods**
UNM & Columbia	**April 28 (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**

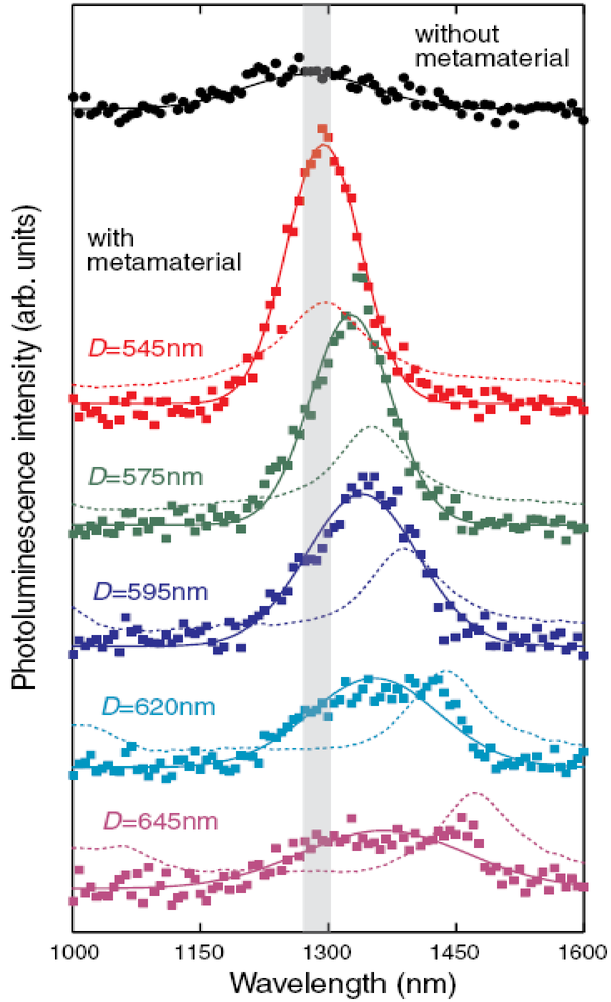
CalTech (Atwater): negative refraction in the visible for MIM waveguide SPPs (2007)

Active Negative-Index Metamaterials

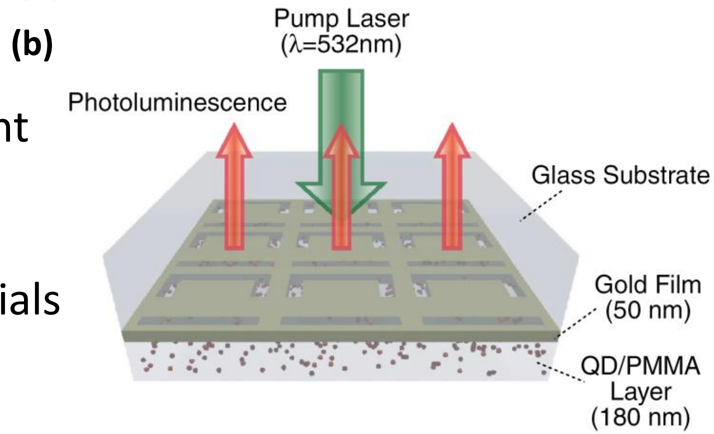
Active Metamaterials (Experiments)

- 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)

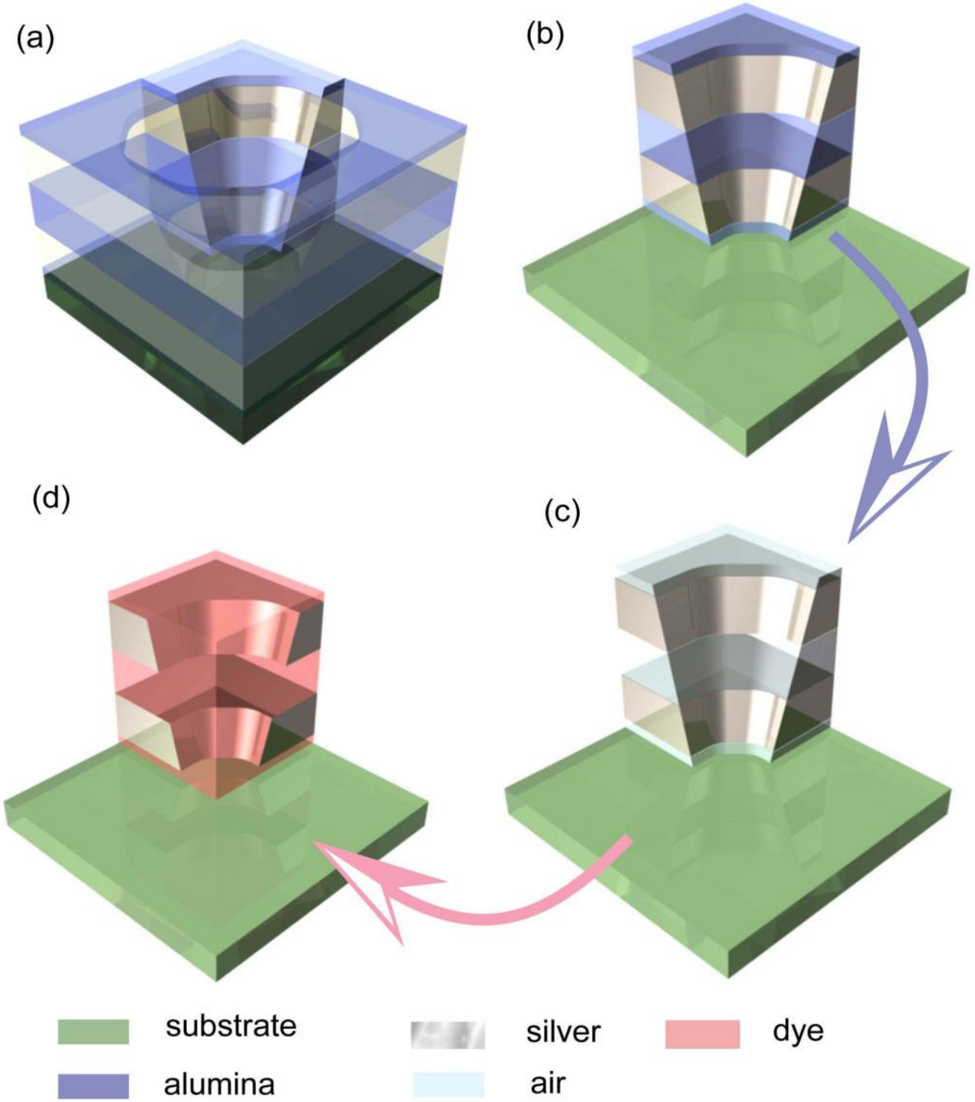
Structure and Fabrication Process

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

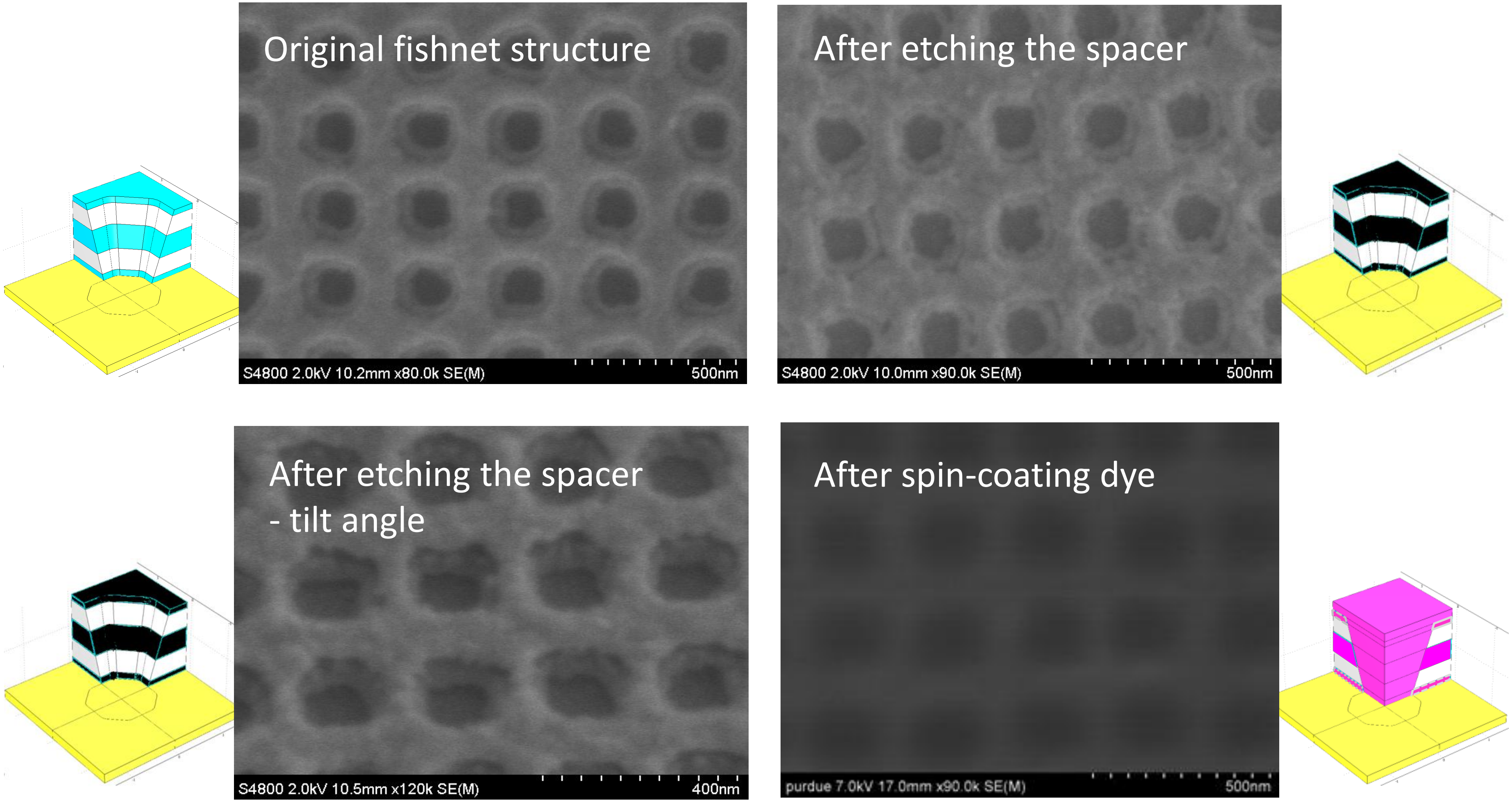
b) A quarter of fishnet with an alumina spacer

c) After etching alumina

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



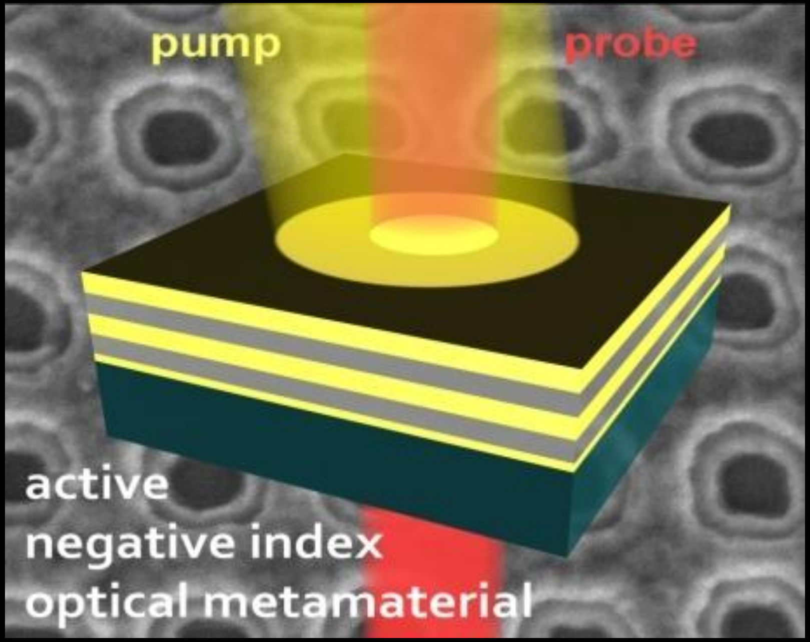
FESEM Images

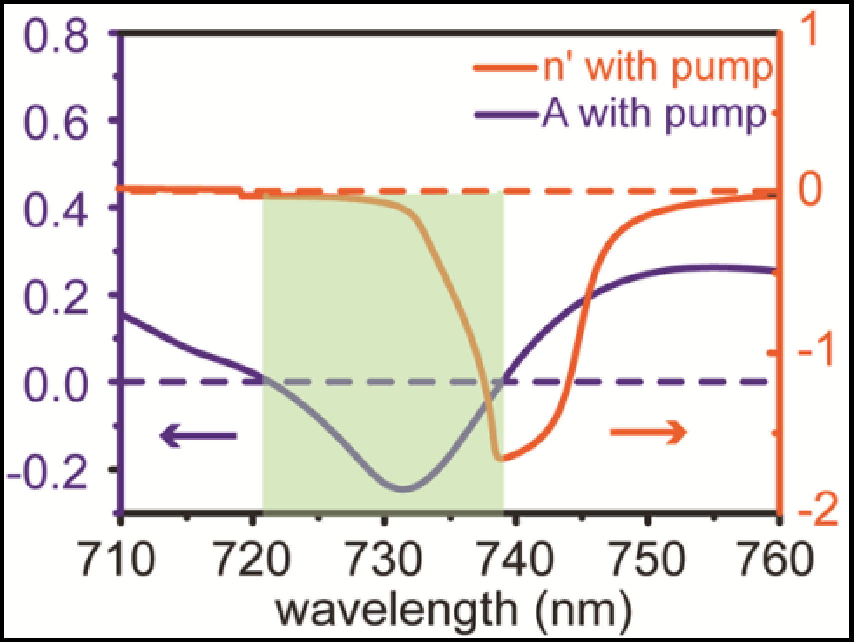


Al_2O_3 | Rh800/SU-8 | Air | Silver

Loss Free NIMs

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)

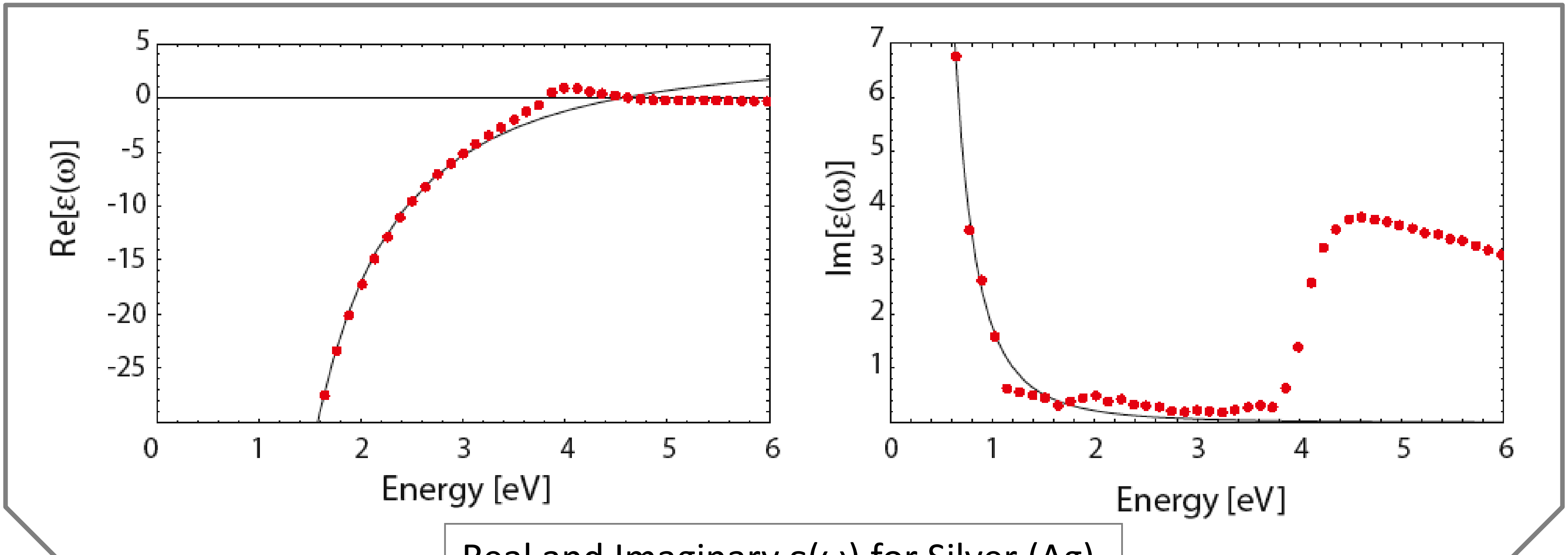
Toward Better Materials for Negative Refraction

(Boltasseva group)

Challenges

Conventional plasmonics: *Gold and Silver*

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



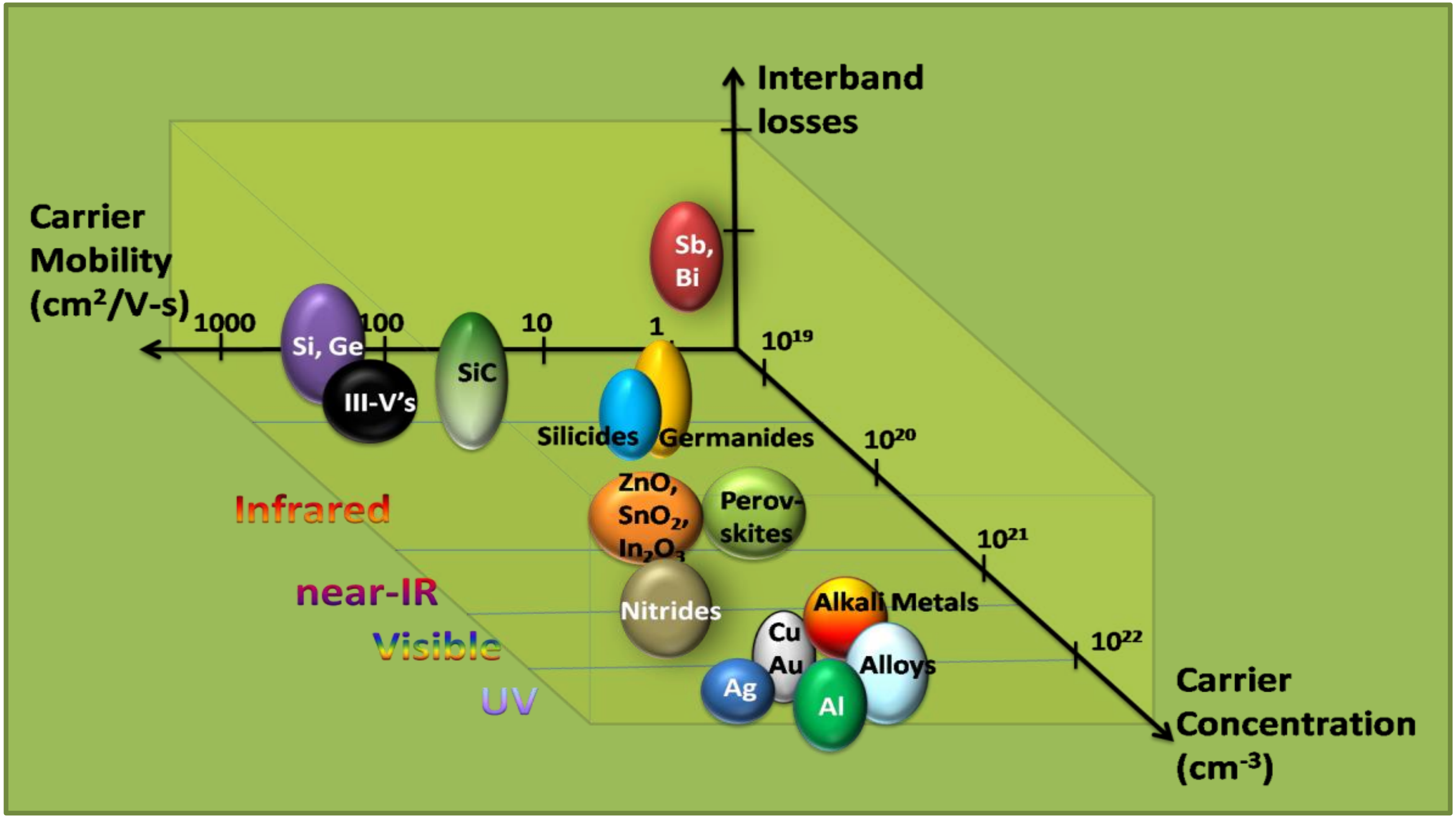
Real and Imaginary ε(ω) for Silver (Ag)

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

New plasmonic materials

METALS TO LESS-METALS:

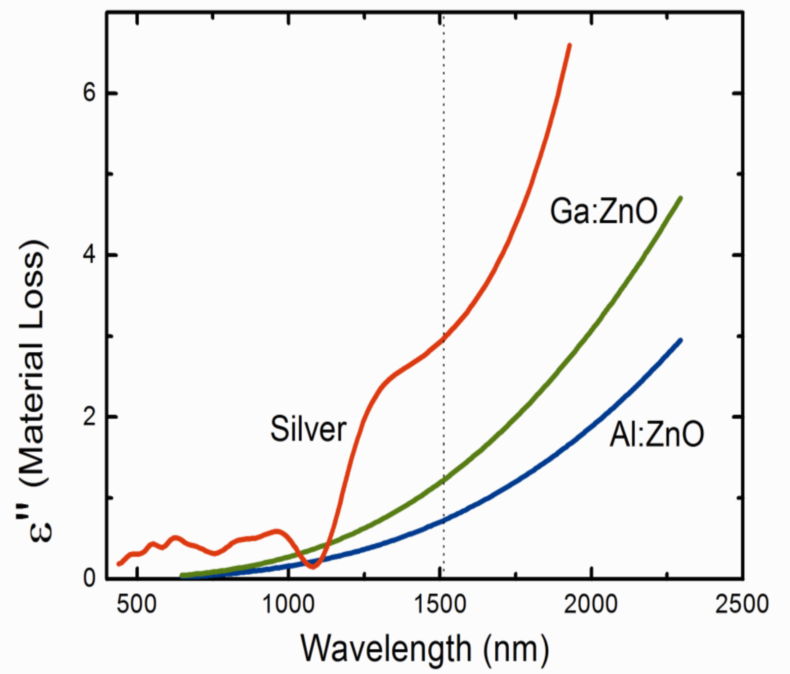
Doped semiconductors + Intermetallics (nitrides, borides, silicides, …)



A. Boltasseva and H.A. Atwater, Science 331 (2011)

Alternative Plasmonic Materials

Transparent Conductive Oxides



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

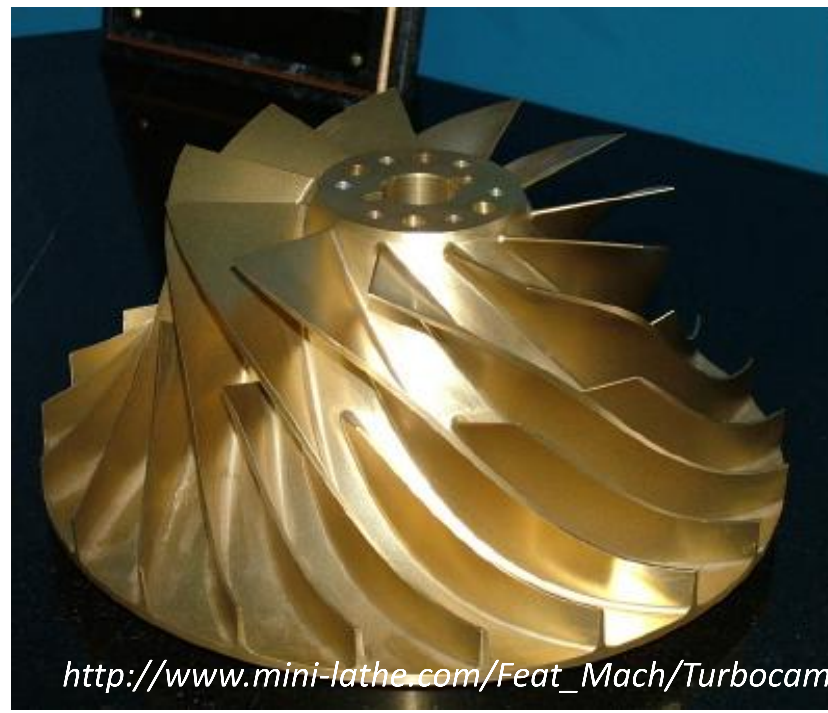
(see also work by the Noginov group)

Titanium Nitride

Metallic: Golden luster

Hard & tough: high speed drill-bits

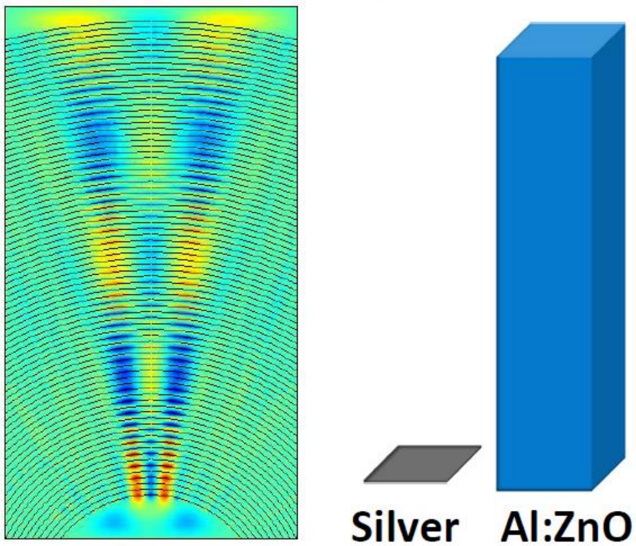
Well-established processing

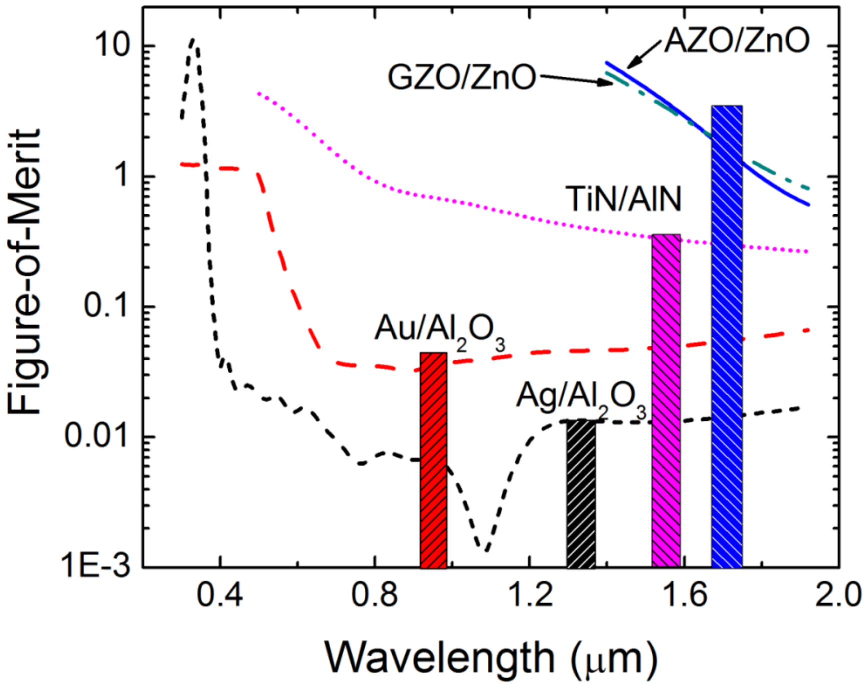


G.V. Naik *et al.*, Optical Materials Express **2** (2012) p. 478

Titanium Nitride

Figure of Merit of Hyperlens @ 1.55 µm





Performance of

HMM devices:

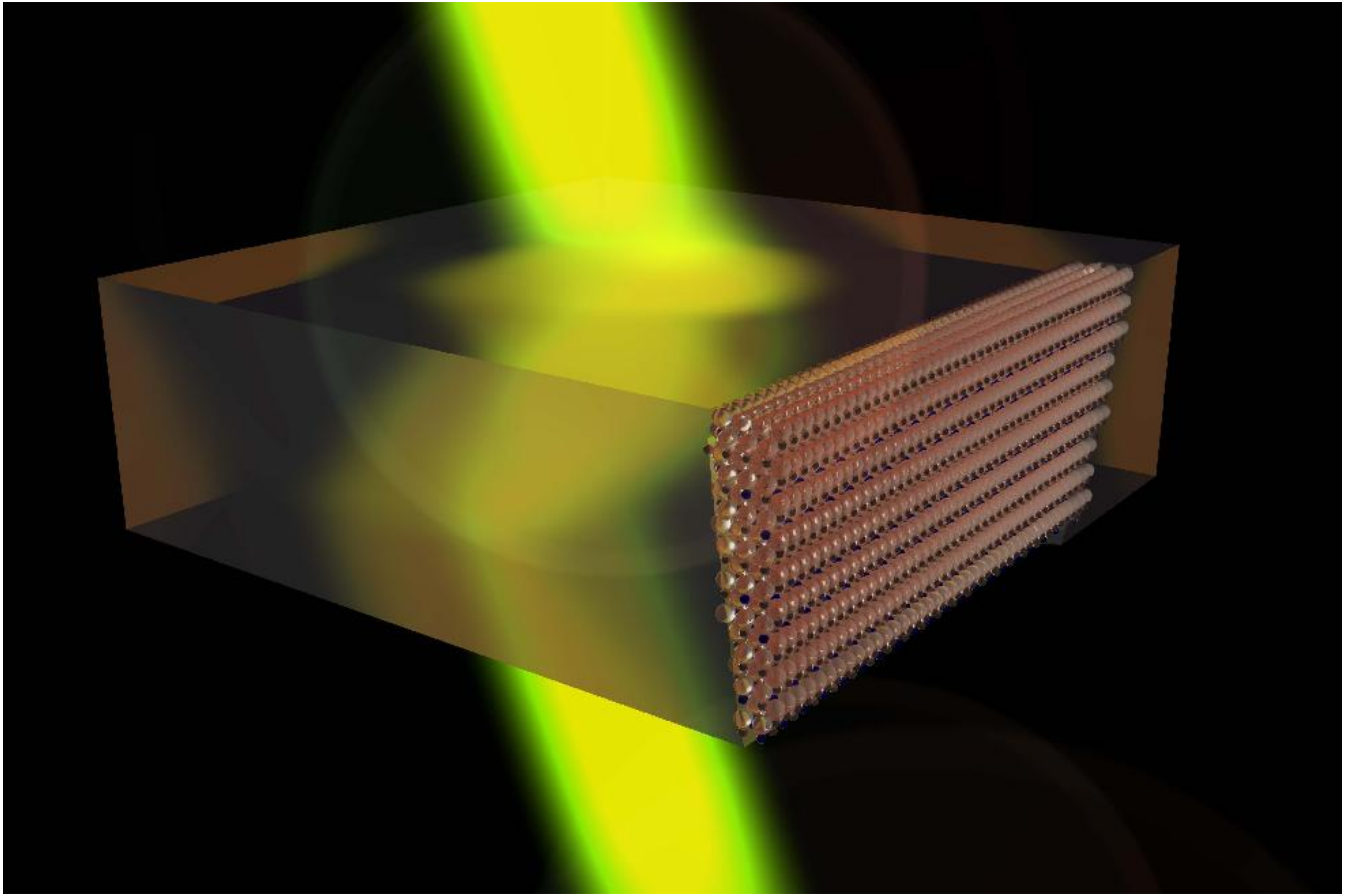
(A. Hoffman, Nature Materials 6(2007) 946–950)

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

G..V. Naik and A. Boltasseva, *Metamaterials* 5(2011) 1-7

Phys. Status Solidi RRL 4, 295 (2010)

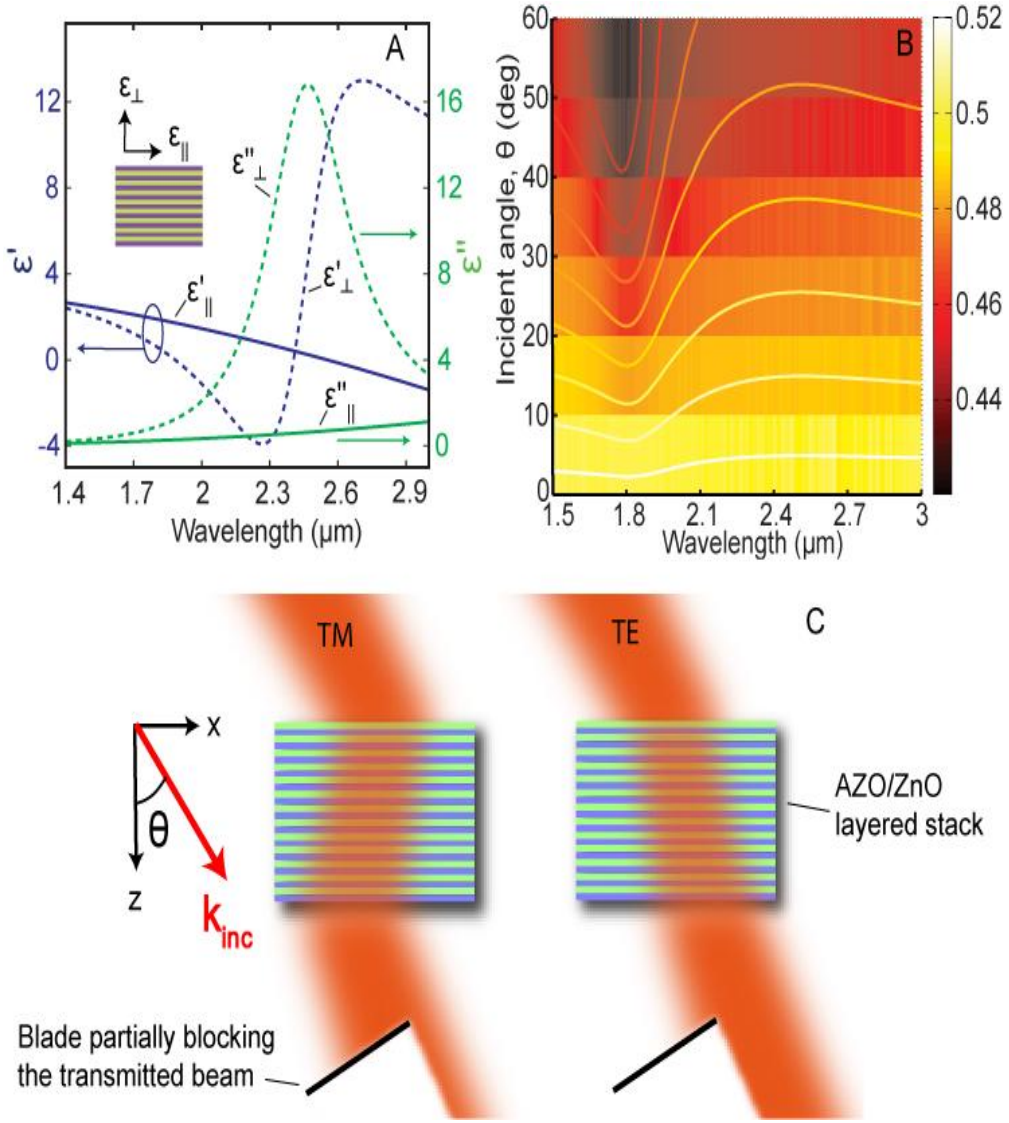
Negative Refraction in all-Semiconductor based HMM



G. Naik, et al, PNAS (2012)

Negative refraction in semiconductor-based metamaterials

- Semiconductors exhibit metallic properties when heavily doped
- Aluminum doped zinc oxide (AZO) exhibits metallic property in the near-infrared
- Conventional metals replaced by semiconductor-based ones such as AZO can produce high performance metamaterials
- The figure-of-merit of AZO/ZnO metamaterial is 11: three orders higher than metal-based designs



G. Naik, et al. PNAS (2012) (Boltasseva /Shalaev groups)

Chiral Metamaterials

Chiral Metamaterials

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

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

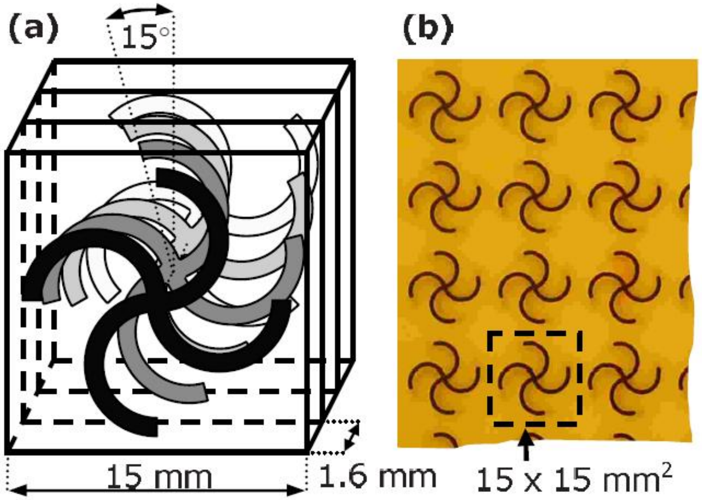
- Right circularly polarized (RCP) / Left circularly polarized (LCP)

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

<Negative index refraction>

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

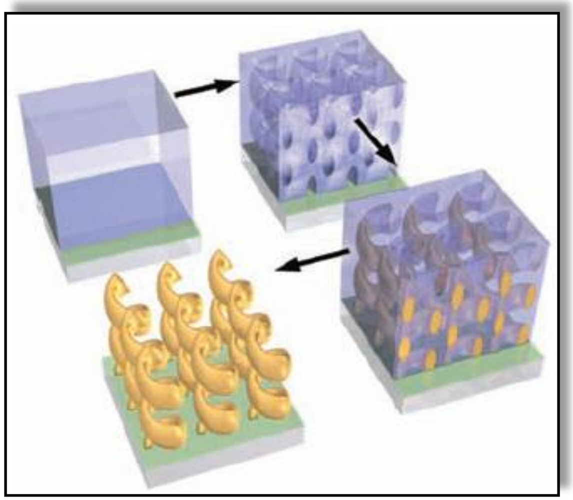
$$k_{-} < 0, \quad n_{-} < 0,$$

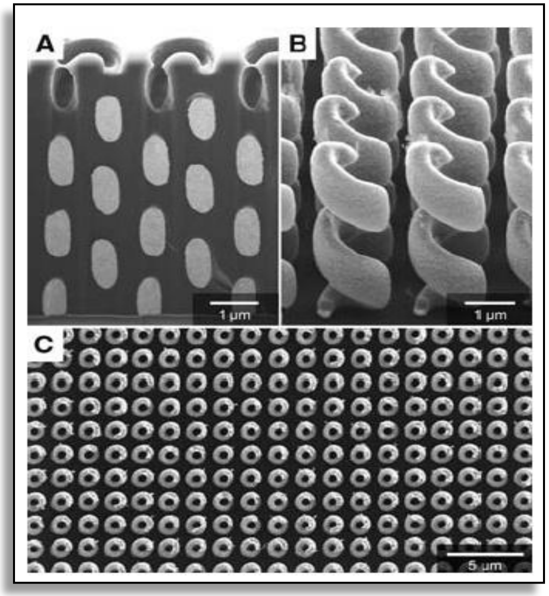


E. Plum, et al, Phys. Rev. (2009) / Zheludev's group

3-D Chiral Metamaterials

[Fabrication process]



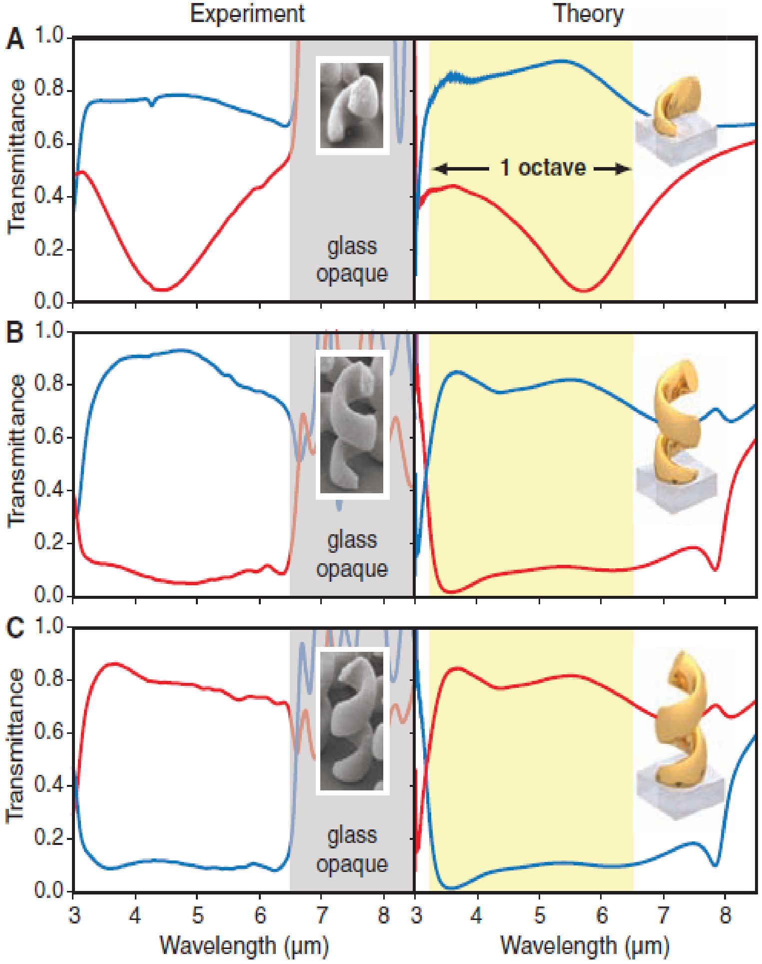


[SEM images]

A Cross view

B Till angle view

C Top view

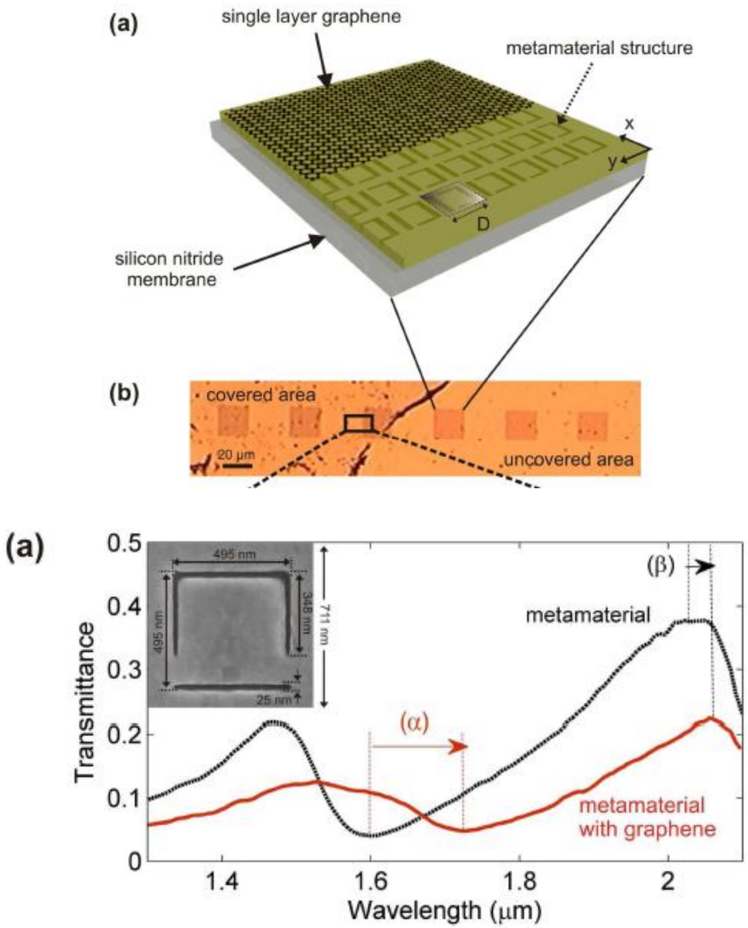


— LCP, — RCL

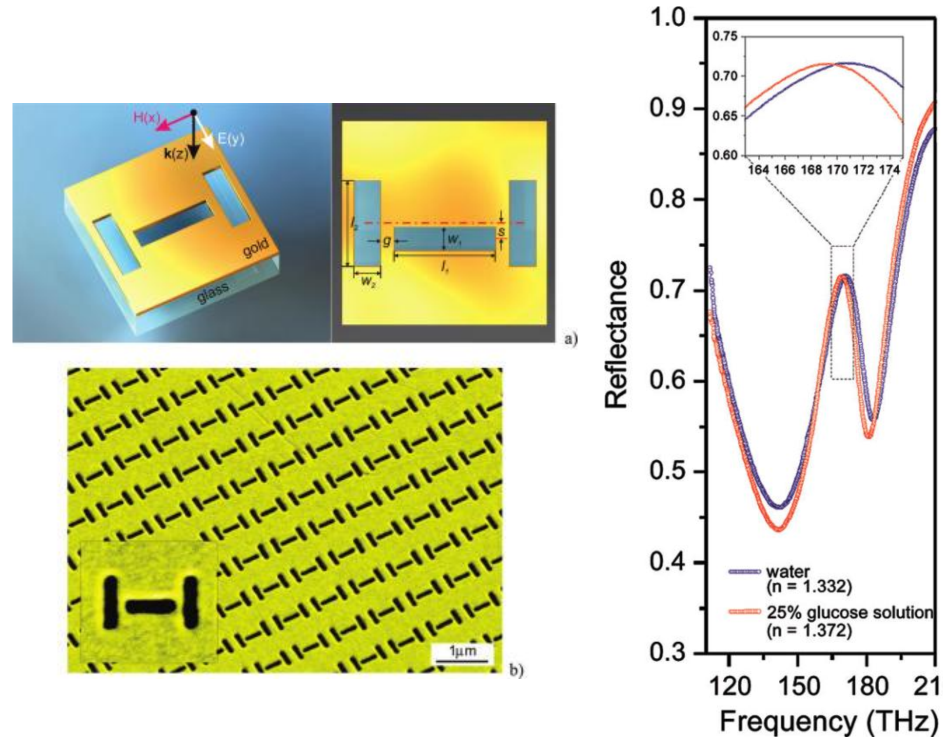
J. K. Gansel, et al, Science (2009) / Wegener group

Metamaterials for Sensing

Metamaterials for Sensing



Graphene+metamaterial for sensing

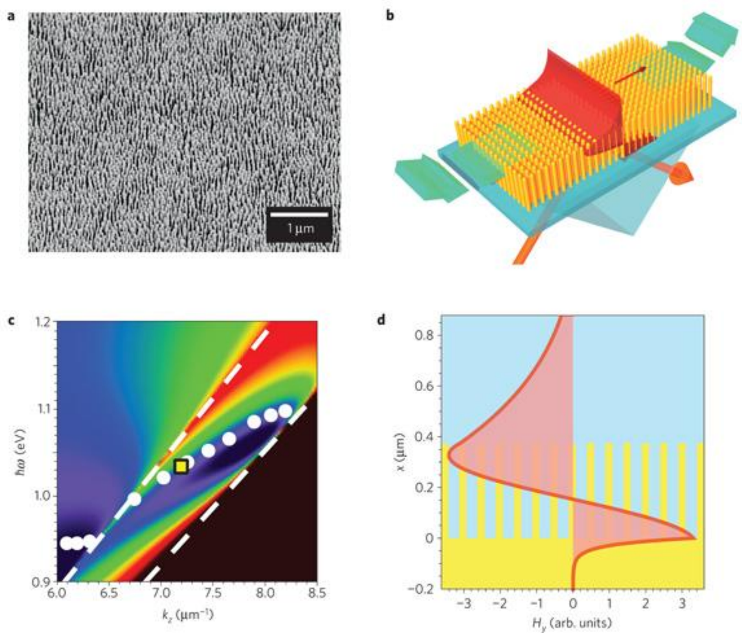


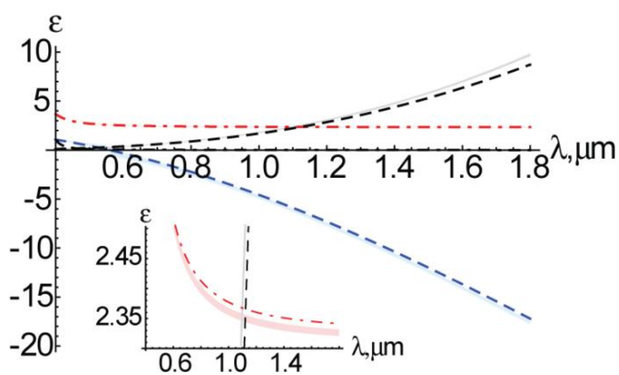
EIT metamaterial for sensing

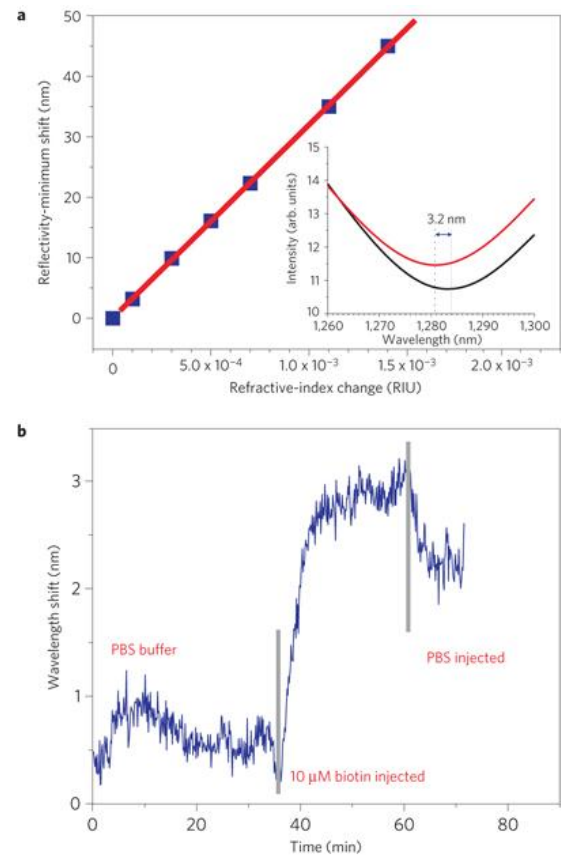
Papasimakis, et al, OE (2010) (Zheludev group)

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

Hyperbolic Metamaterials for Biosensing







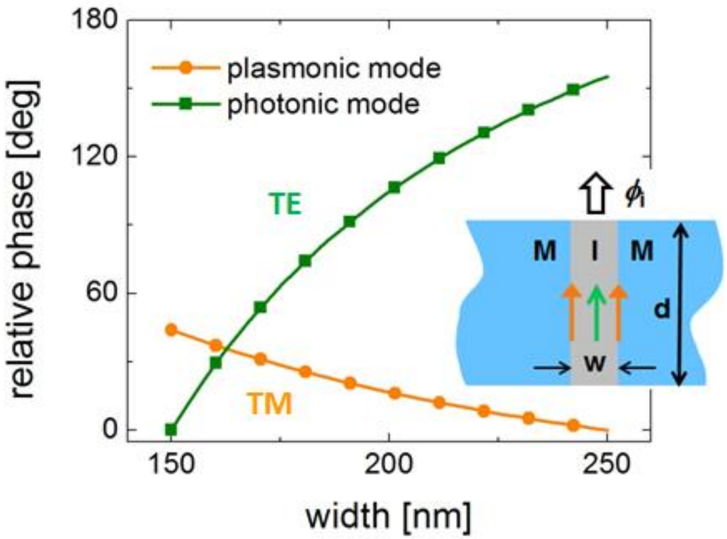
More than <u>100 times</u> sensitive than other SPR based sensors

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

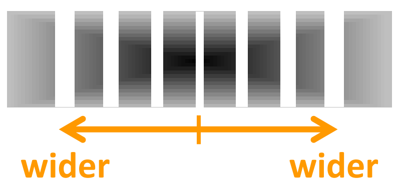
Nanoslit Lenses

Key author: Satoshi Ishii
(see his poster)

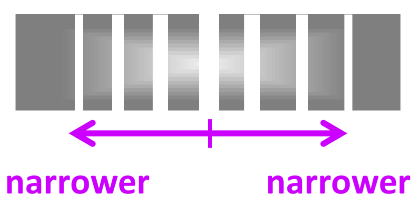
Nanoslit lenses (TM-lens & TE-lens)

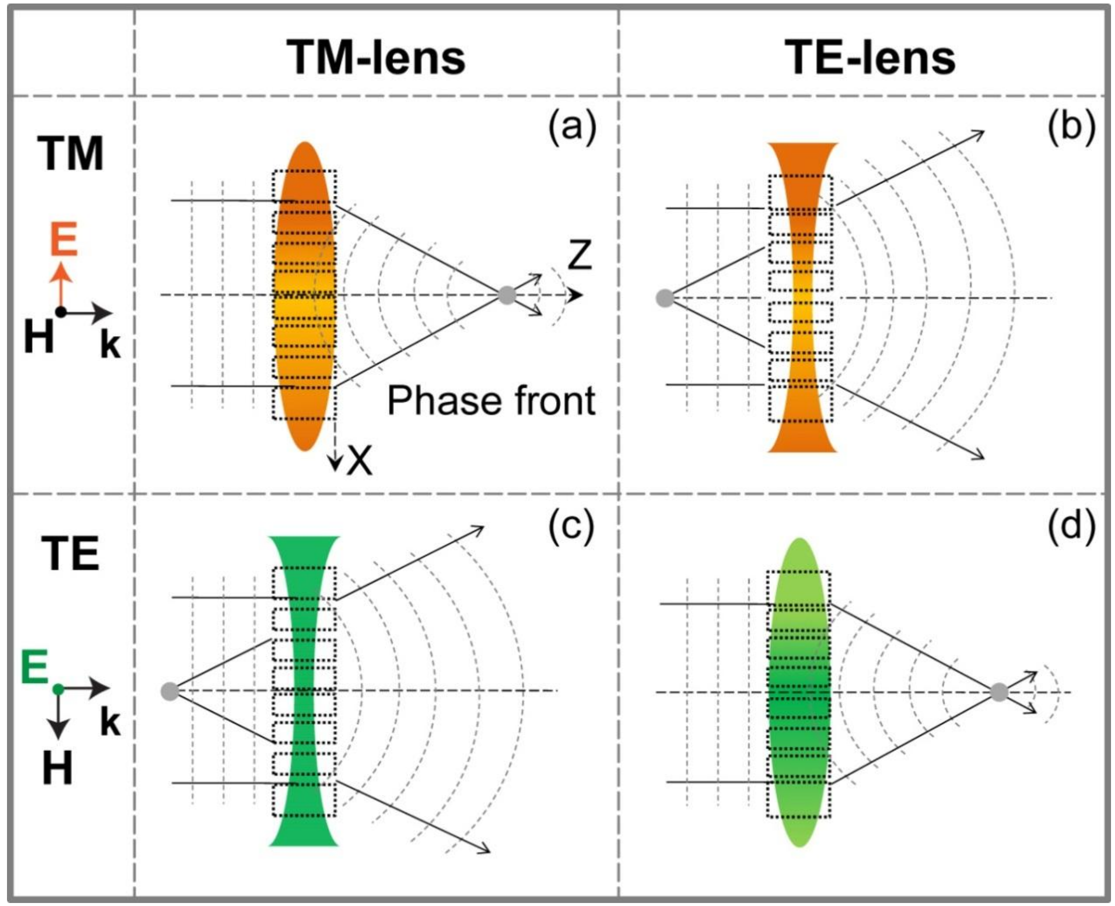


- TM-lens



- TE-lens

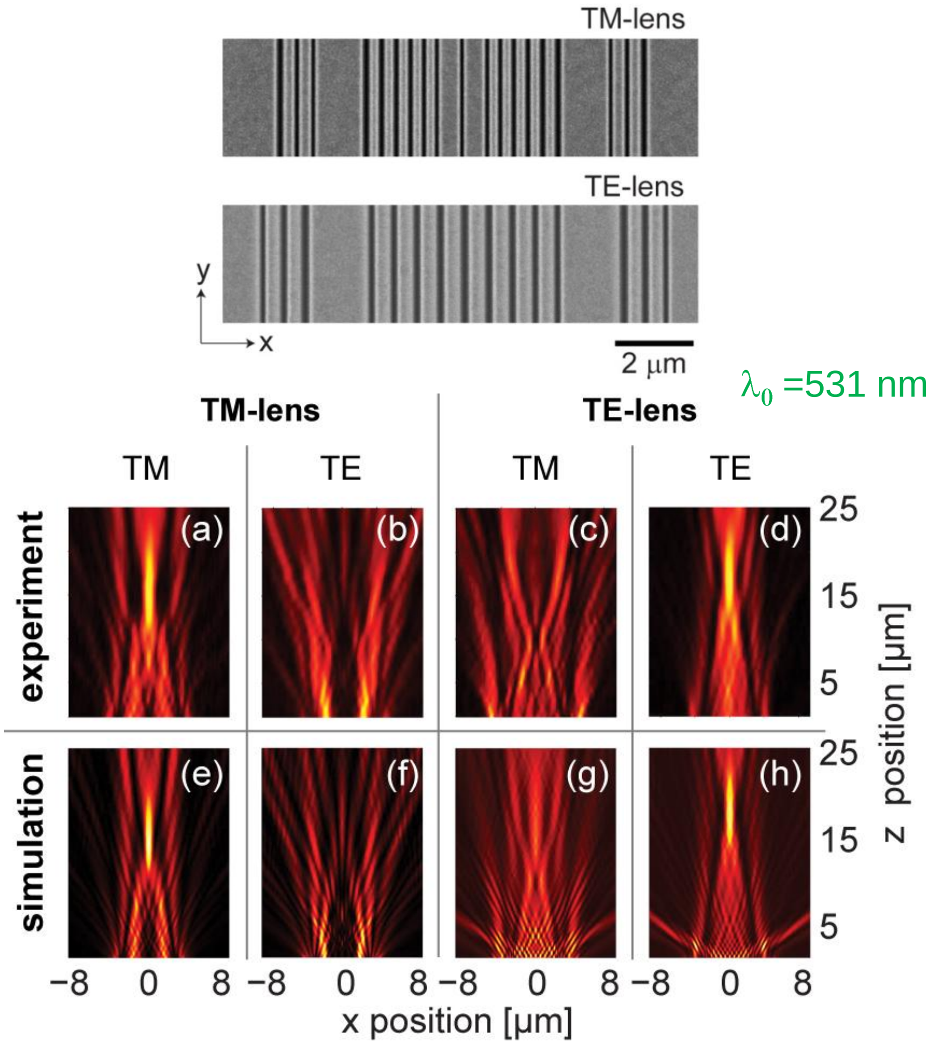




Related work by Brongersma, Fan, et al

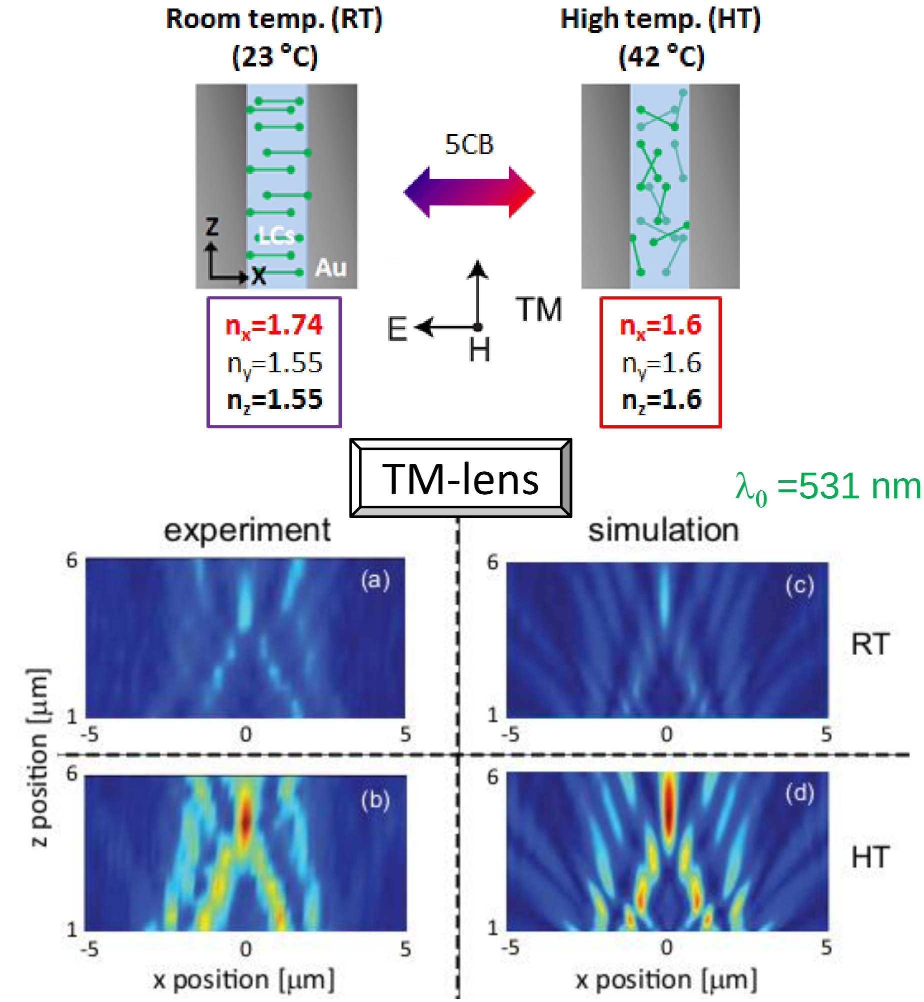
Experimental demonstrations of nanoslit lenses

- Polarization selective design



S. Ishii, A. V. Kildishev, V. M. Shalaev, K. Chen, and V. P. Drachev, Opt. Lett. (2011)

- Liquid crystal controlled lenses

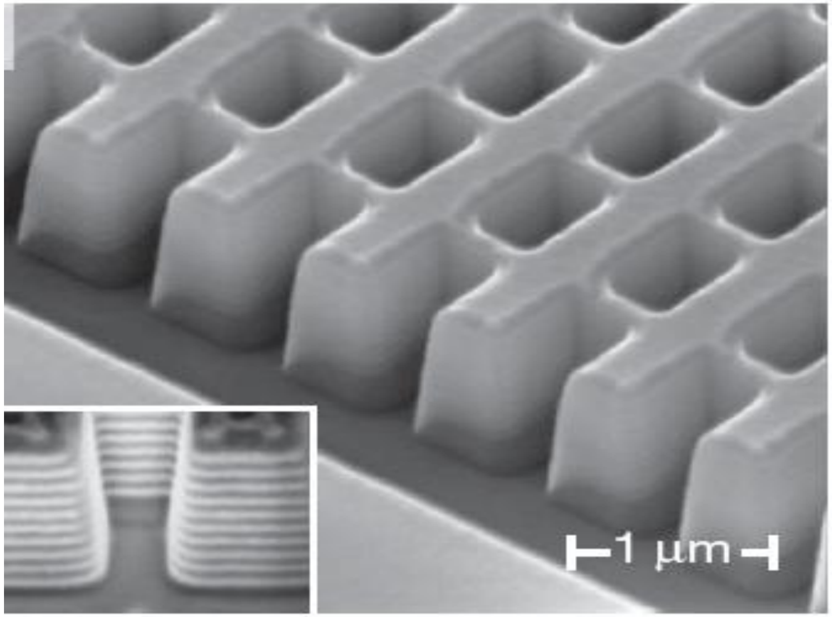


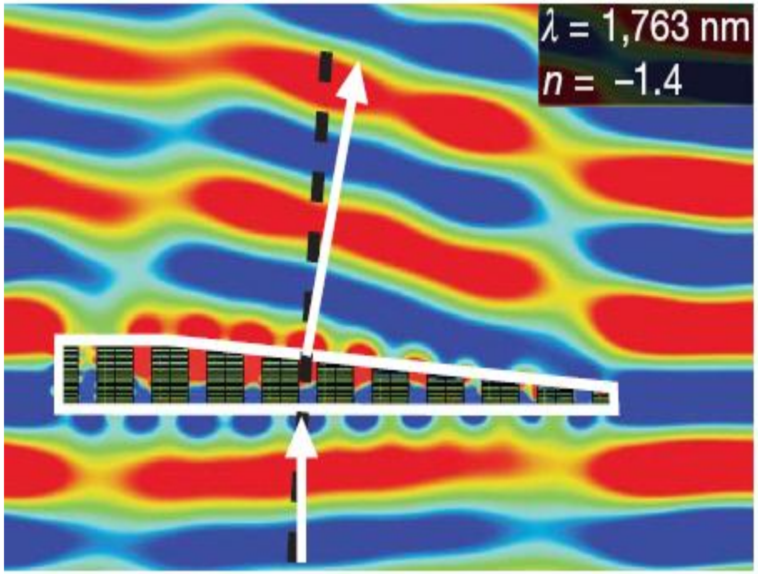
S. Ishii, A. V. Kildishev, V. M. Shalaev and V. P. Drachev, *Laser Phys. Lett*. **8**, 828-832 (2011) (cover page article)

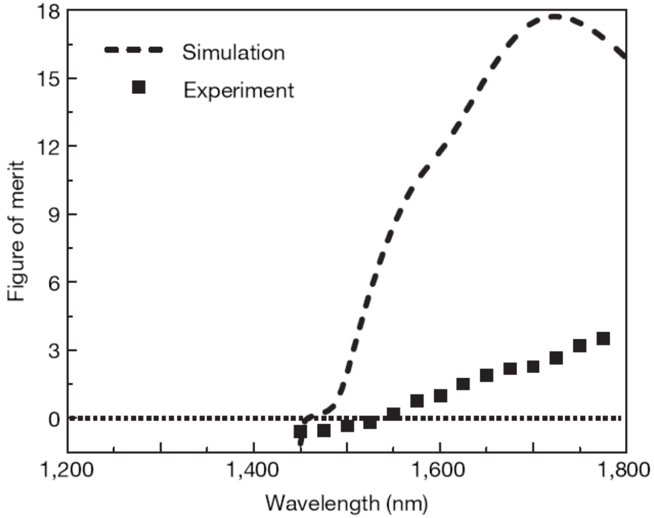
Negative-Index Metamaterials and Nonlinear Optics

Bulk NIMs enable new NLO

- Three-dimensional optical metamaterial with a negative refractive index



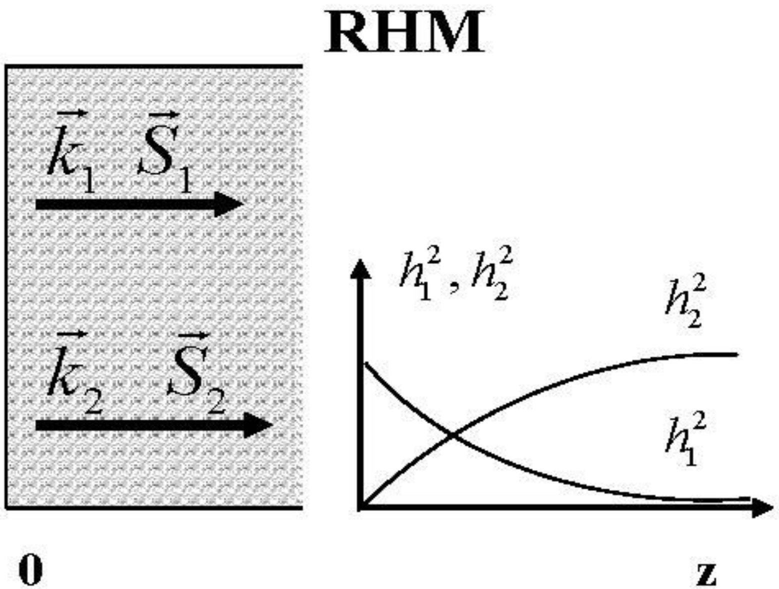


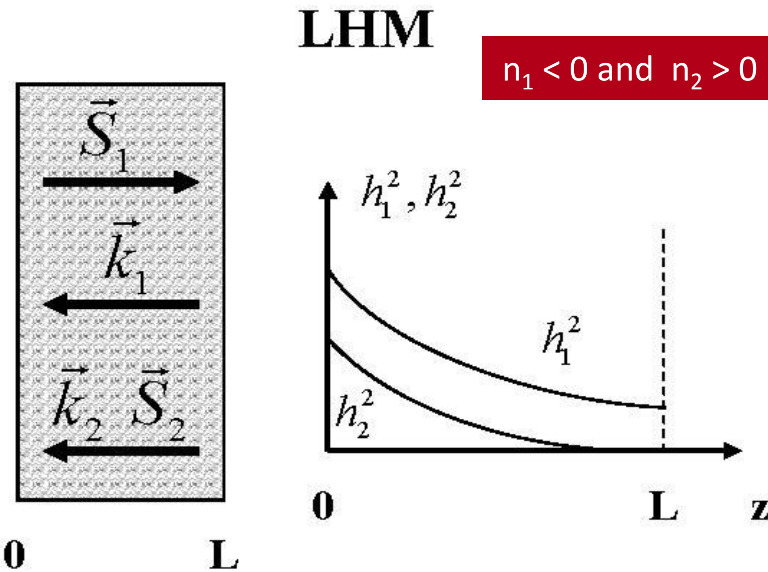


(Zhang group, Nature. 455, 376 (2008)

Backward Waves in Nonlinear NIMs

Backward Waves in NIMs: Popov and Shalaev (APB, 2006), Popov, Slabko, and Shalaev (LPL, 2006)
[Others groups: Kivshar, Shadrivov, et al; Zakhidov, Agranovich, et al; AKP and Myslevets]





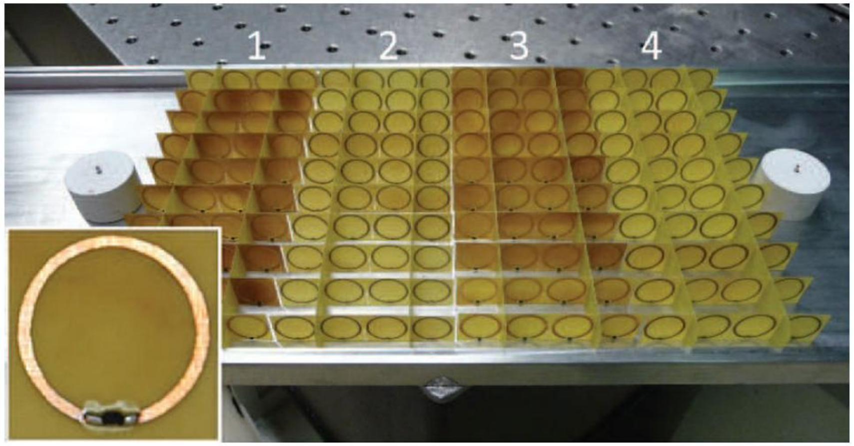
$n_1 < 0$ and $n_2 > 0$

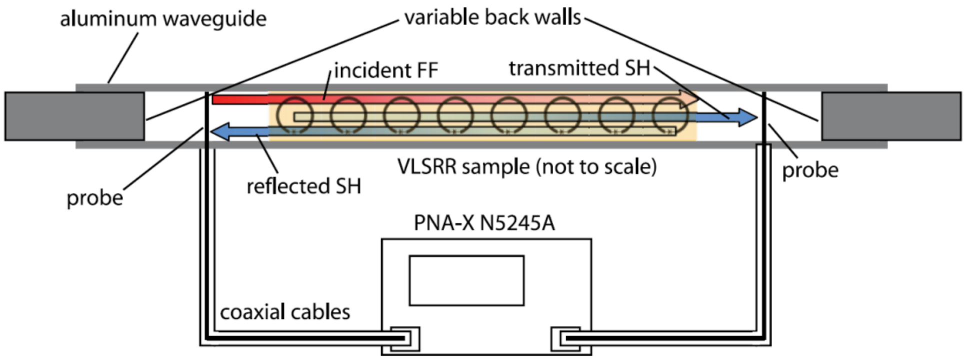
Manley-Rowe Relations

$$\frac{dS_1}{dz} - \frac{dS_2}{dz} = 0,$$

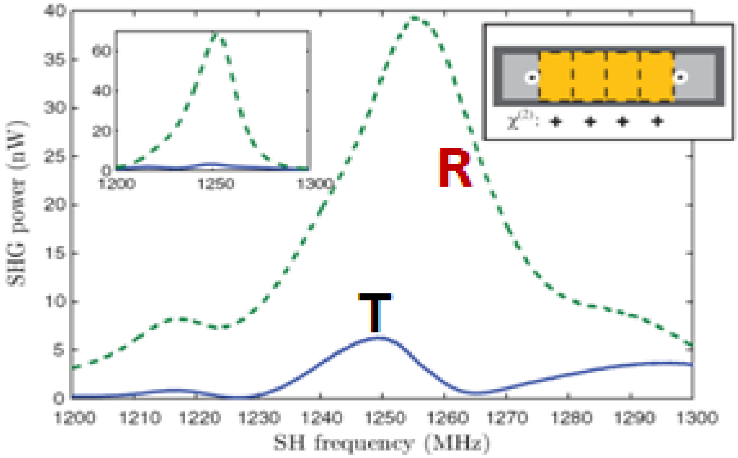
Phase-matching: $\varepsilon_1 = -\varepsilon_2, k_2 = 2k_1$ ➡ $h_1^2(z) - h_2^2(z) = C$

Second Harmonic generation in a Phase-Matched NIM





Experimental setup



R. SH enhancement
(nonlinear optical mirror)

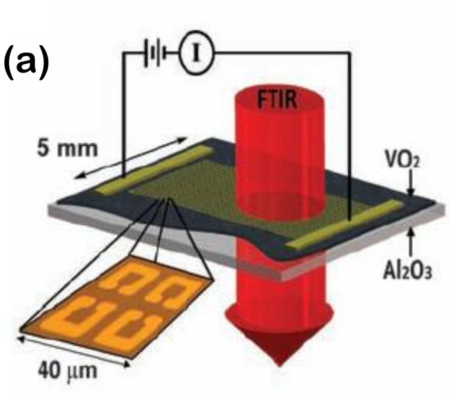
A. Rose, et al, PRL (2011) (Smith Group)

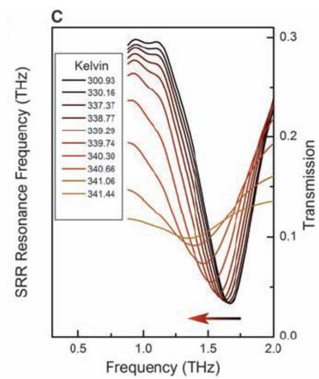
Tunable, Ultrafast, & Nonlinear Metamaterials

Tunable MMs with Phase Change Components

Electrically controllable memory with VO_2

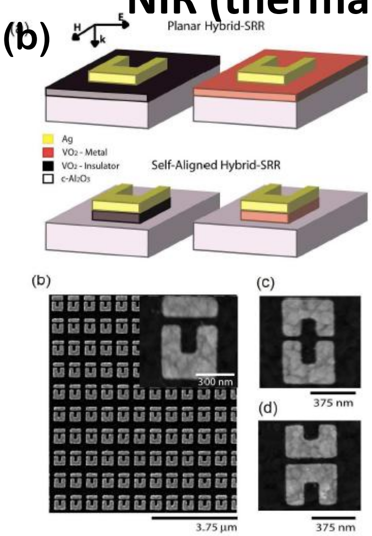
(a)

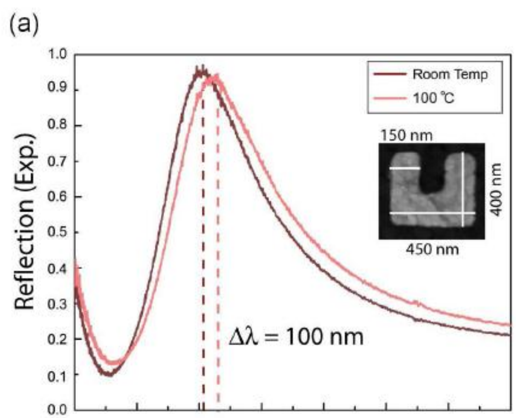




NIR (thermal) tunability with VO_2

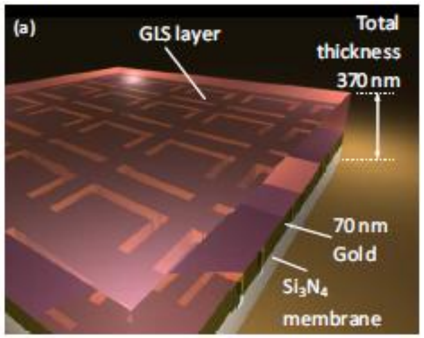
(b)

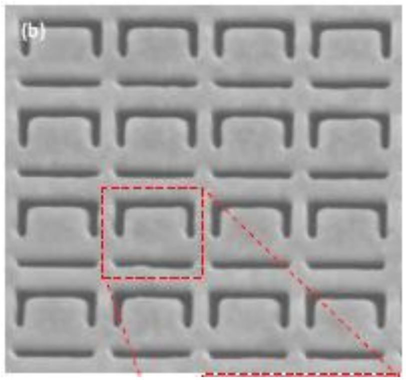


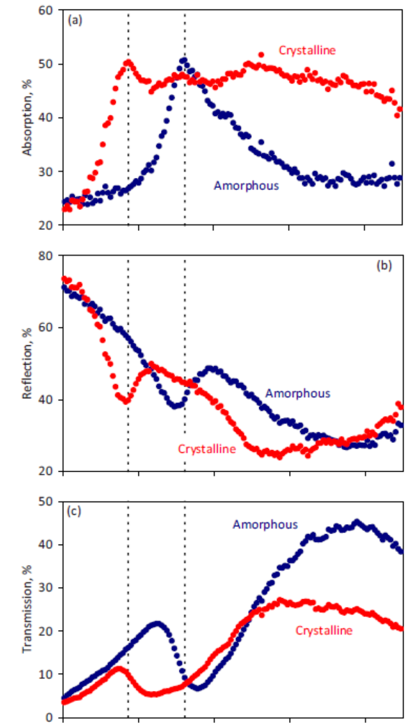


(c)

Tunability with ChG





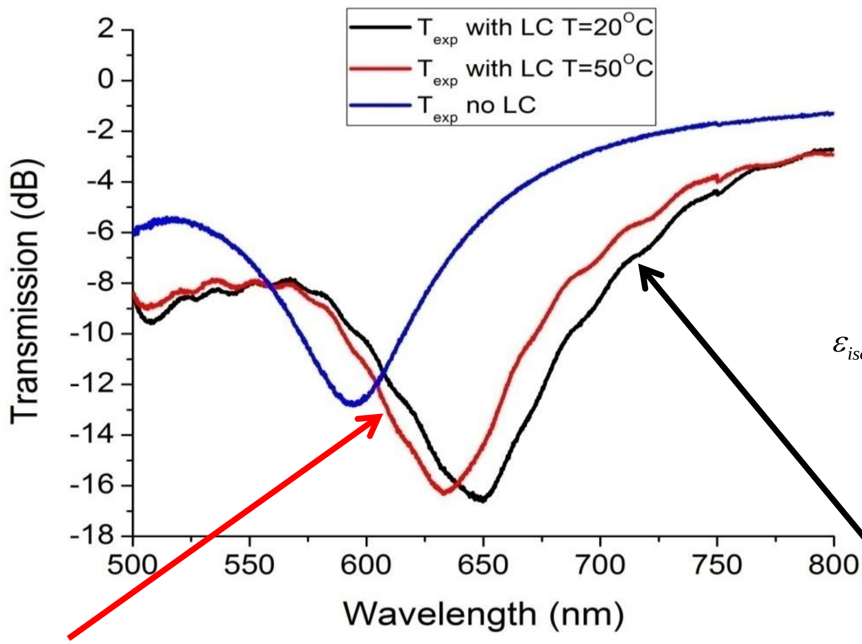


(a) T. Driscol, et al, Science, (2009) (Smith and Basov)

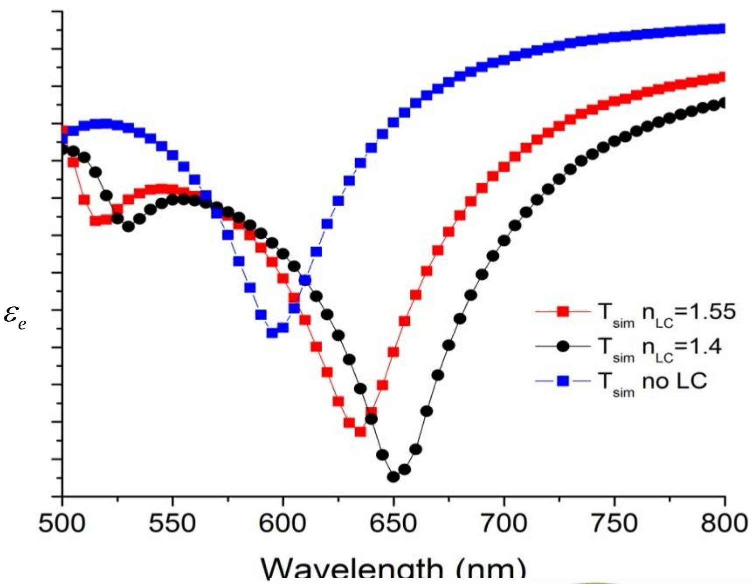
(b) M. J. Dicken, et al, OE (2009) (Atwater group)

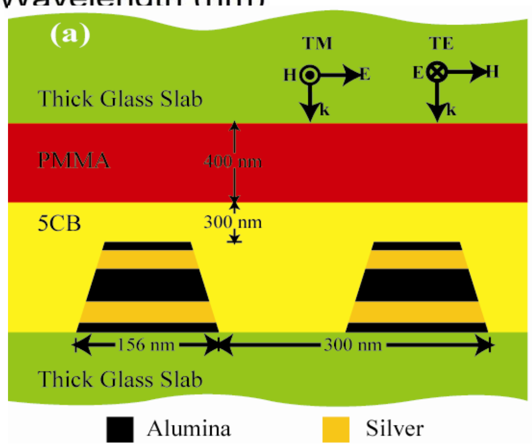
(c) Sámson, et al, APL, (2010) (Zheludev group)

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

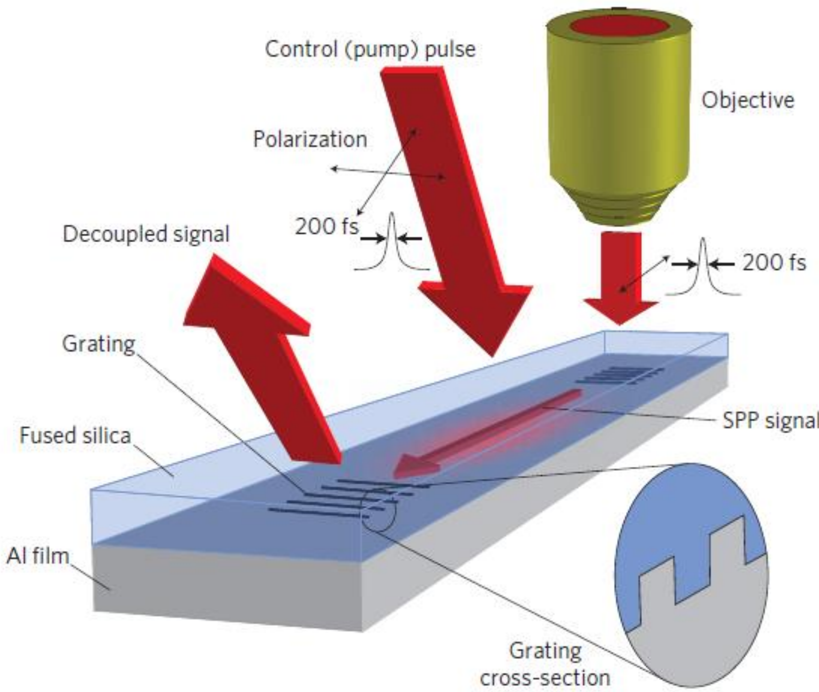
$T > T_e$

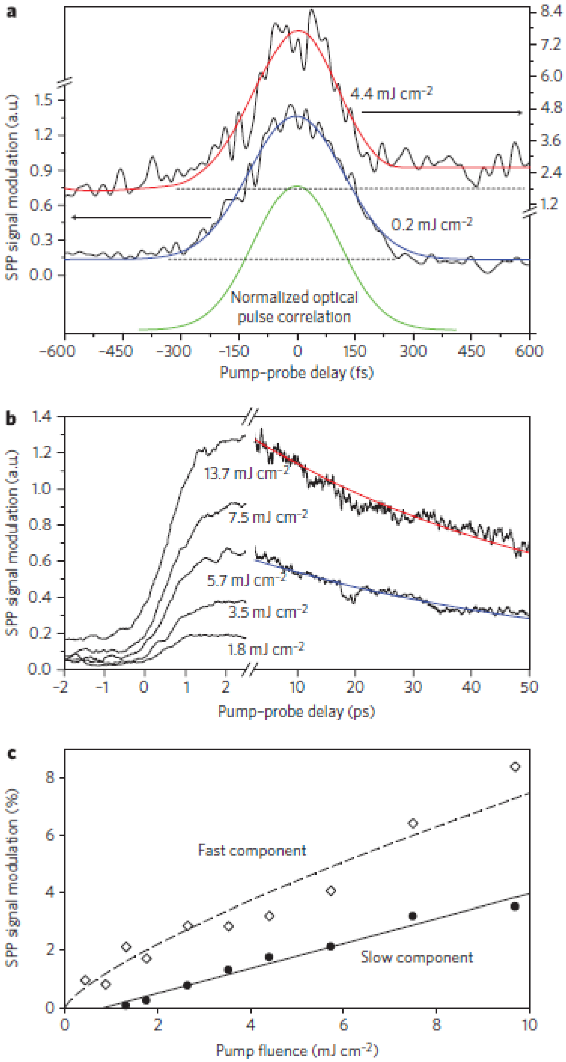
(Nematic)

$$n_{eff} = n_e$$

S. Xiao et al, APL (2009)

Ultrafast Active Plasmonics





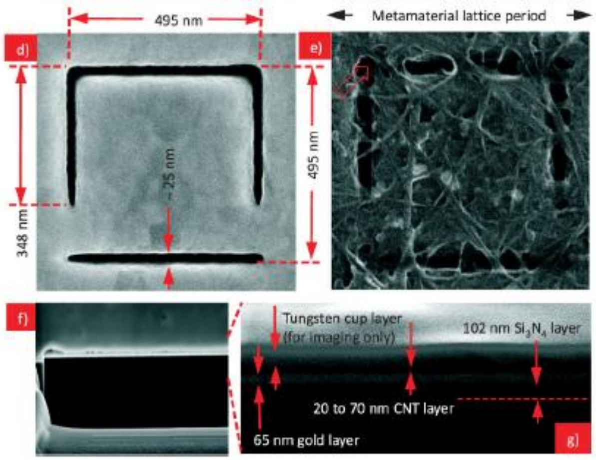
- SPP propagation influenced by optical pump
- Sub-ps control on SPPs

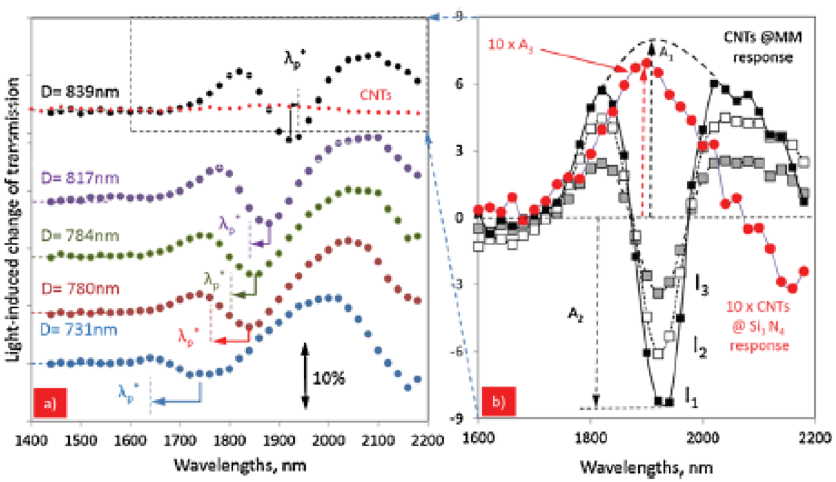
K. F. MacDonald, et al, Nature Photon. (2008) (Zheludev group and Stockman)

Nonlinear Materials + Metamaterials

Carbon nanotubes + MM

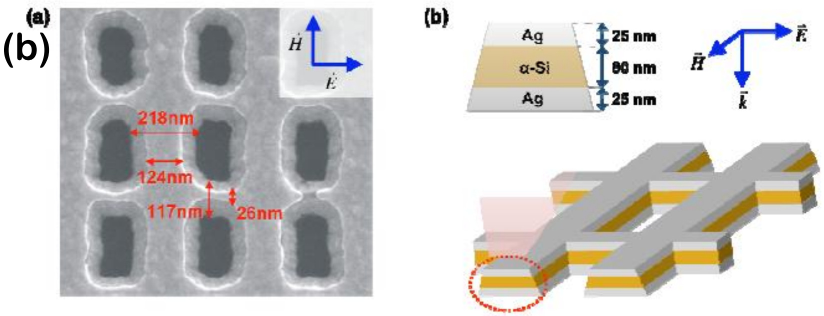
(a)

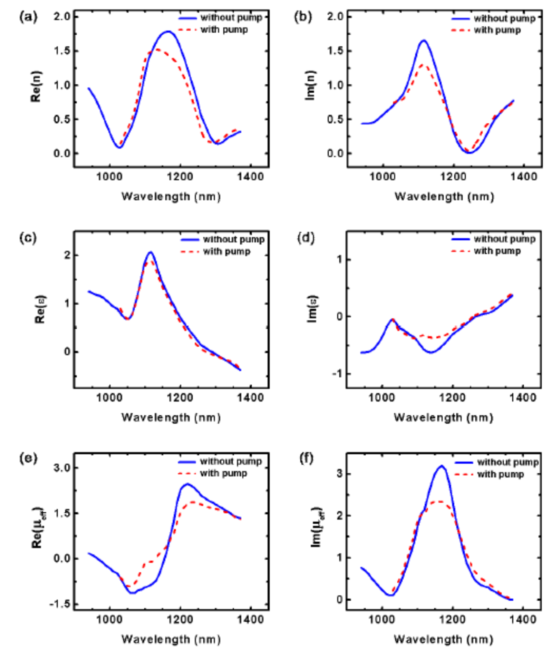




α-Si+ MM

(b)





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

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

Engineering Photonic Density of States with Metamaterials

J.-Y. Kim, G. V. Naik, Z. Jacob, V. P. Drachev,
Alexandra Boltasseva, Evgenii E. Narimanov and Vladimir M. Shalaev

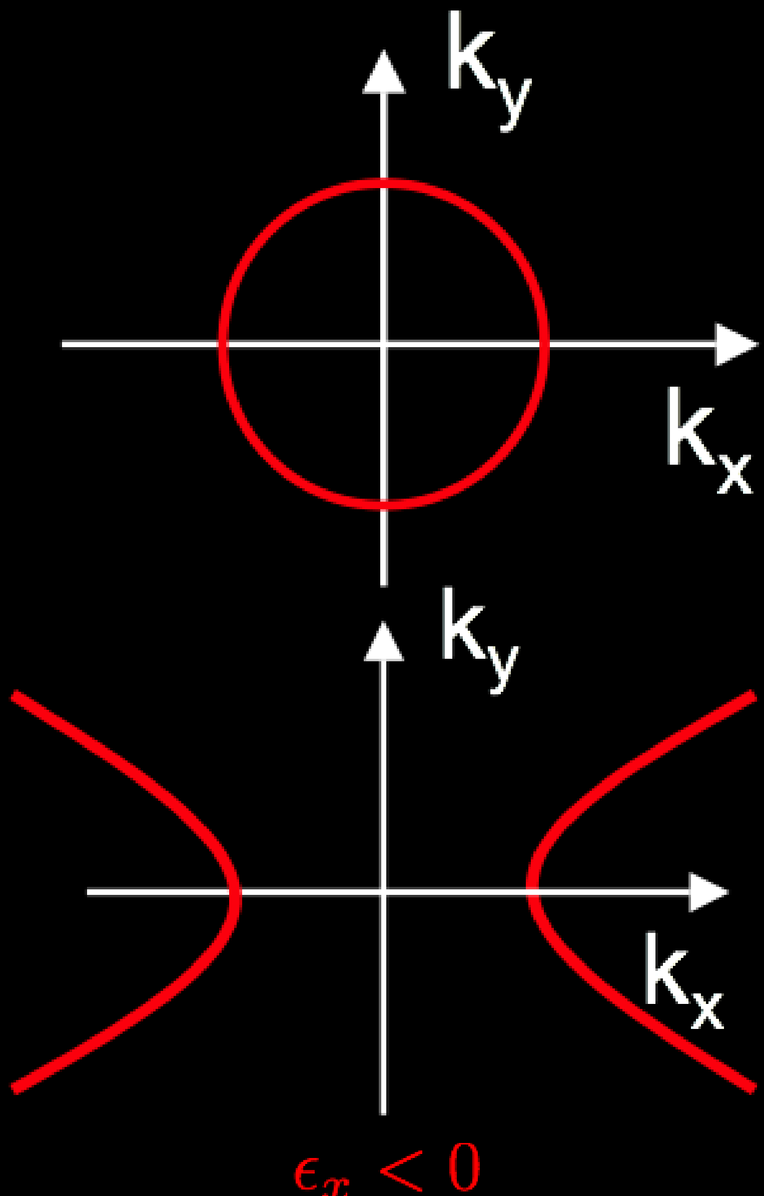
HYPERBOLIC DISPERSION

"Regular" dielectric

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

"Strongly Anisotropic" media

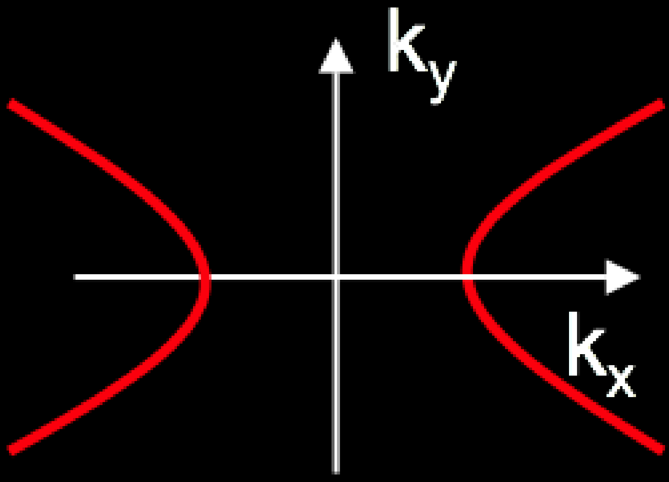
$$\frac{k_x^2}{\epsilon_y} + \frac{k_y^2}{\epsilon_x} = \frac{\omega^2}{c^2}$$



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

'STRONGLY ANISOTROPIC' MEDIA

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



$$\epsilon_x < 0$$

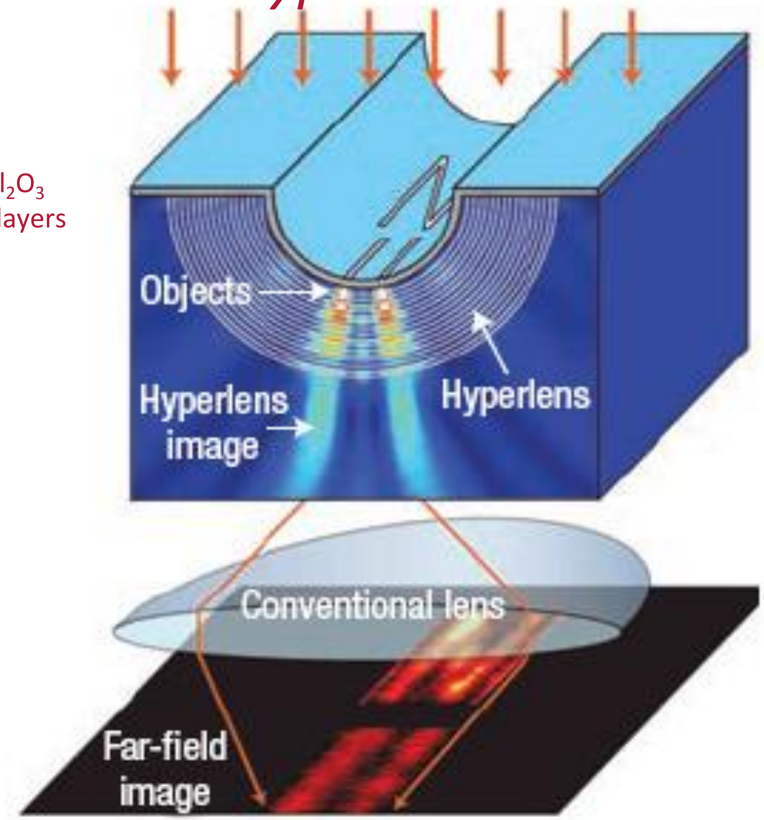
- Unlimited wavenumbers
- "Infinite" refractive index
- No diffraction limit for imaging

Z. Jacob et. al, Opt. Express (2007), Hyperlens

’STRONGLY ANISOTROPIC’ MEDIA

Hyperlens

$Ag/\ Al_2O_3$ multilayers



- Unlimited wavenumbers
- “Infinite” refractive index
- No diffraction limit for imaging
- HYPERLENS

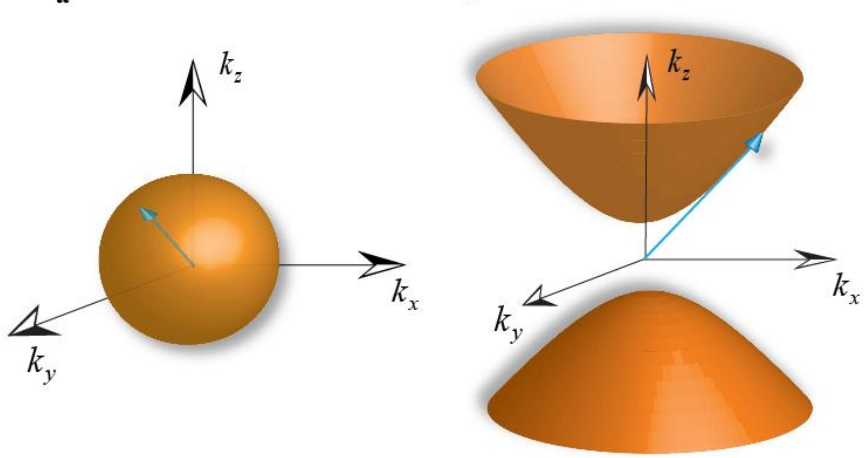
Theory : E.Narimanov et al, N. Engheta et at, 2006
Experiment : X. Zhang et al, 2007

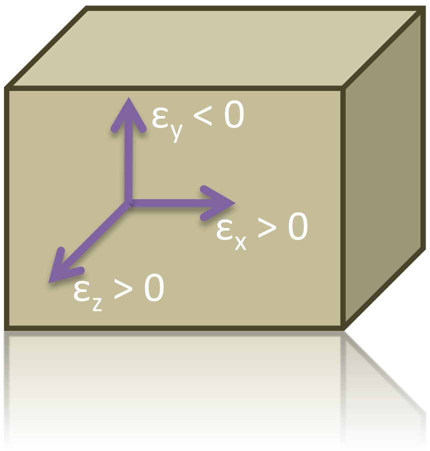
PDOS in hyperbolic metamaterial?

[vacuum]

[metamaterial]
(|k| unbounded)

a b

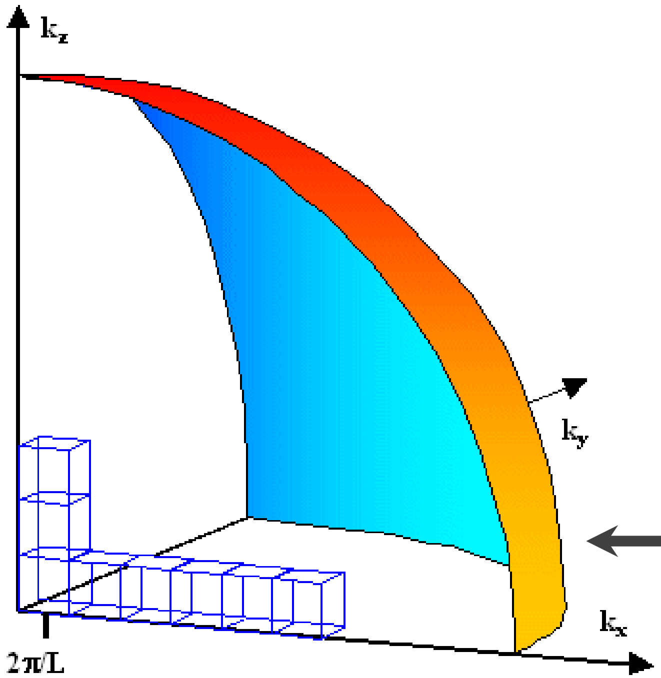




Singularity in density of states!!!!

- **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)



$$\rho(\omega) = \frac{dN}{d\omega}$$

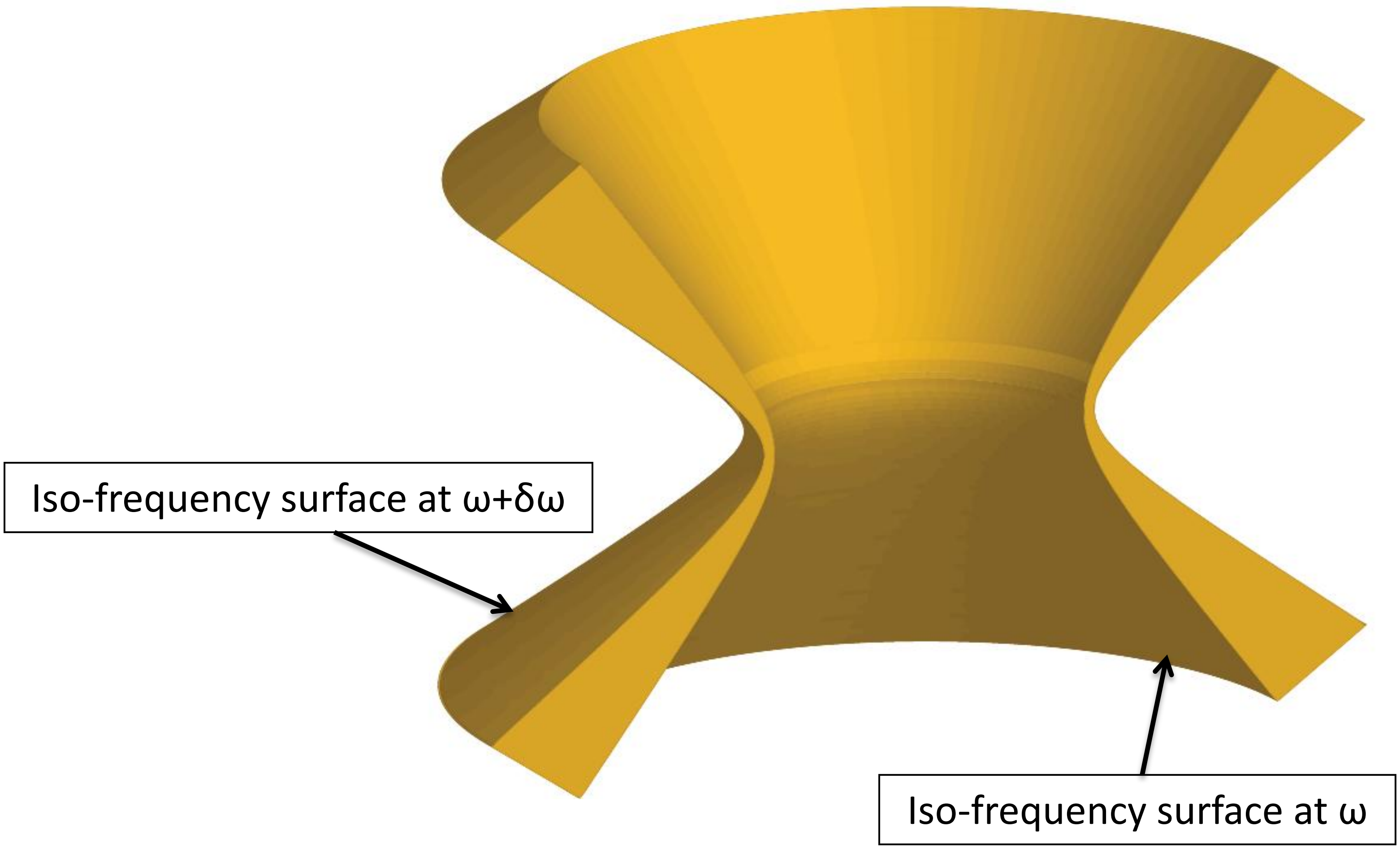
N(ω) - number of states with frequency below *ω*

$$k_x^{\ 2} + k_y^{\ 2} + k_z^{\ 2} = \varepsilon \frac{\omega^2}{c^2}$$

Free space :

$$\rho(\omega) \sim \omega^2$$

PHOTONIC DENSITY OF STATES (PDOS)



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

QED IN THE 'HYPERSPACE'

Fermi's Golden Rule: $\Gamma = \frac{2\pi}{\hbar}\rho(\omega_f) \times$ (Dipole matrix element)^2

Available density of states for emitted light

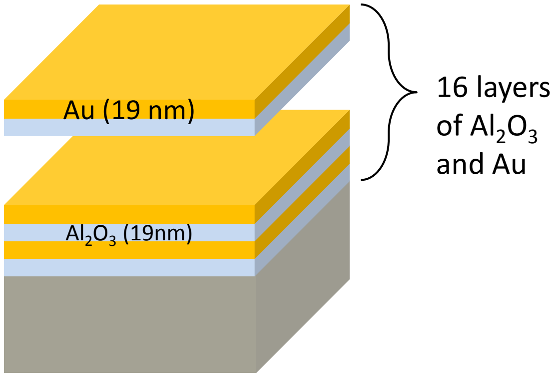
Coupling of emitter to field (depends on the mode volume)

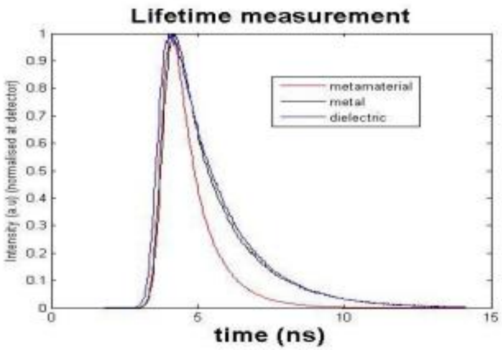
- Rate of SE, can be understood as property of atom-environment system
- Environment (cavity, PhC, nanowire) enhances density of states

Environment strongly alters the rate of SE through the available PDOS!

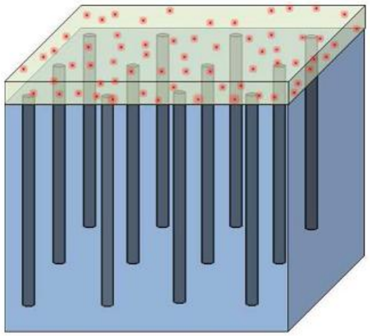
Research Goals I

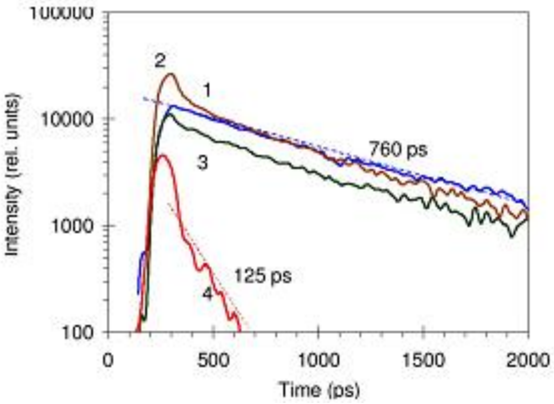
Design 1. Shalaev's group:
Stacked metal-dielectric layer
$\varepsilon_x, \varepsilon_y < 0, \varepsilon_z > 0$
$\varepsilon_\perp = 12.5+0.5i$
$\varepsilon_{||} = -8.2+0.9i$
Applied Physic B 2010



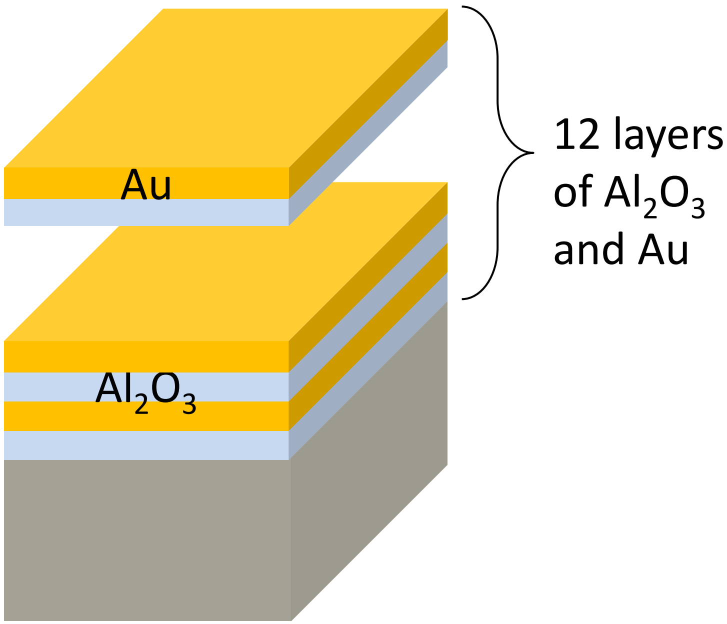


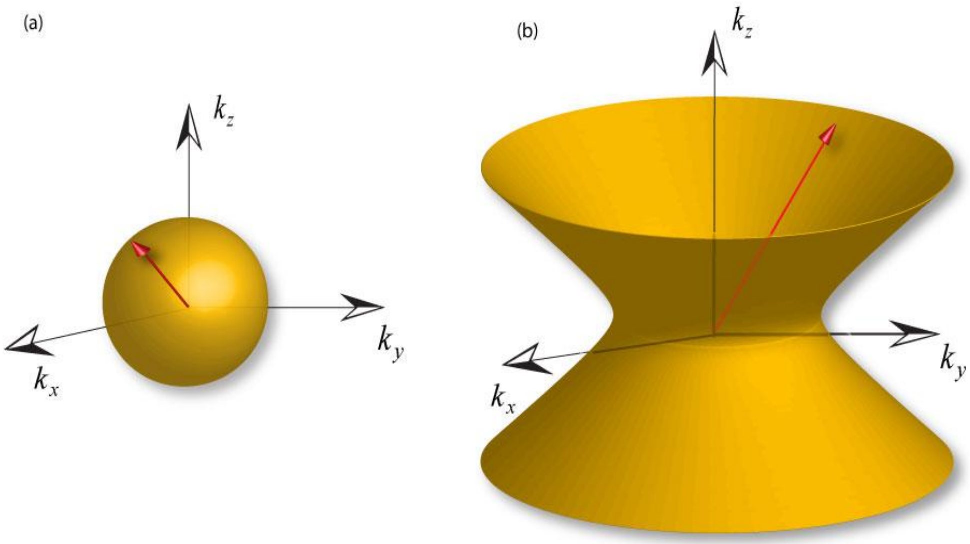
Design 2. Noginov's group:
Silver nanowire
$\varepsilon_x, \varepsilon_y > 0, \varepsilon_z < 0$
$\varepsilon_\perp = -0.15+1.07i$
$\varepsilon_{||} = 4.99+0.22i$
Optics Letters 2010





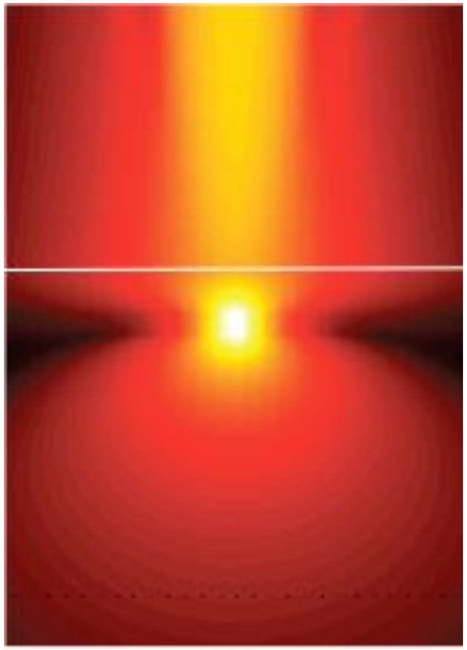
Engineering the photonic density of states using hyperbolic metamaterials

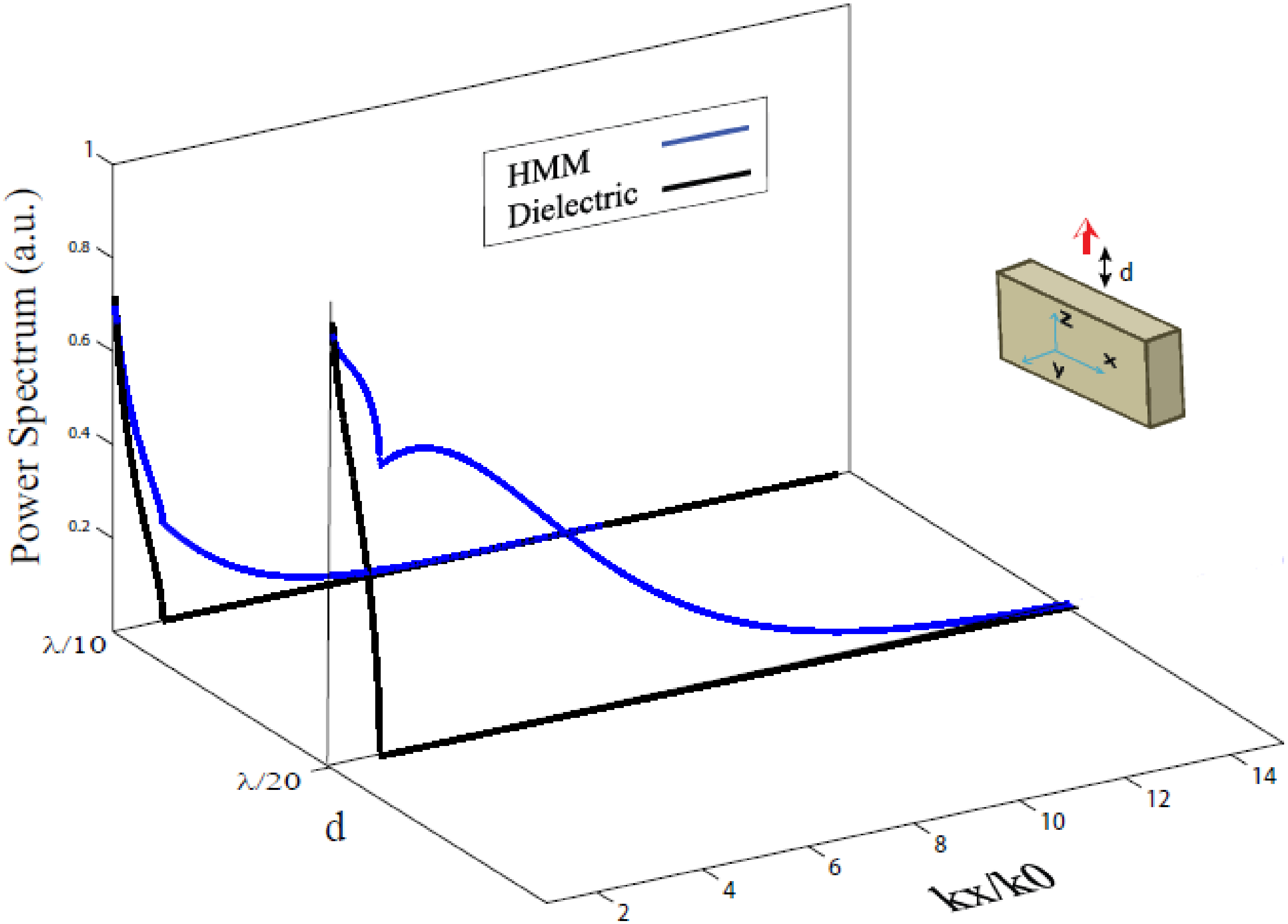




- Electromagnetic vacuum (spontaneous emission) engineering
- Thermal radiation engineering
- nanoscale control of thermal radiation

EMISSION POWER SPECTRUM





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

QED: Hughes group (2009)

Transformation Optics

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

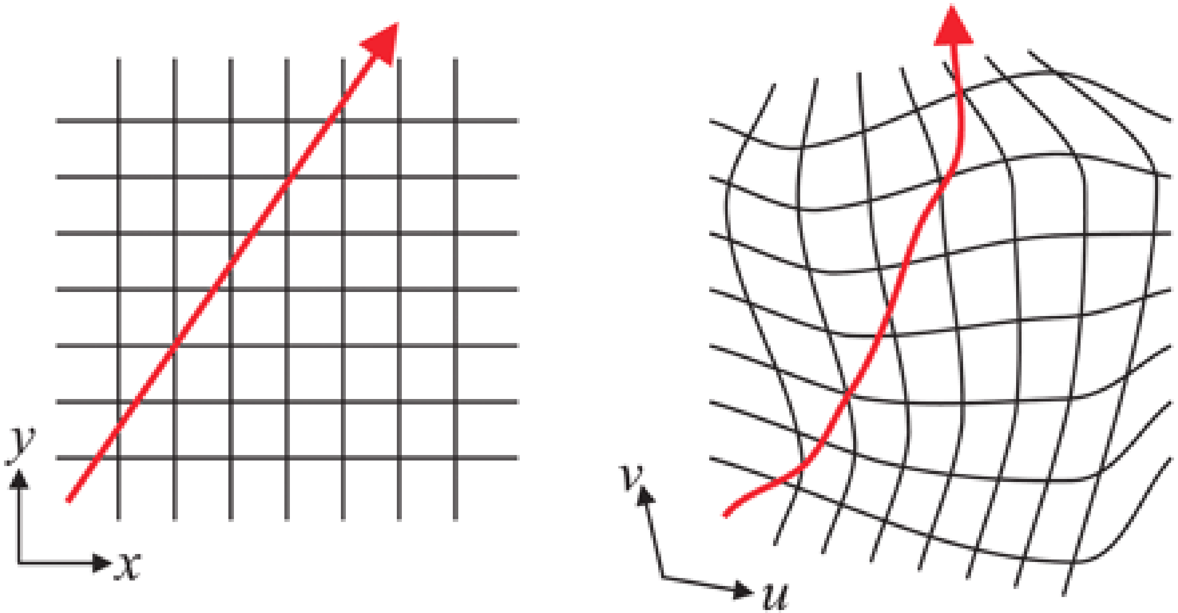
Designing Space for Light with Transformation Optics

Fermat:

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

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

"curving" optical space



Straight field line in Cartesian coordinate

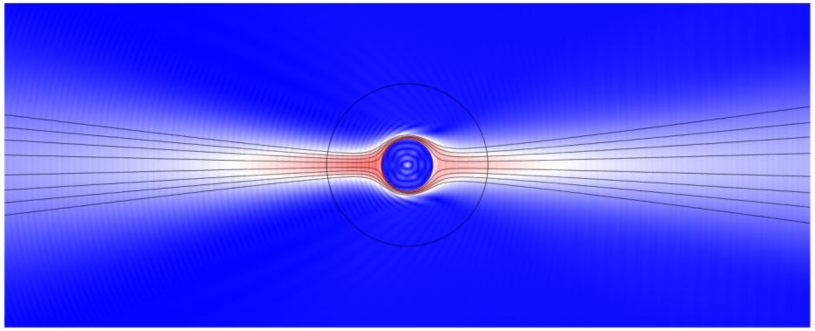
Distorted field line in distorted coordinate

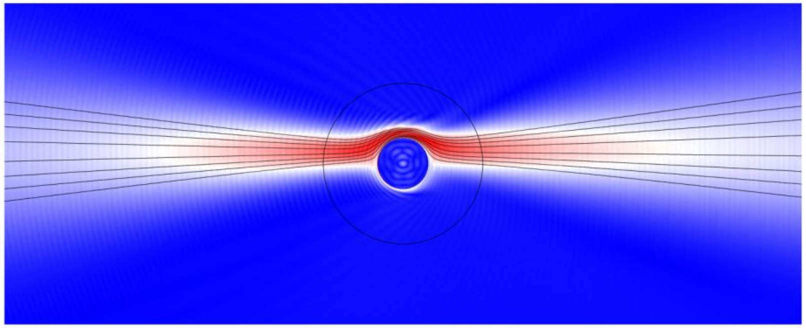
- Spatial profile of ε & μ tensors determines the distortion of coordinates
- Seeking for profile of ε & μ to make light avoid particular region in space — optical cloaking

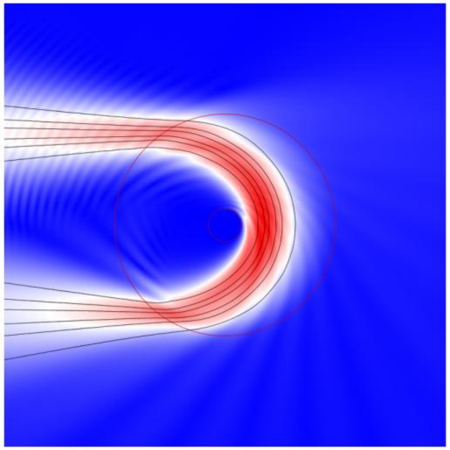
Pendry et al., Science, 2006
Leonhard, Science, 2006
Greenleaf et al (2003)
L. S. Dolin, Izv. VUZ, 19614

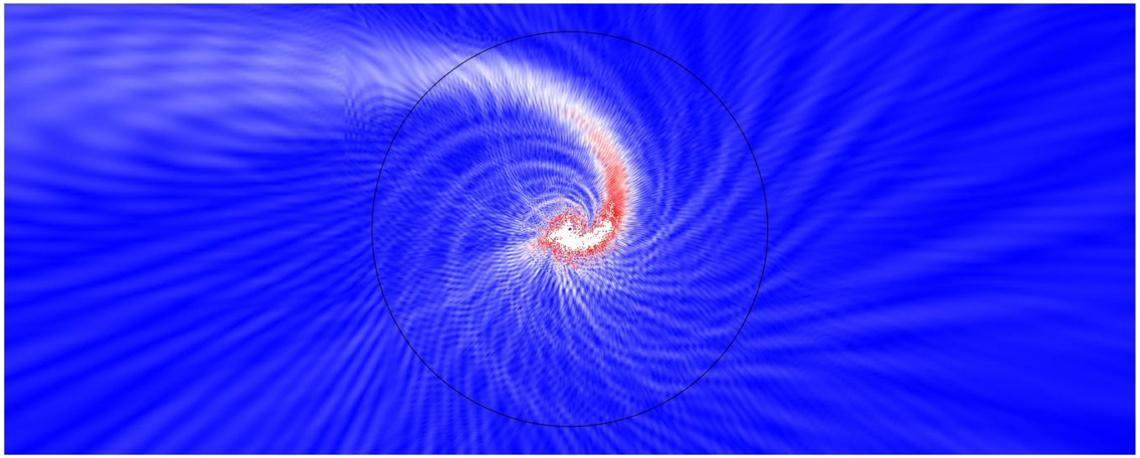
Trapping and Manipulating Light

Narimanov, Kildishev









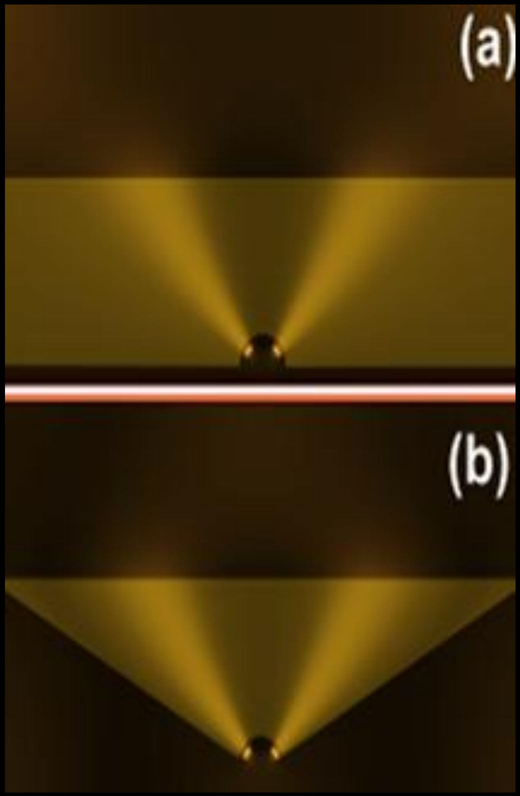
Engineering Meta-Space for Light: via Transformation Optics

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

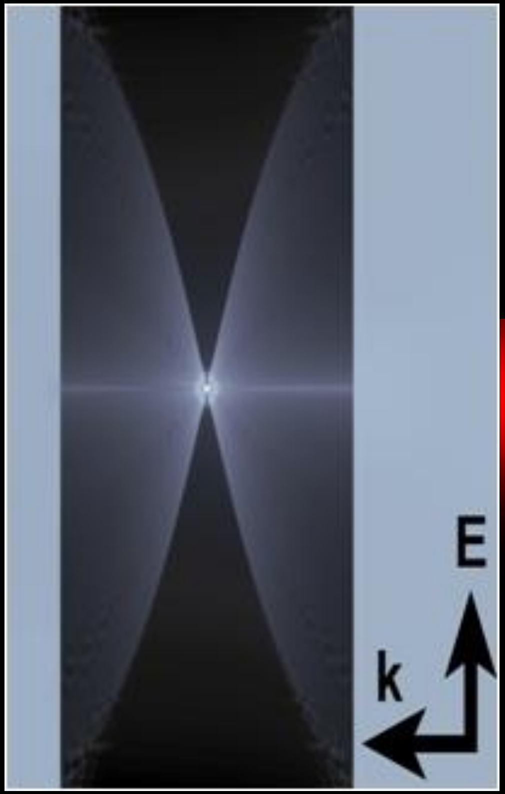
Fermat: $\delta \int n dl = 0$

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

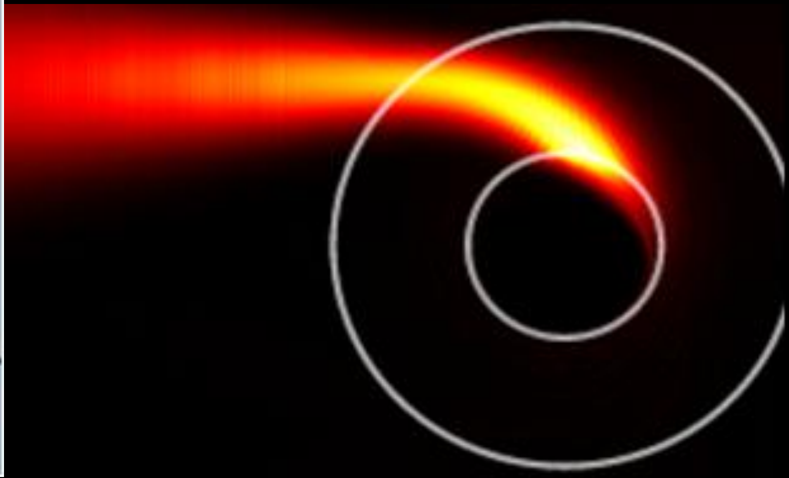
curving optical space



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



Light concentrator
(also, Schurig et al)

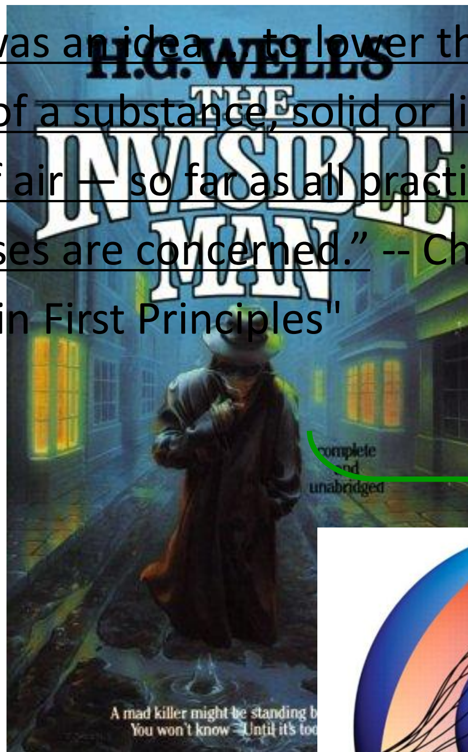


Optical Black Hole
(Zhang group;
Narimanov,Kildishev)

Examples with scientific elements:

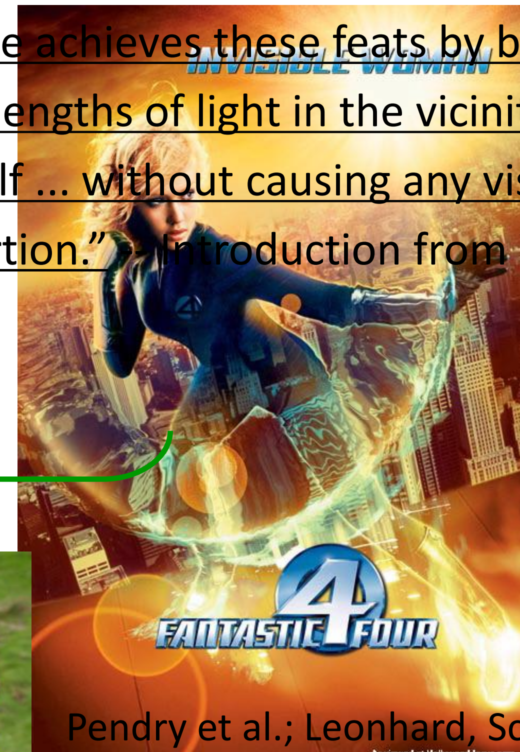
- The Invisible Man by H. G. Wells (1897)

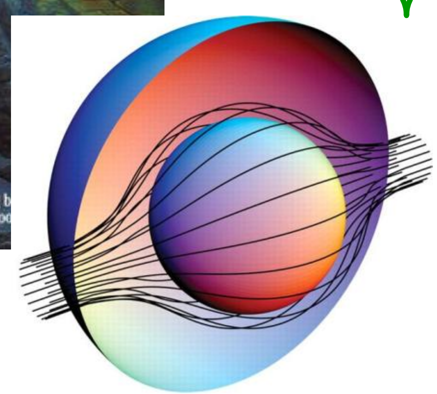
"... it was an idea ... to lower the refractive index of a substance, solid or liquid, to that of air — so far as all practical purposes are concerned." -- Chapter 19 "Certain First Principles"



- "The invisible woman" in The Fantastic 4 by Lee & Kirby (1961)

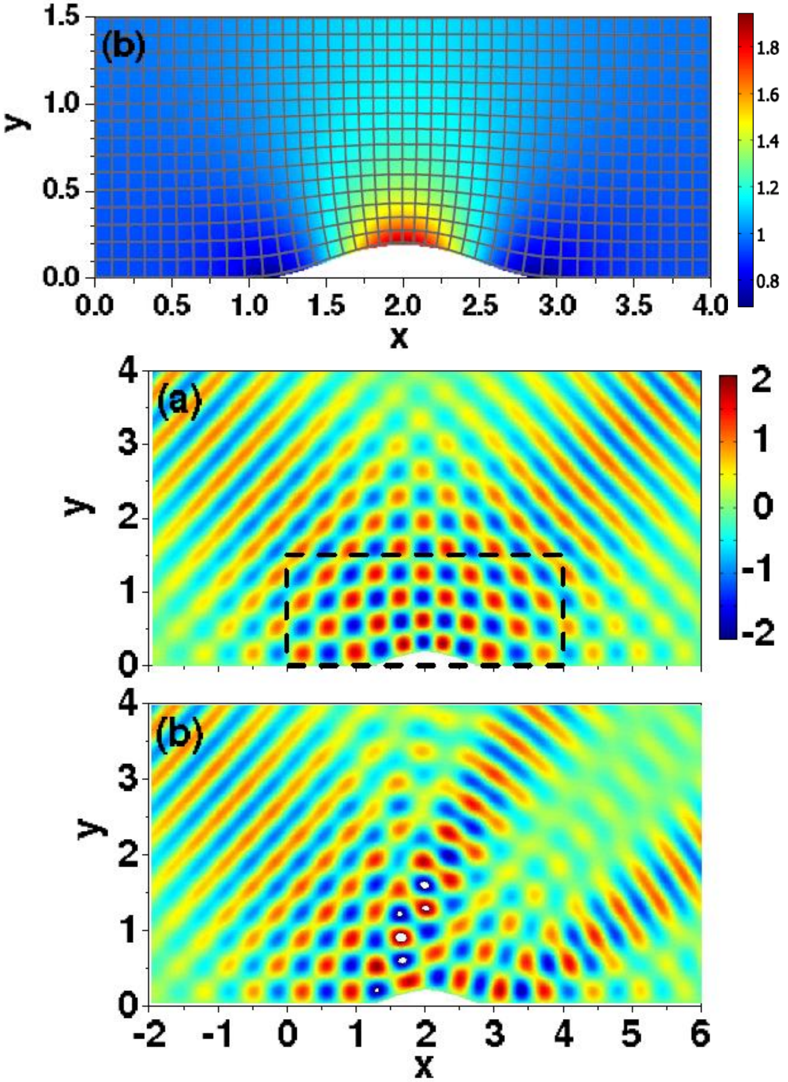
"... she achieves these feats by bending all wavelengths of light in the vicinity around herself ... without causing any visible distortion." -- Introduction from Wikipedia





Pendry et al.; Leonhard, Science, 2006
(Earlier work: cloak of thermal conductivity by Greenleaf et al., 2003)

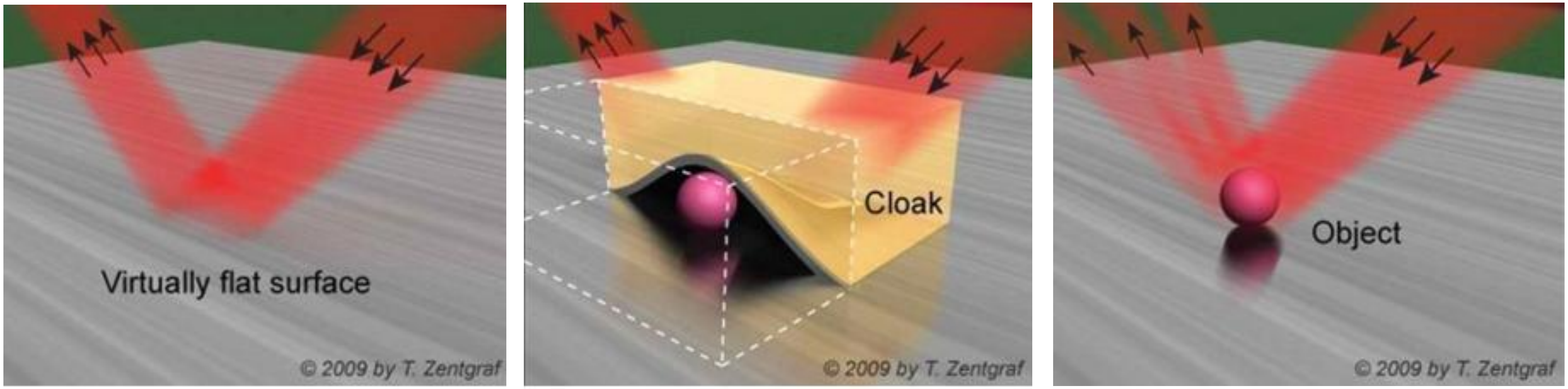
Invisible Carpet (ground-plane cloak)



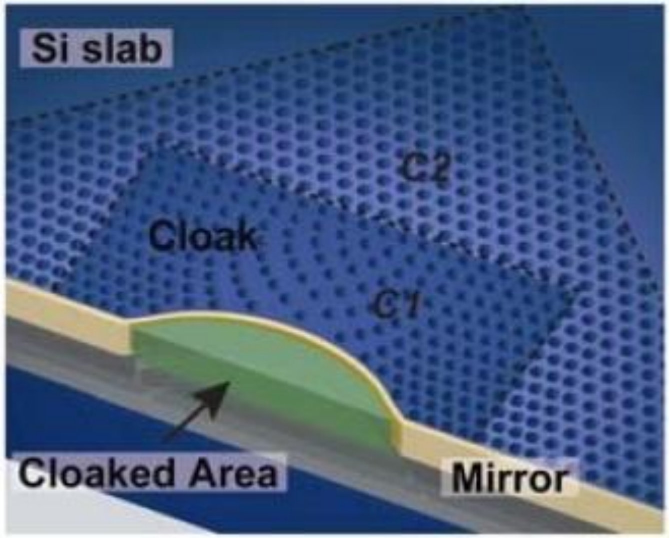
picture from discovery.com

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

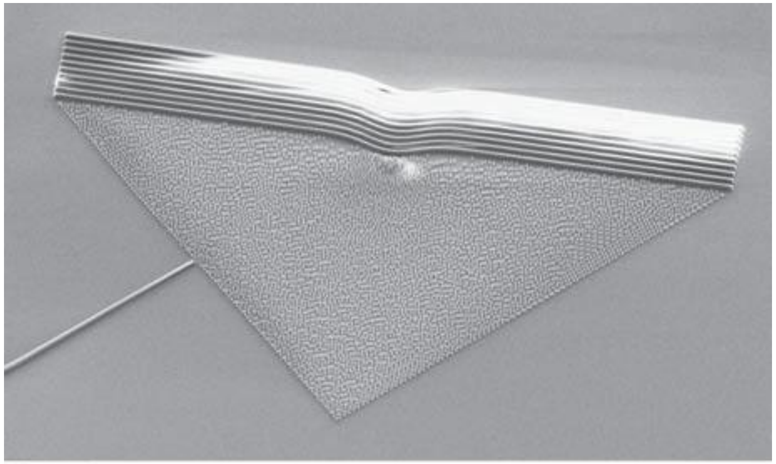
Optical Mimicry

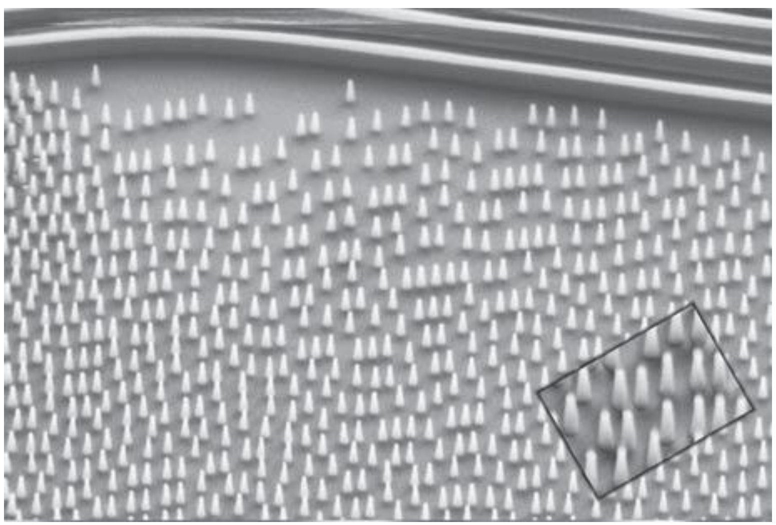


Progress Towards True Invisibility on May.17, 2009, under Science
www.codingfuture.com

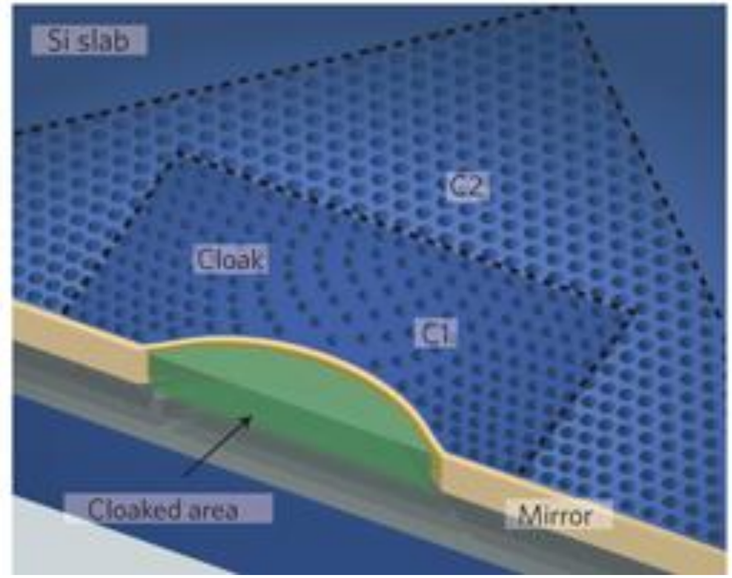


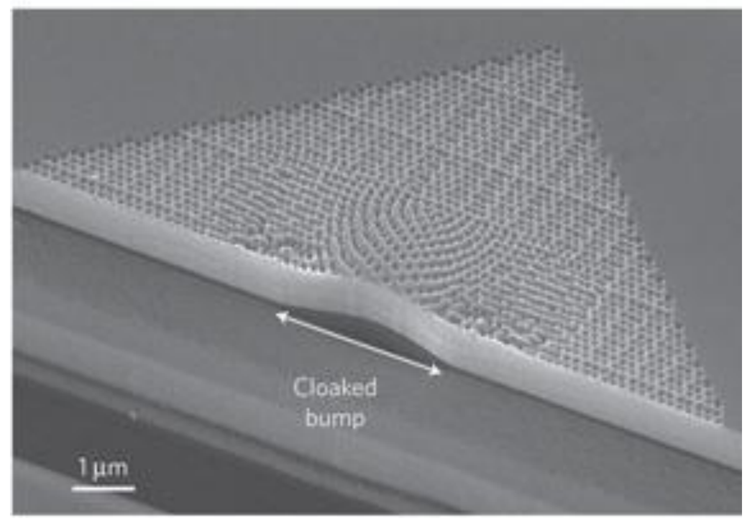
Theory: J. Li, J. Pendry
GHz: Smith et al (Duke)
Optical: Zhang et al (Berkeley)
Lipson et al (Cornel)



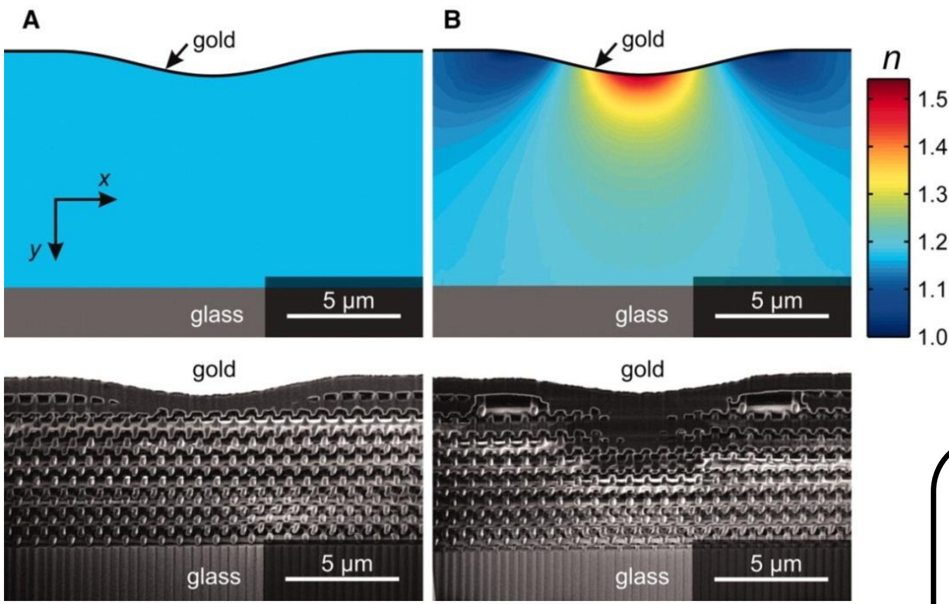


L. H. Gabrielli*, et al.*, *Nat. Photonics* **3***,* p.461, Aug 2009. (M. Lipson group)

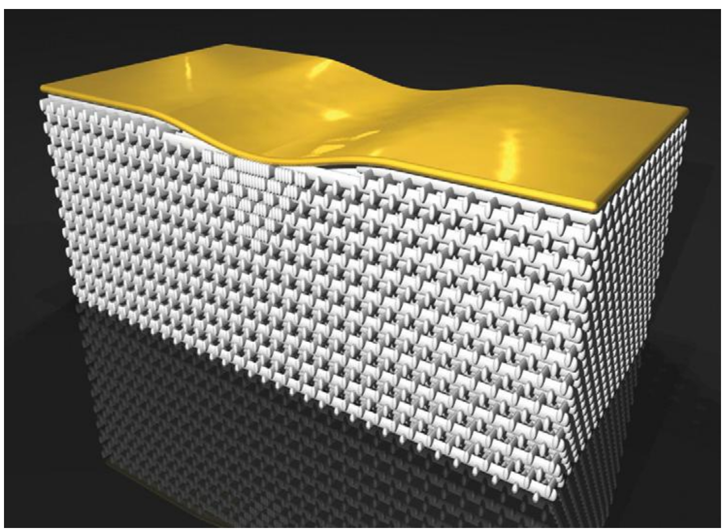




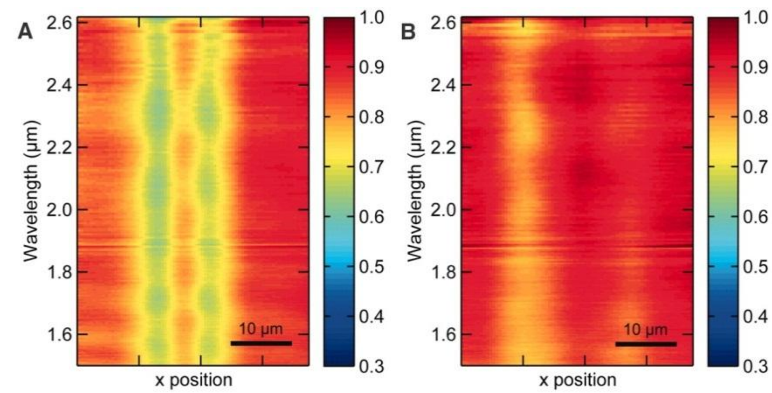
J. Valentine*, et al.*, *Nat. Mater.* **8**, p.568, Jul 2009. (X. Zhang group)



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.



Blueprint of the 3D carpet-cloak structure



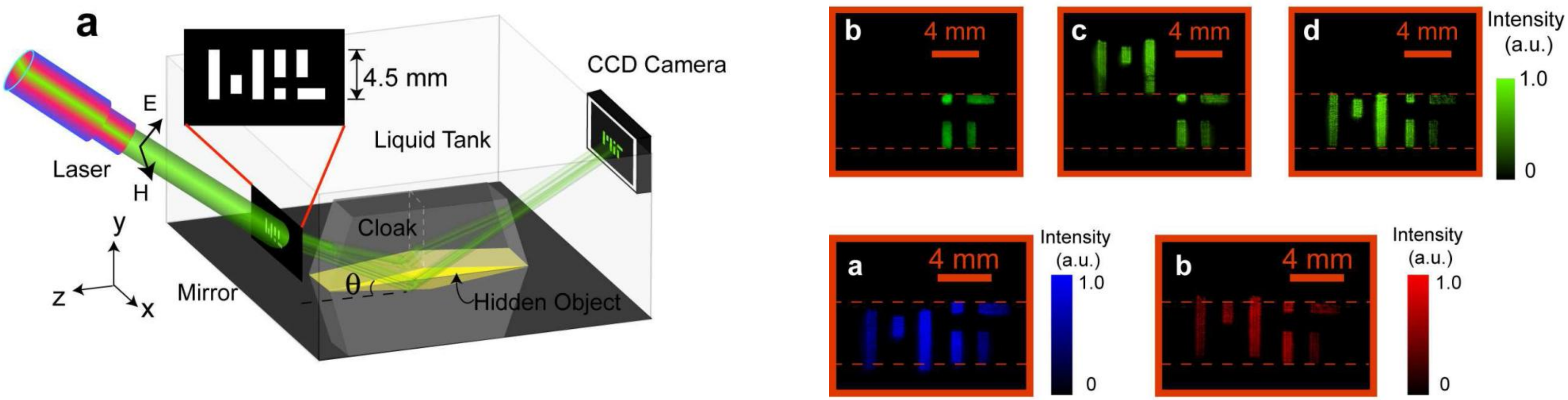
Optical characterization of the 3D structures with **unpolarized** light in bright-field mode.

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

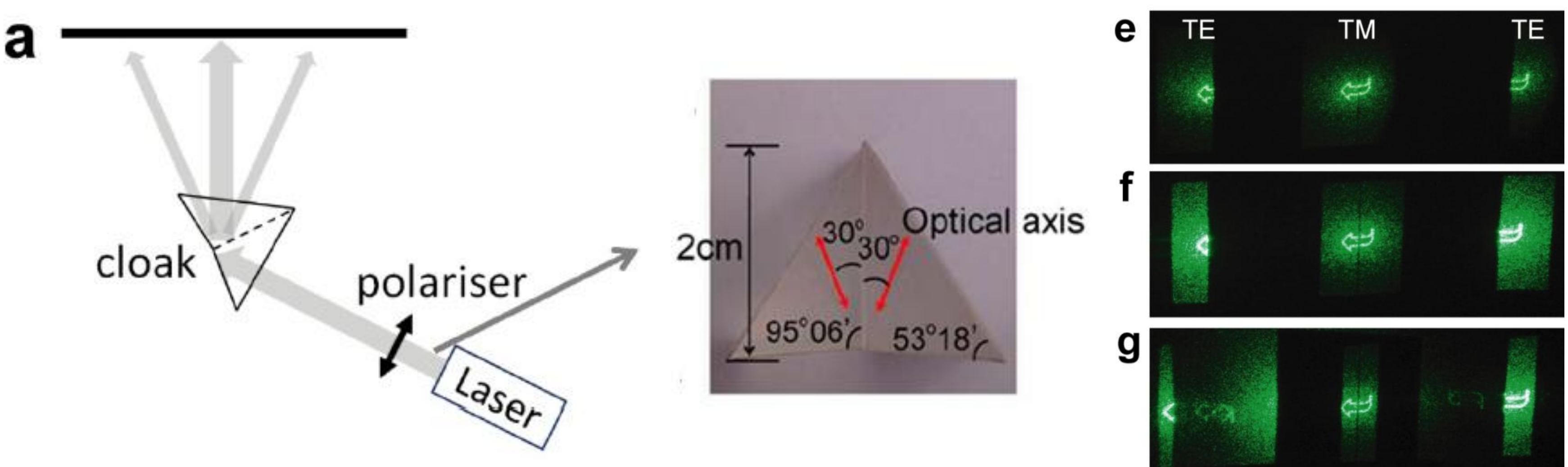
(B) (**B**) Result for a bump with a cloak that approaches the expectation for an ideal cloak (constant intensity).

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

Macroscopic Cloaking Based on Calcite

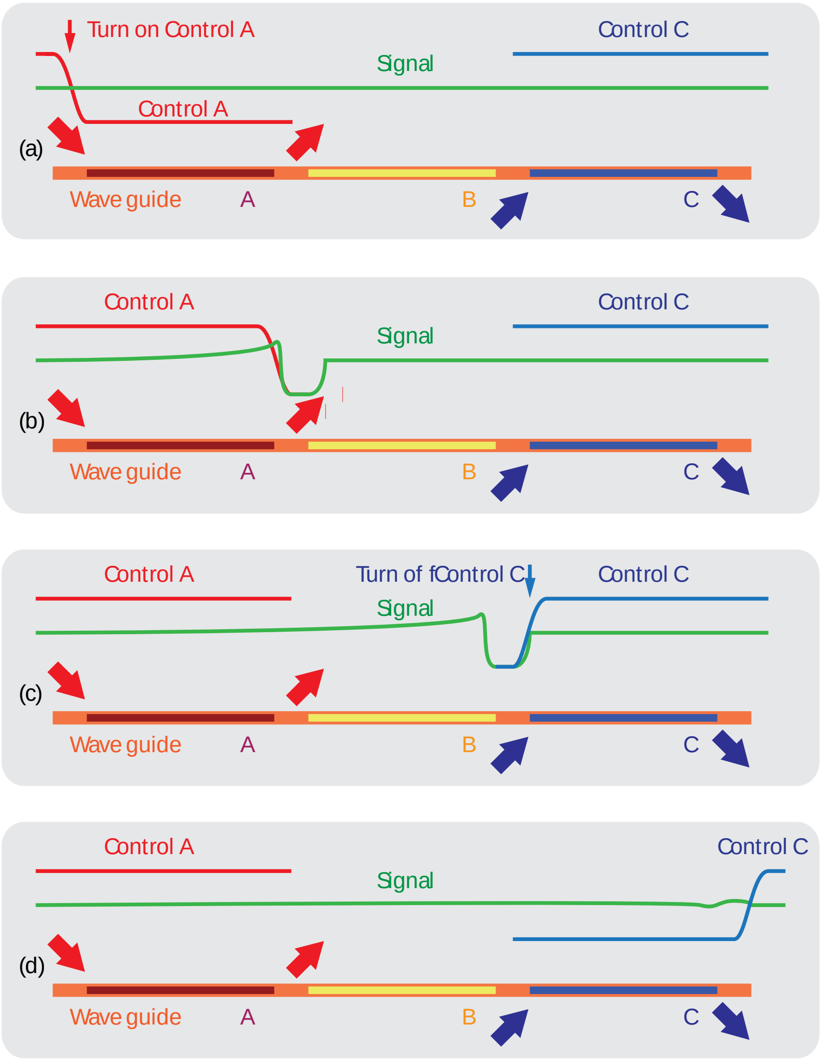


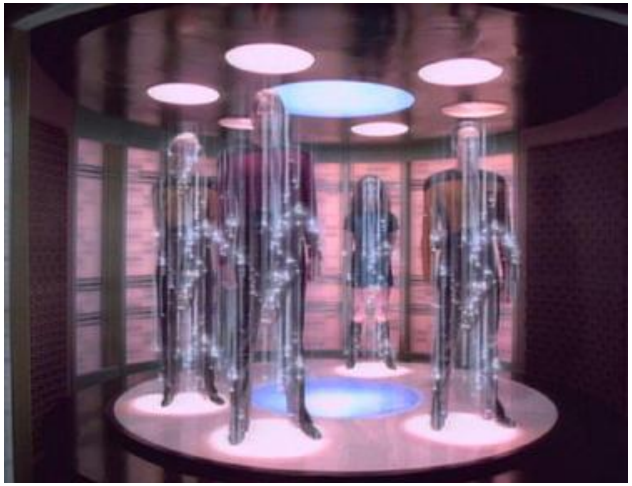
B. Zhang, et al, arXiv:1012.2238 (Singapore-MIT)



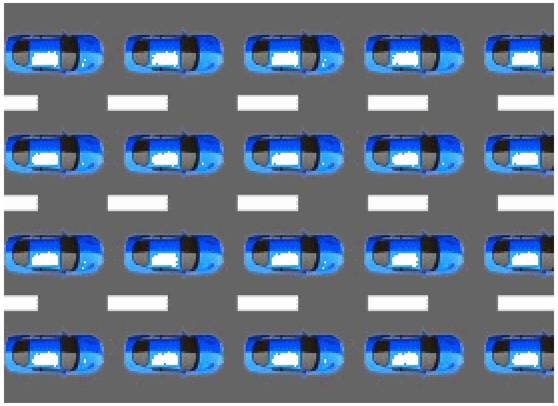
X. Chen, et al, arXiv:1012.2783 (Brimingham, DTU, Imperial)

Space-time Cloak – History Editor





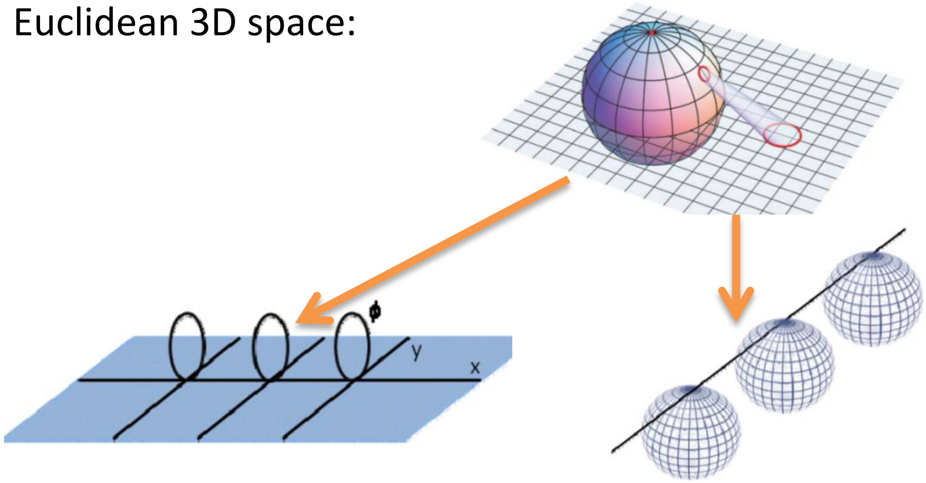
Star Trek transporter

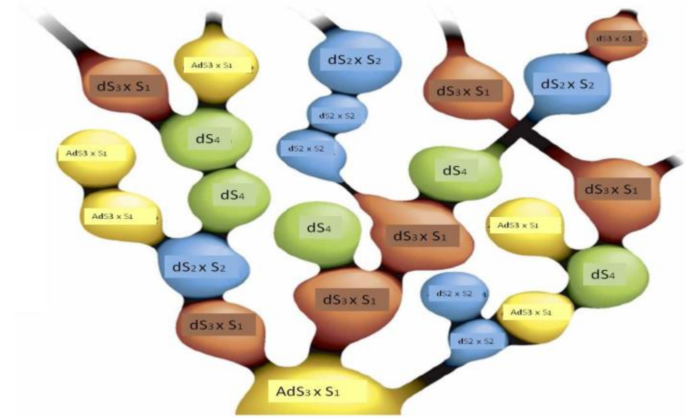


M. W. McCall and et al., *Journal of Optics*, 2011.
Experiment: Gaeta et al Nature (2012)

Metamaterial "Multiverse" (Smolyaninov)

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





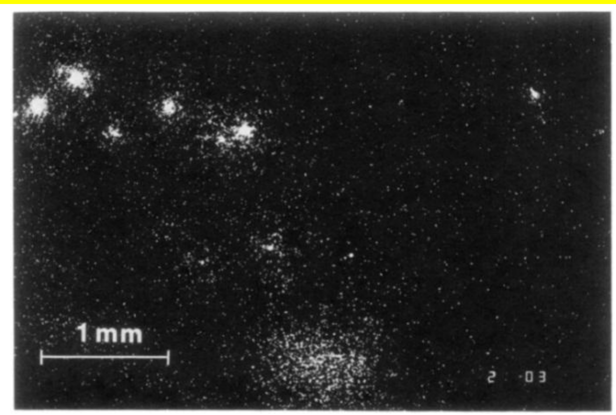
Modern cosmology describes Universe as collection of spaces connected by black holes and wormholes. These spaces may have different topology and different number of dimensions.

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

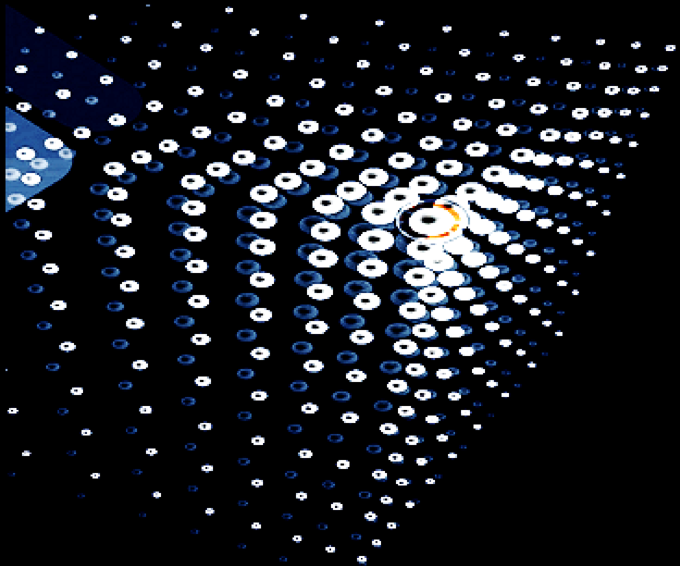
$$\frac{\partial^2\varphi}{c^2\partial t^2} = \frac{\partial^2\varphi}{\varepsilon_1\partial z^2} + \frac{1}{\varepsilon_2}\left(\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2}\right) \qquad \varepsilon_1 < 0, \quad \varepsilon_2 > 0$$

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

2T K-G



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



Generalized Snell's Law and Negative Refraction with Plasmonic Nanoantennas

Principle of least action

Pierre Louis Maupertuis (1698-1759)

Maupertuis felt that **"Nature is thrifty in all its actions"**, and applied the principle broadly:

"The laws of movement and of rest deduced from this principle being precisely the same as those observed in nature, we can admire the application of it to all phenomena. The movement of animals, the vegetative growth of plants … are only its consequences …"

Euler's formulation

The action functional from point A to point B is

where **p** is the momentum, and **q** is the coordinate.

From the *principle of least action* the true path of a system from point A to point B is a **stationary point** of the functional.

It works for any physical system!

Leonhard Euler (1707-1783)

Principle of least action → Fermat's principle

"Fermat's principle applied to phase waves is identical to Maupertuis' principle applied to the moving body; the possible dynamic trajectories of the moving body are identical to the possible rays of the wave."

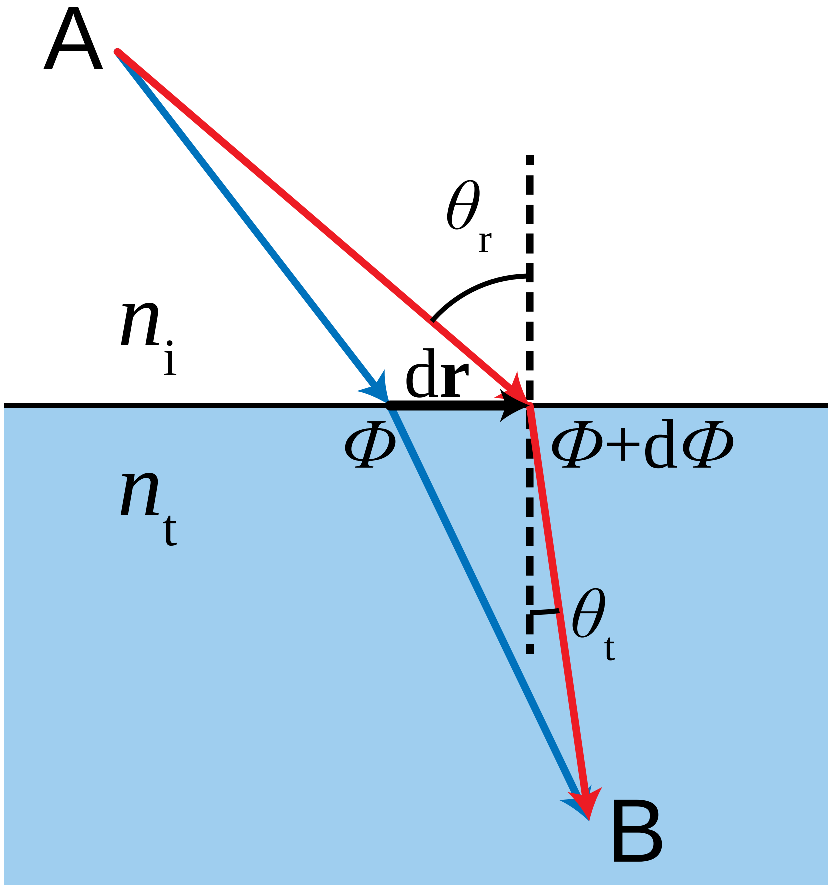
Maupertuis' principle

Fermat's principle

Louis de Broglie (1892-1987)

$$\mathbf{p} = \hbar \mathbf{k}$$

Generalized Snell's law (Capasso group)



Principle of least action → The momenta difference between blue and red path is zero

( )

( )

†

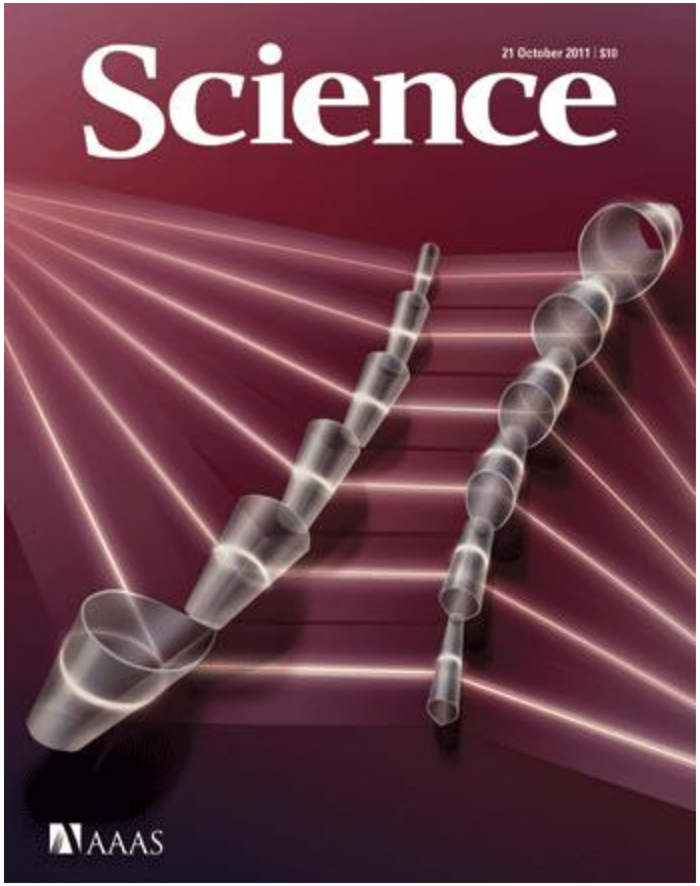
For reflection

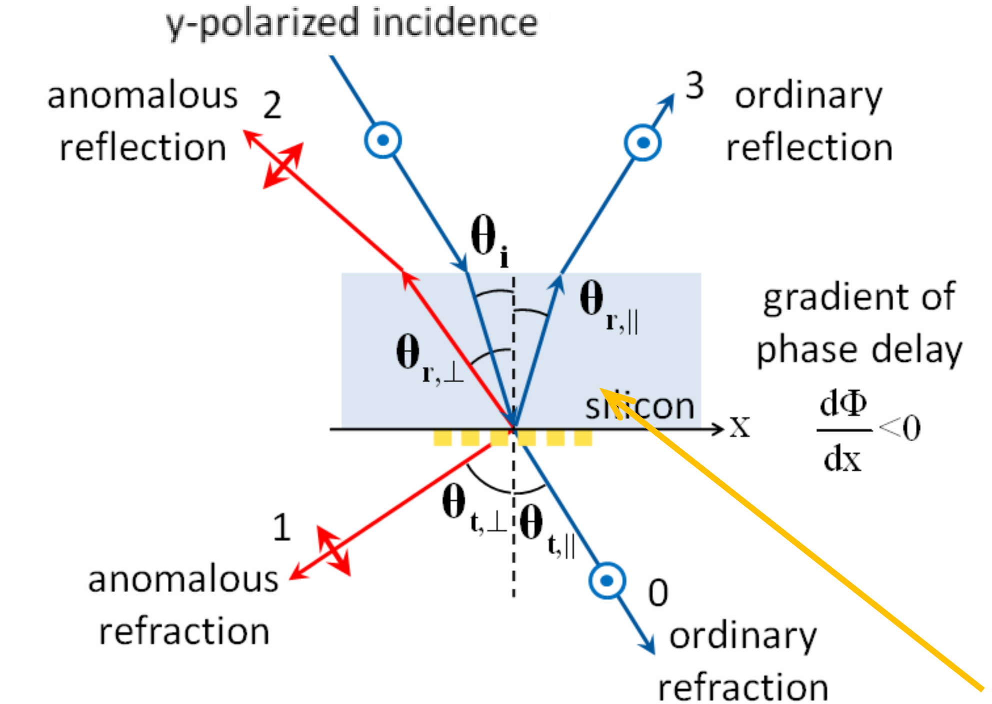
For refraction

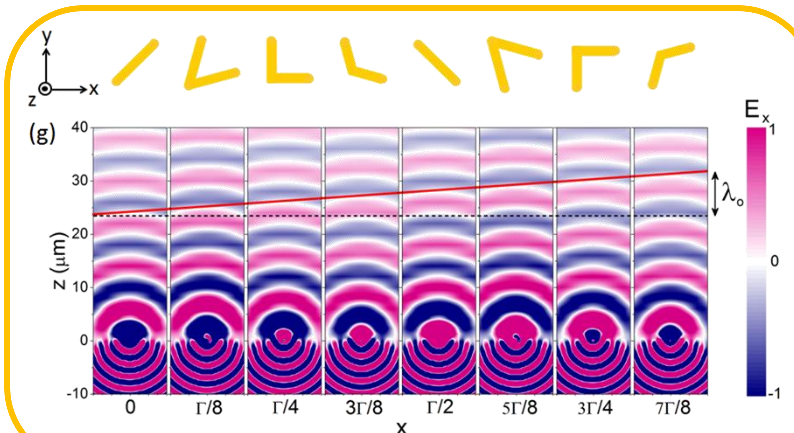
In essence, momentum conservation!

† Landau and Lifshitz, The Classical Theory of Fields (4 ed.)

Generalized Snell's law



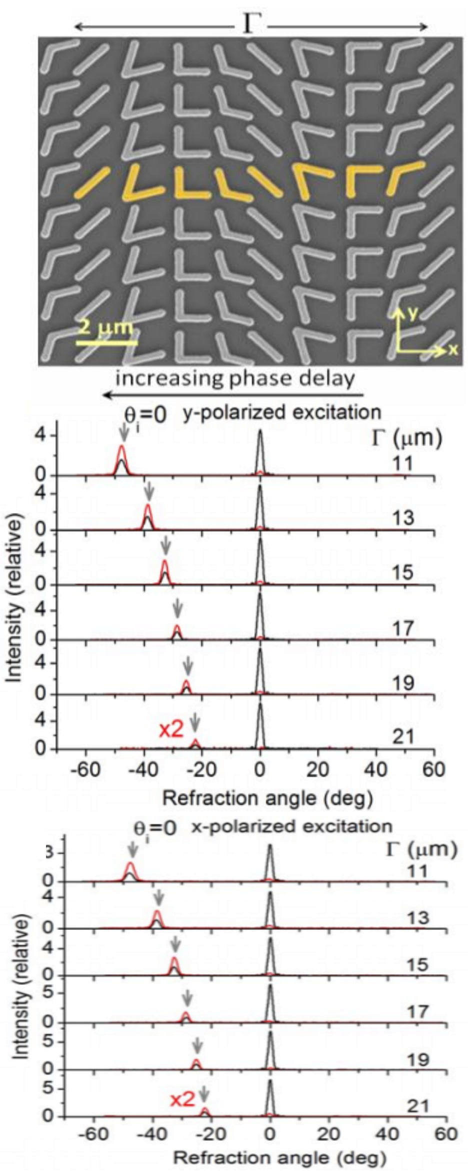




Demonstrated at 8 μm wavelength

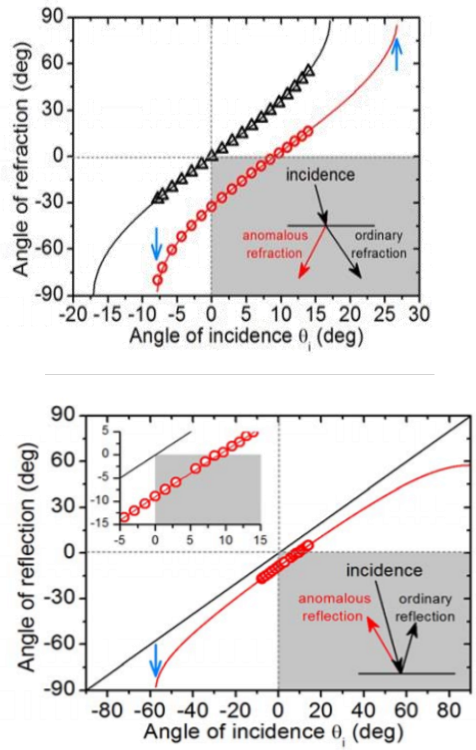
N. Yu, et al. Science, 2011 (Capasso Group)

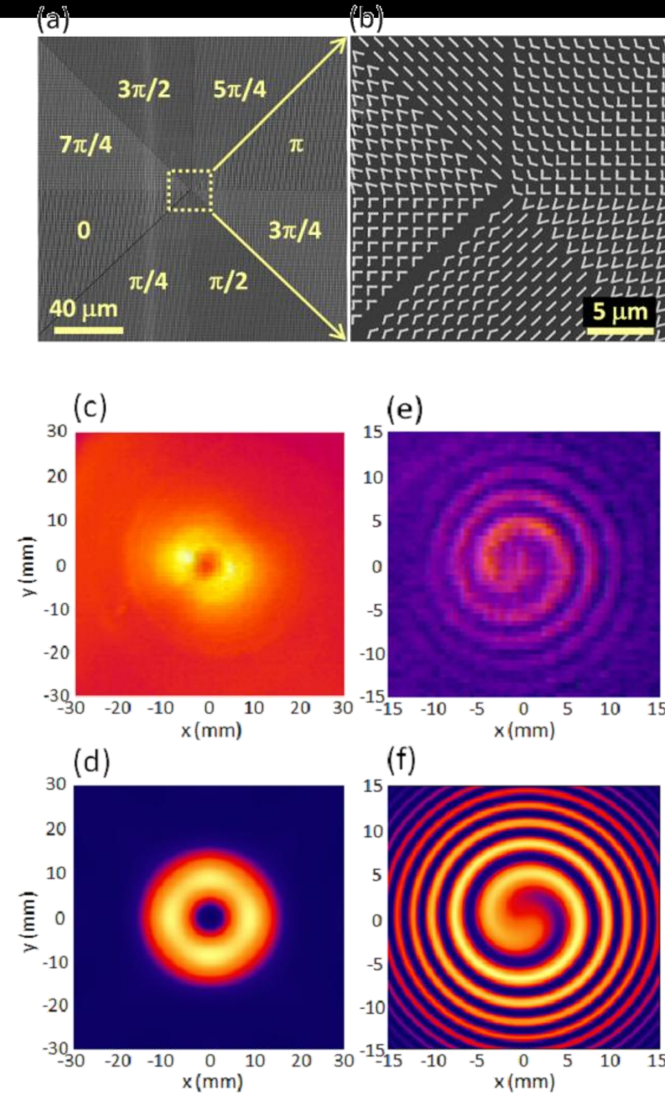
Generalized Snell's law: experimental demonstrations by Capasso group



λ = 8 μm

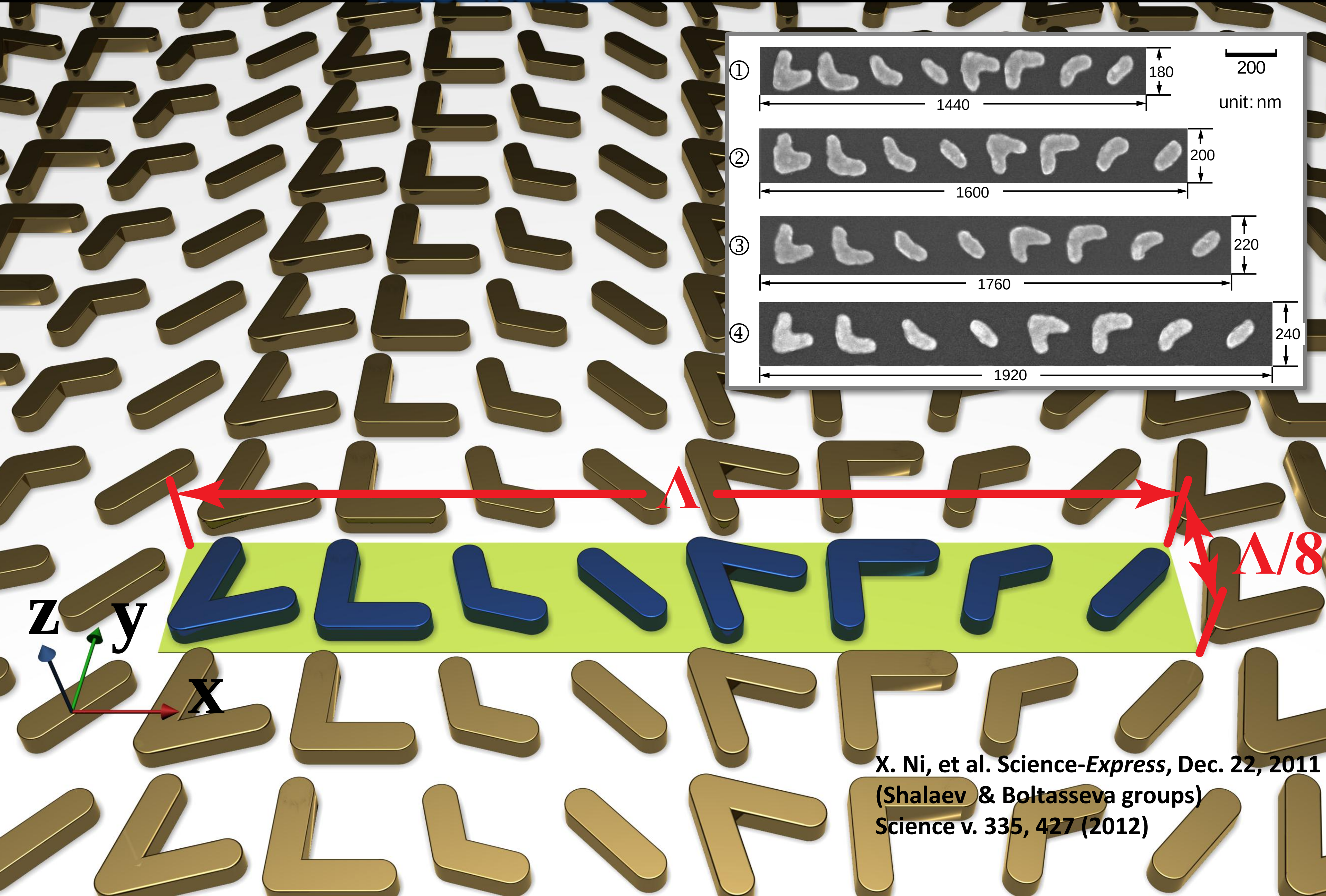
Normal light
Anomalous light





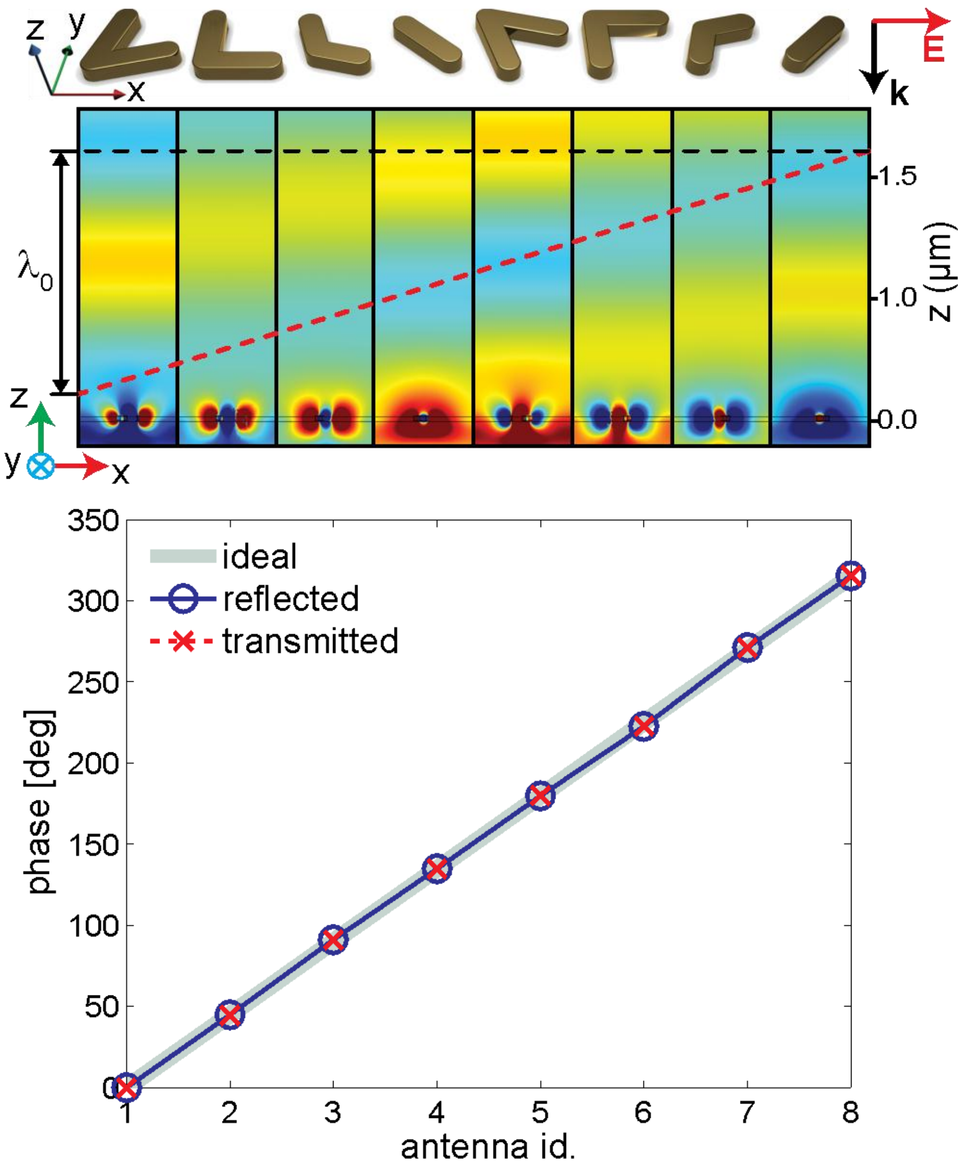
N. Yu, et al. Science, 2011 (Capasso Group)

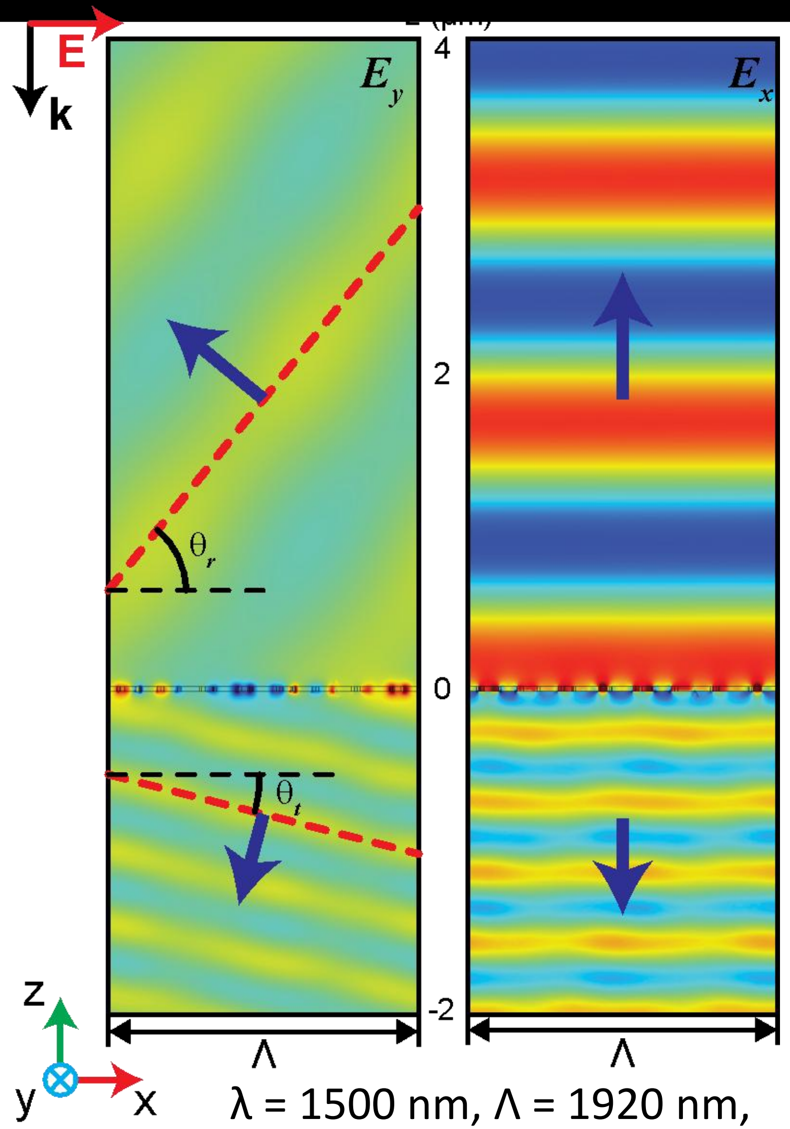
Broadband light bending with plasmonic nanoantennas



X. Ni, et al. Science-*Express*, Dec. 22, 2011
(Shalaev & Boltasseva groups)
Science v. 335, 427 (2012)

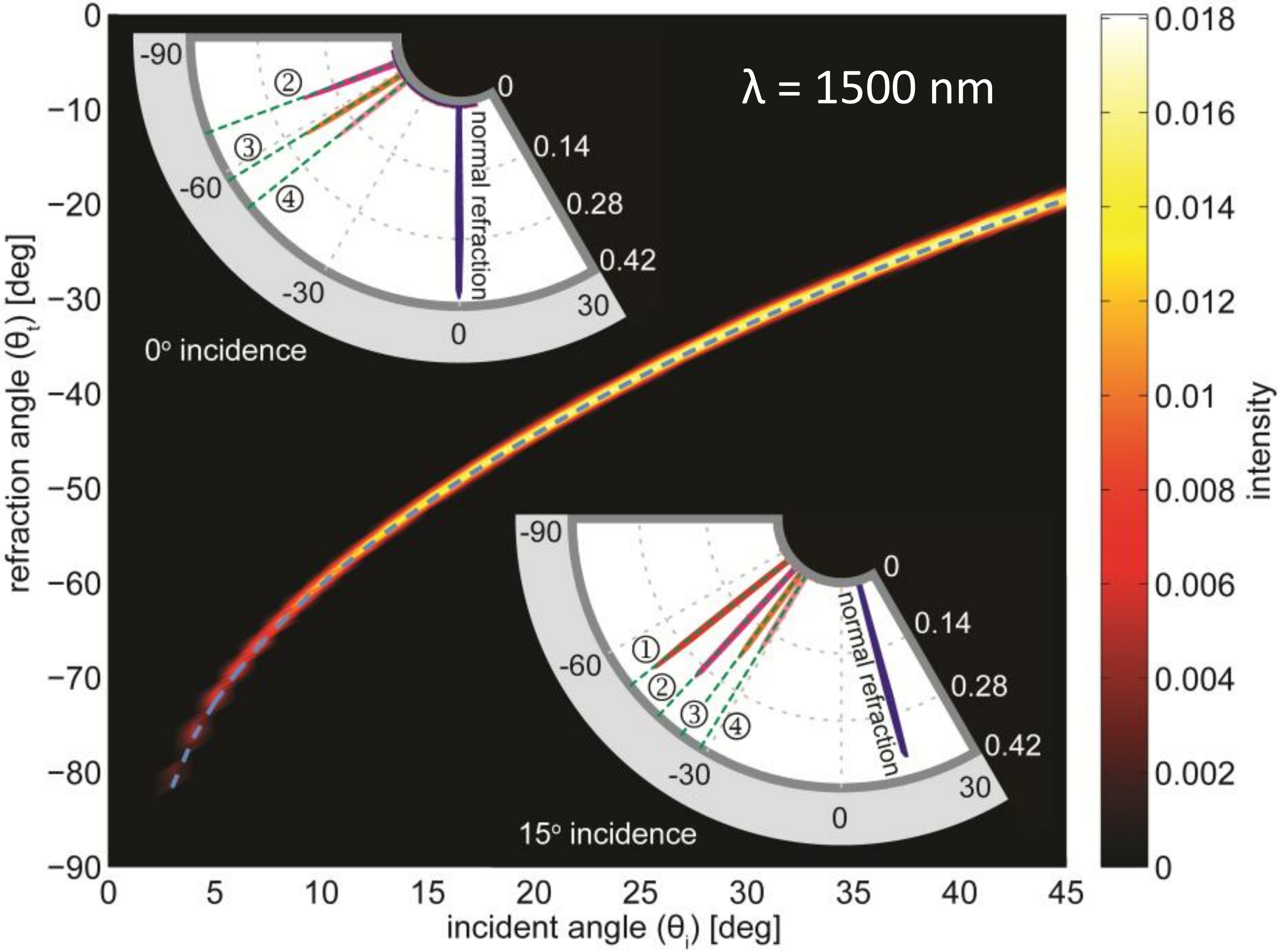
Full-wave simulation



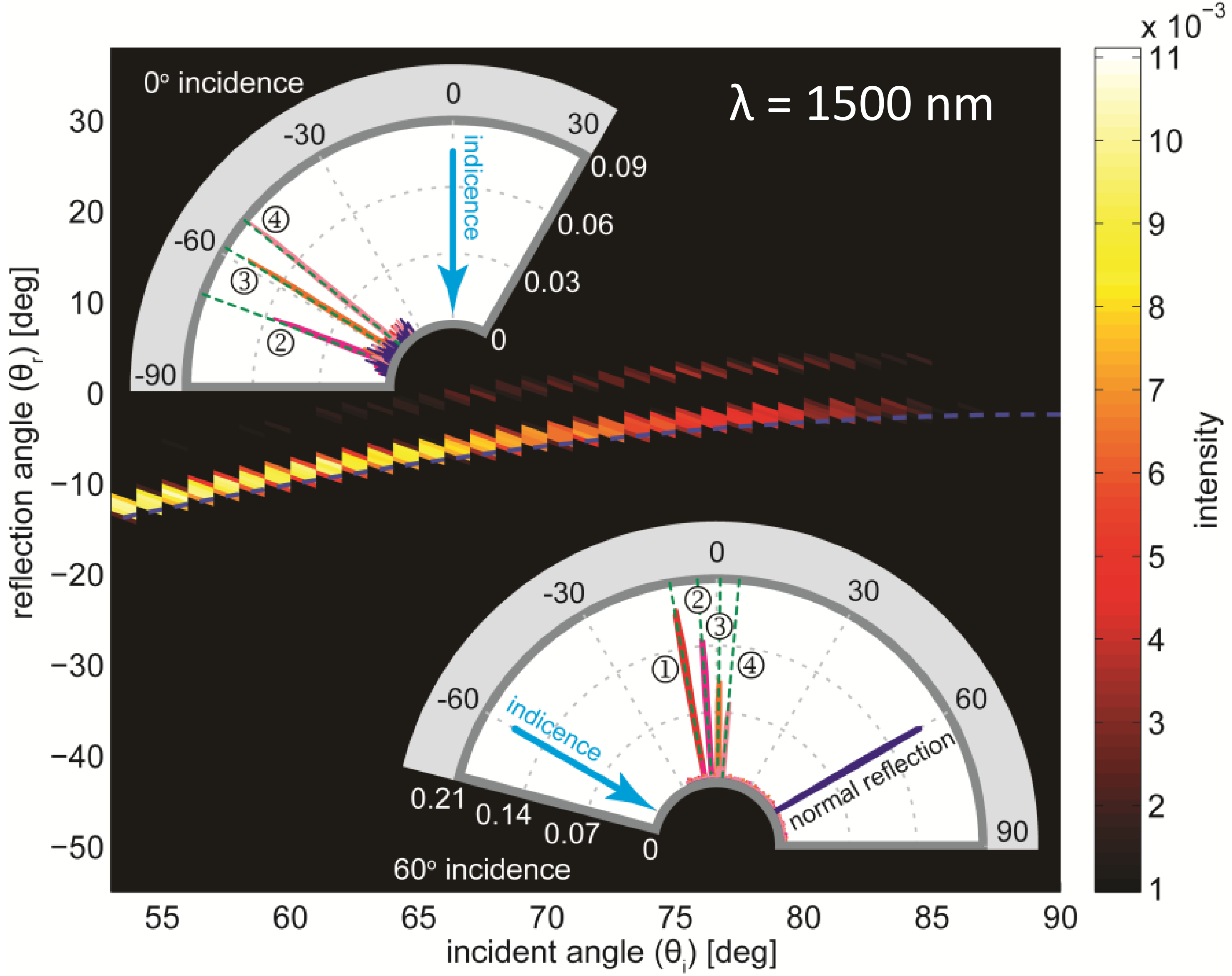


λ = 1500 nm, Λ = 1920 nm,
θ_r = 51.4^o, θ_t = 13.0 ^{o}

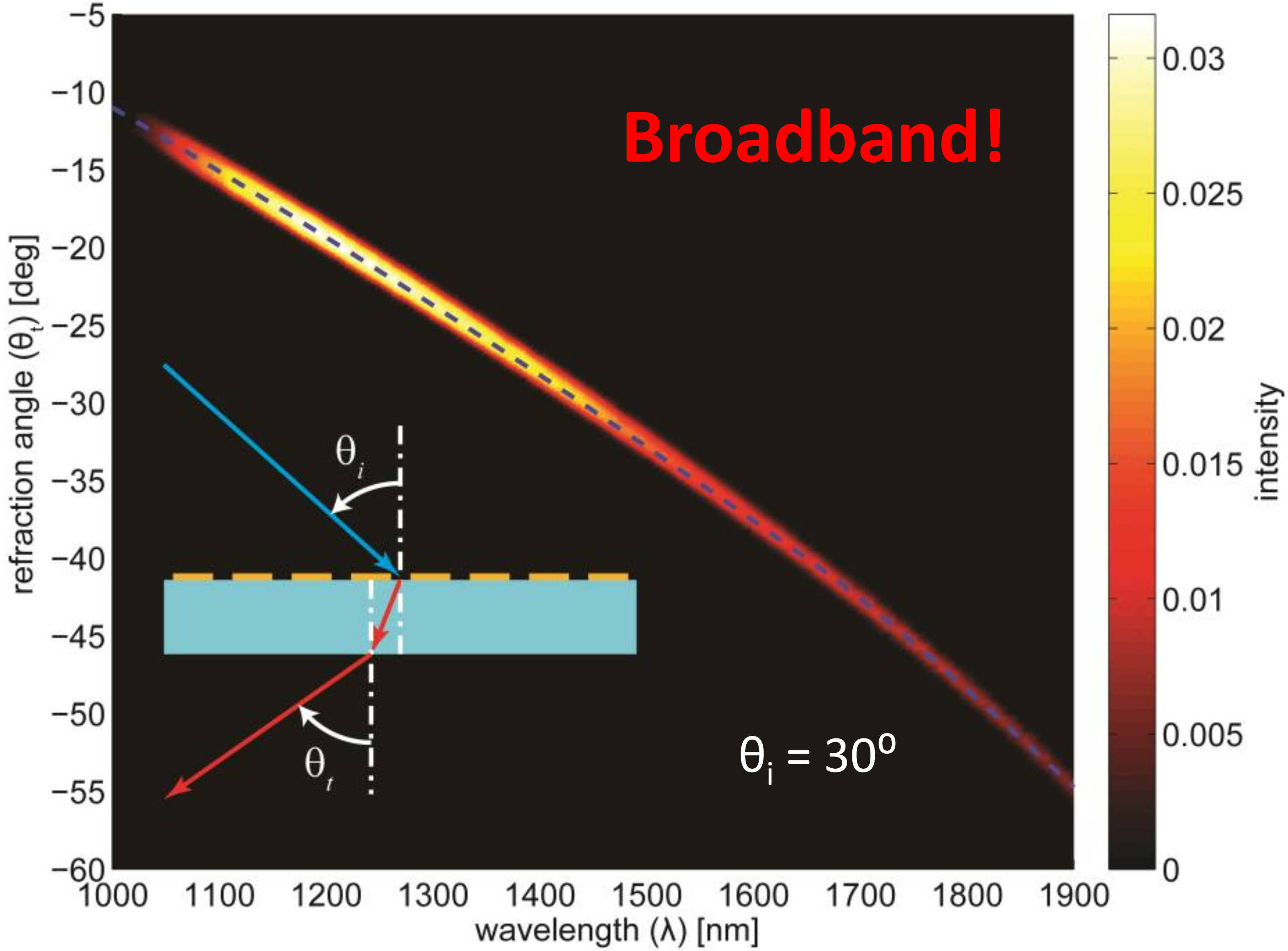
Incident angle sweep – refraction



Incident angle sweep – reflection



Broadband Negative Refraction



Outline

- Electrical Metamaterials (Plasmonics): A Route to Nanophotonics
- Optical Metamagnetics
- Negative-Index Metamaterials
- Active and Loss-Free Metamaterials
- New Plasmonic Materials
- Chiral Metamaterials
- Metamaterials for Sensing
- Nonlinear, Tunable, and Ultrafast Metamaterials
- Quantum Optics with Metamaterials
- Transformation Optics , Cloaking, and “Multiverse”
- Generalized Snell’s Law and Light Bending with Nanoantennas

Further reading