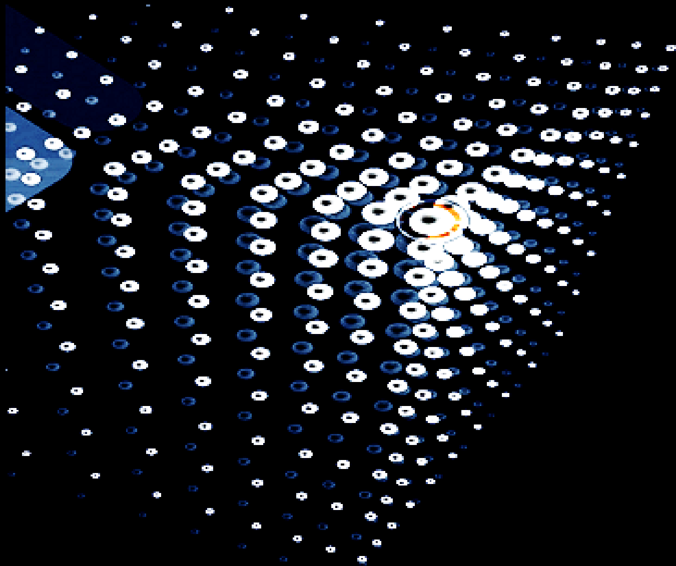


Transforming Light with Metamaterials

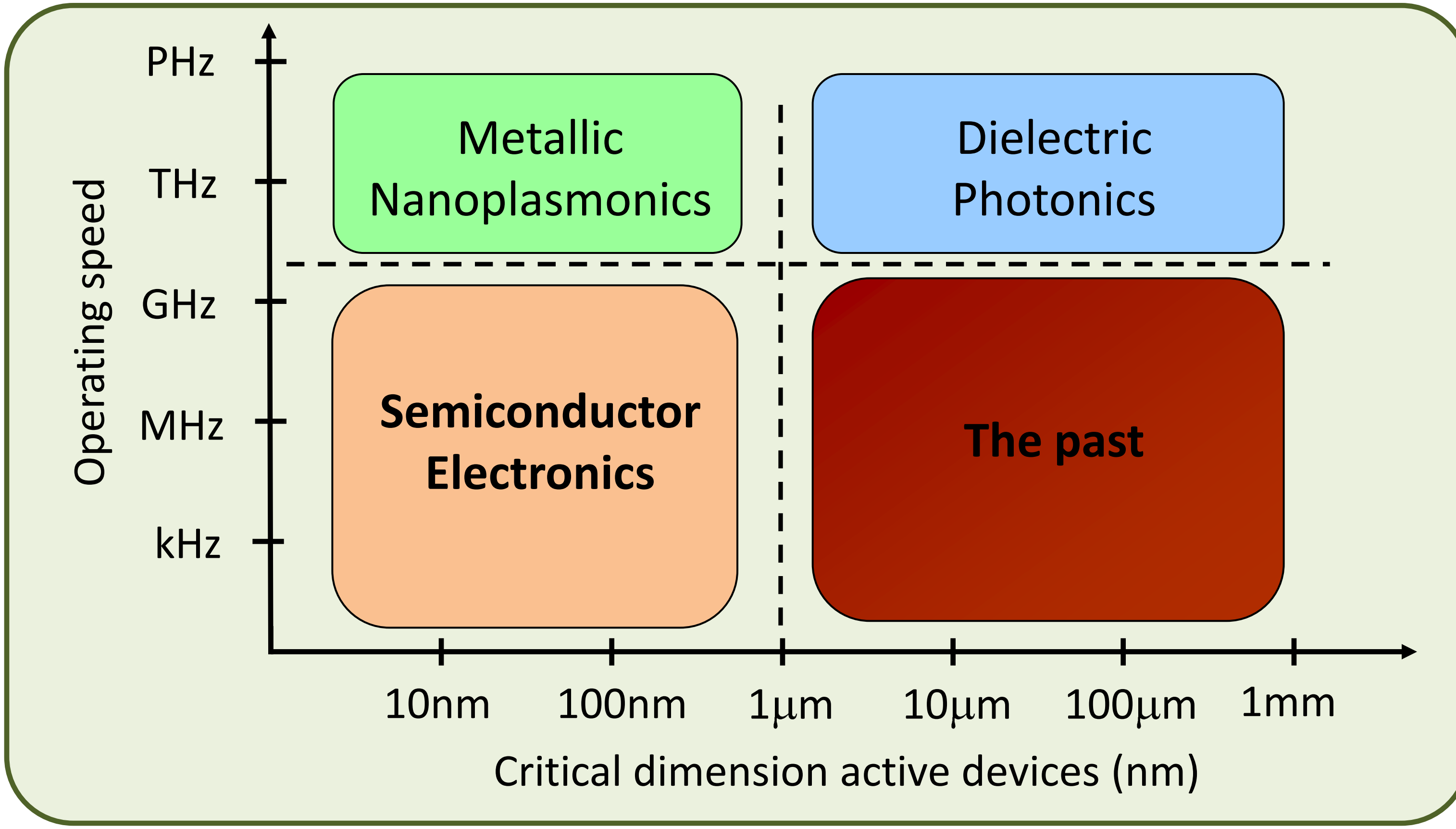
Vladimir M. Shalaev

Outline

- Electrical Metamaterials (Plasmonics): A Route to Nanophotonics
- Artificial Optical Magnetism in Metamaterials
- Optical Negative-index Metamaterials
- Active and Loss-Free Metamaterials
- Toward Better Materials & Fabrication
- Negative-Refraction in Semiconductor-based Metamaterials
- Metamaterials for Sensing
- Tunable, Ultrafast, and Nonlinear Metamaterials
- Quantum Metamaterials
- Transformation Optics and Cloaking

Electrical Metamaterials (Plasmonics): Route to Nanophotonics

Why Plasmonics/Electric MMs?

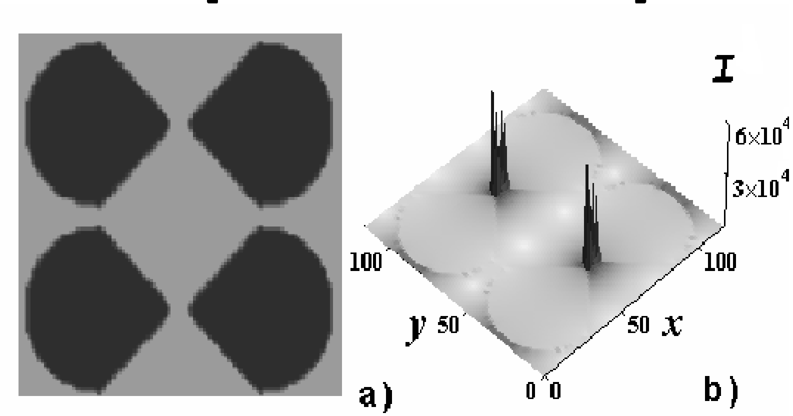


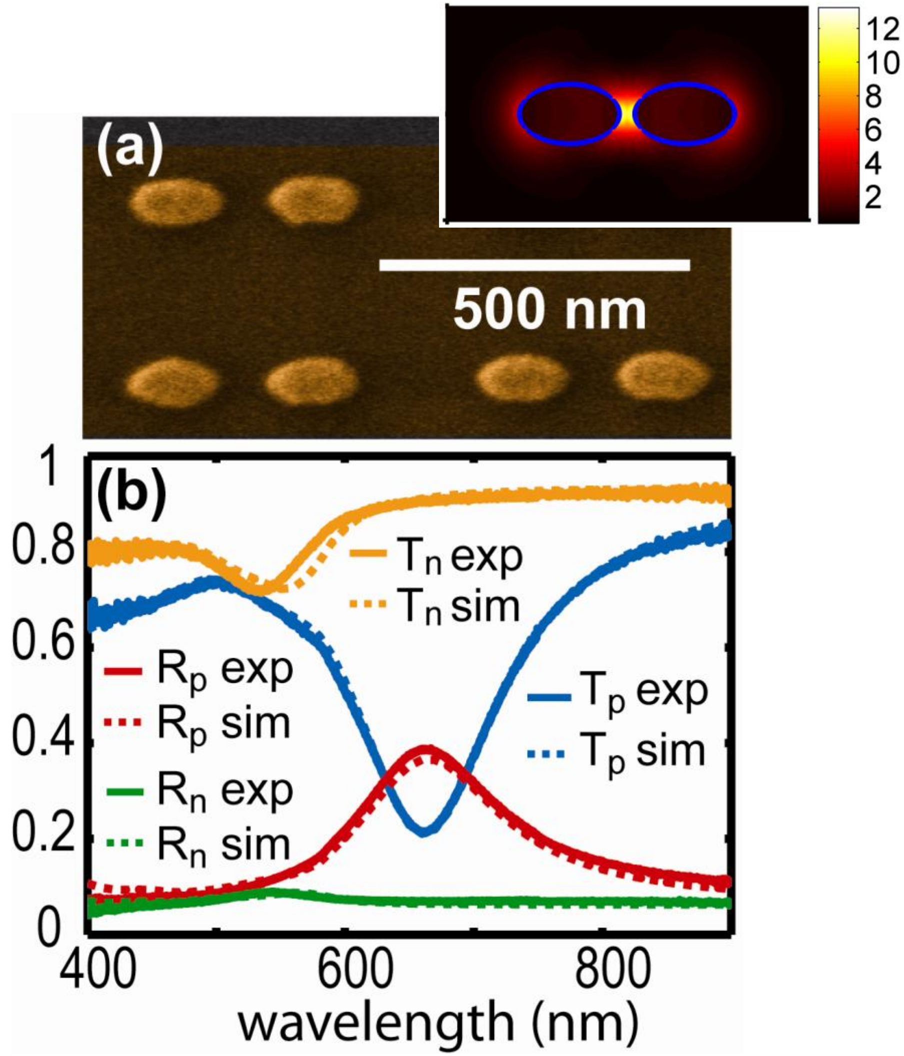
- **Plasmonics will enable an improved synergy between electronic and photonic devices**
  - **Plasmonics naturally interfaces with similar size electronic components**
  - **Plasmonics naturally interfaces with similar operating speed photonic networks**

M. Brongersma, V. Shalaev, Science (2010)

Optical Antennae: Focusing Light to Nanoscale

[Bow-tie antennas]





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

<u>Other Applications:</u>

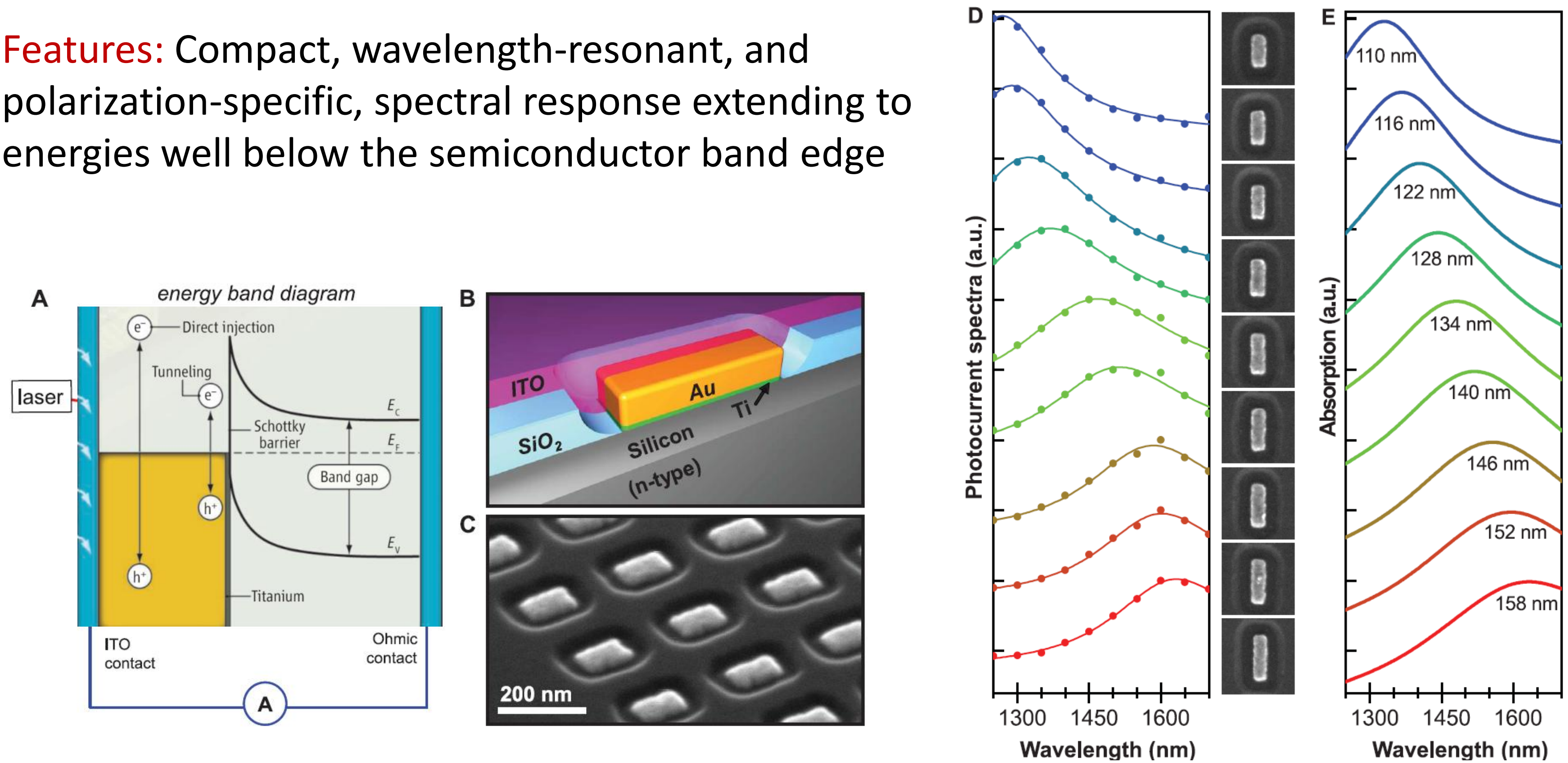
Sensors

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

Photodetection with Active Optical Antennas

- Idea: Photons coupled into a metallic nanoantenna excite resonant plasmons, which decay into energetic, “hot” electrons injected over a potential barrier at the nano-antenna semiconductor interface, resulting in a photocurrent

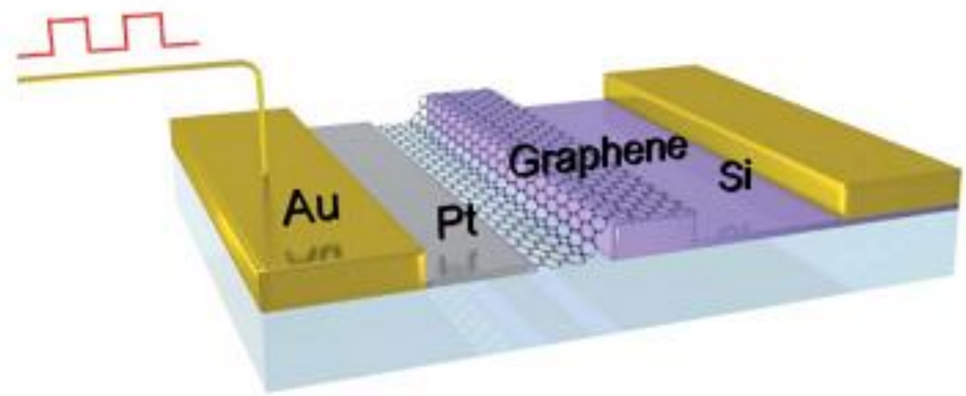
- Features: Compact, wavelength-resonant, and polarization-specific, spectral response extending to energies well below the semiconductor band edge

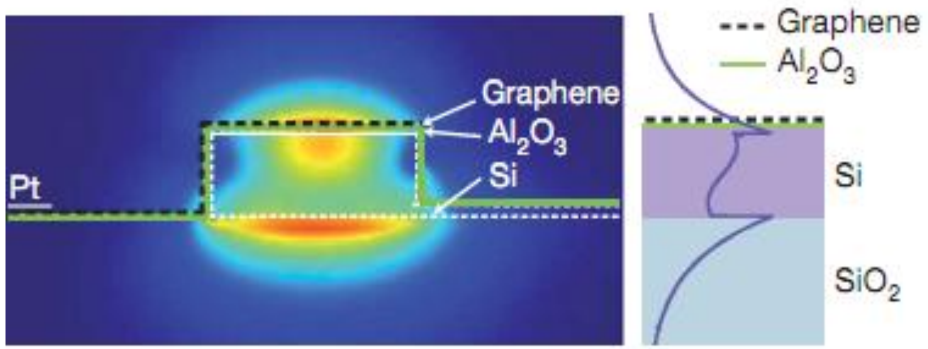


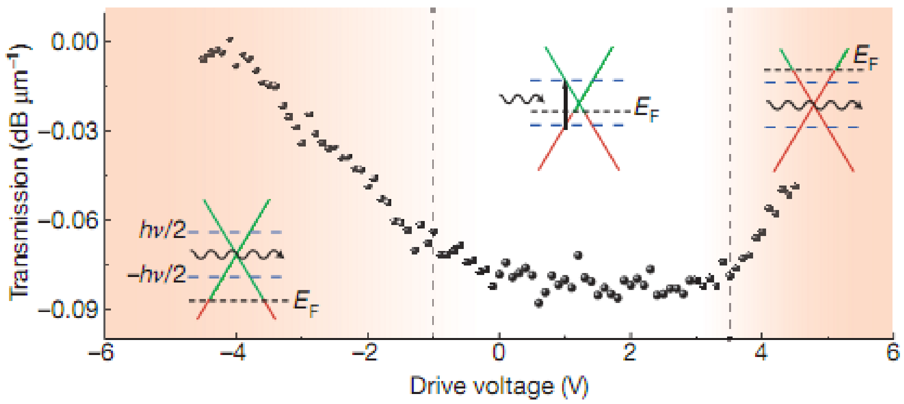
M. Knight, et al, Science (2011) (Halas group)

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.

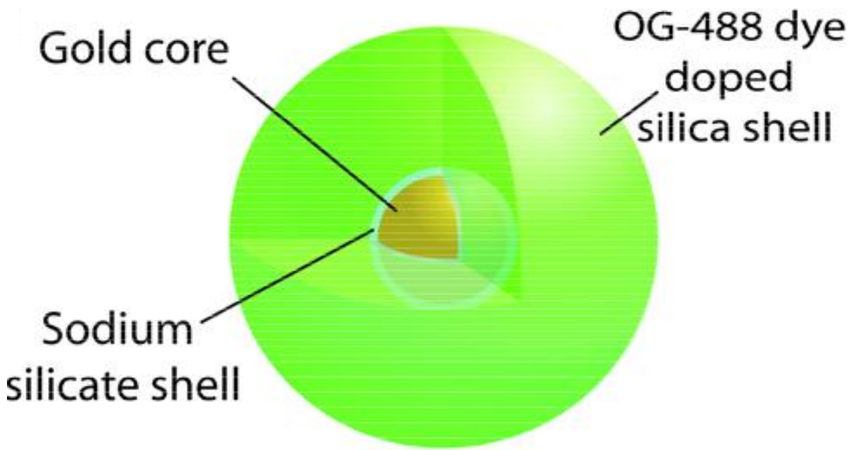




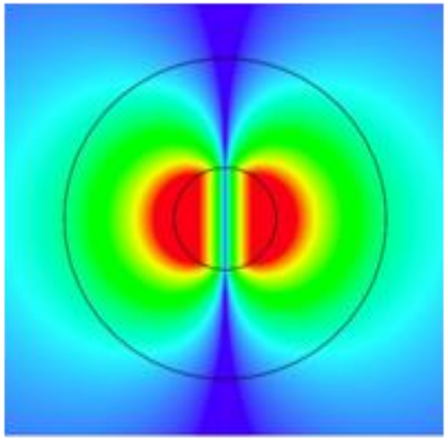


M. Liu, et al, Nature (2011) (Zhang Group)

Optical Nanolaser Enabled by SPASER



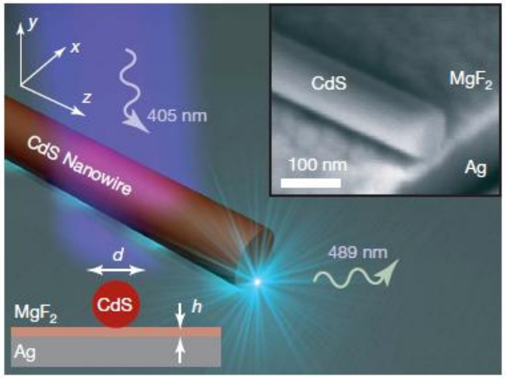
Related prior theory:
Stockman (SPASER)



Optical MOSFET
(Stockman)

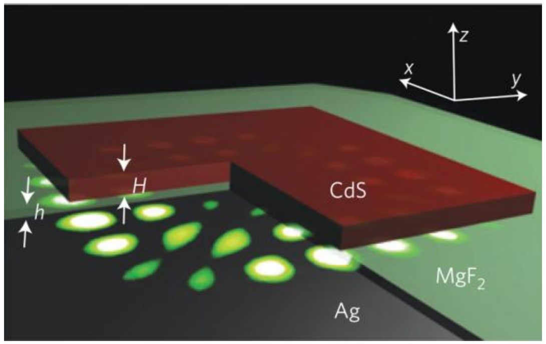
Noginov, Shalaev, Wiesner groups, Nature (2009)

Zhang group: Plasmon laser (Nature, 2009)



Room-T Plasmon Laser (Nature Materials, 2010)

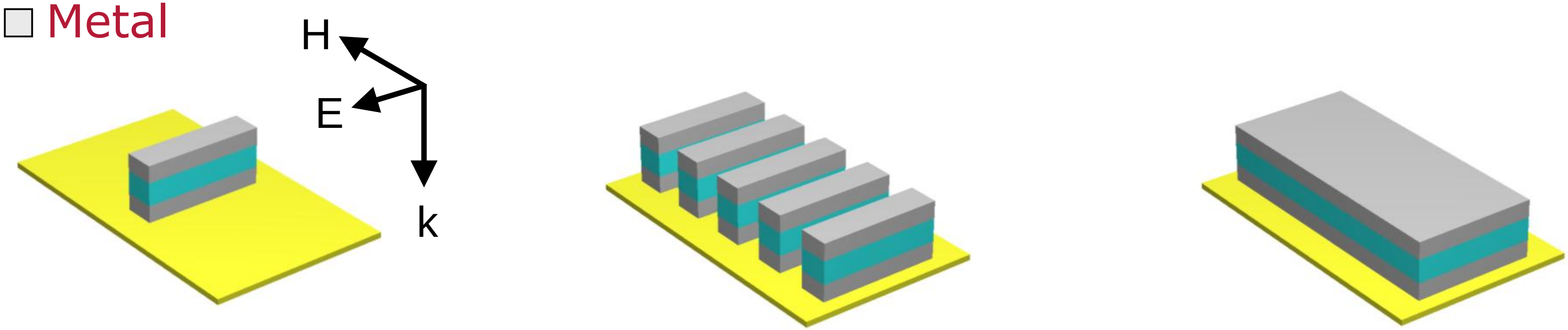
Spotlight on Plasmon Lasers (Perspective, Science, 2011)



Metamagnetics for optical range

Artificial Magnetic Metamaterials for Visible

- Dielectric
- Metal



Nanorod pair | Nanorod pair array | Nanostrip pair

Nanostrip pair has a much stronger magnetic response

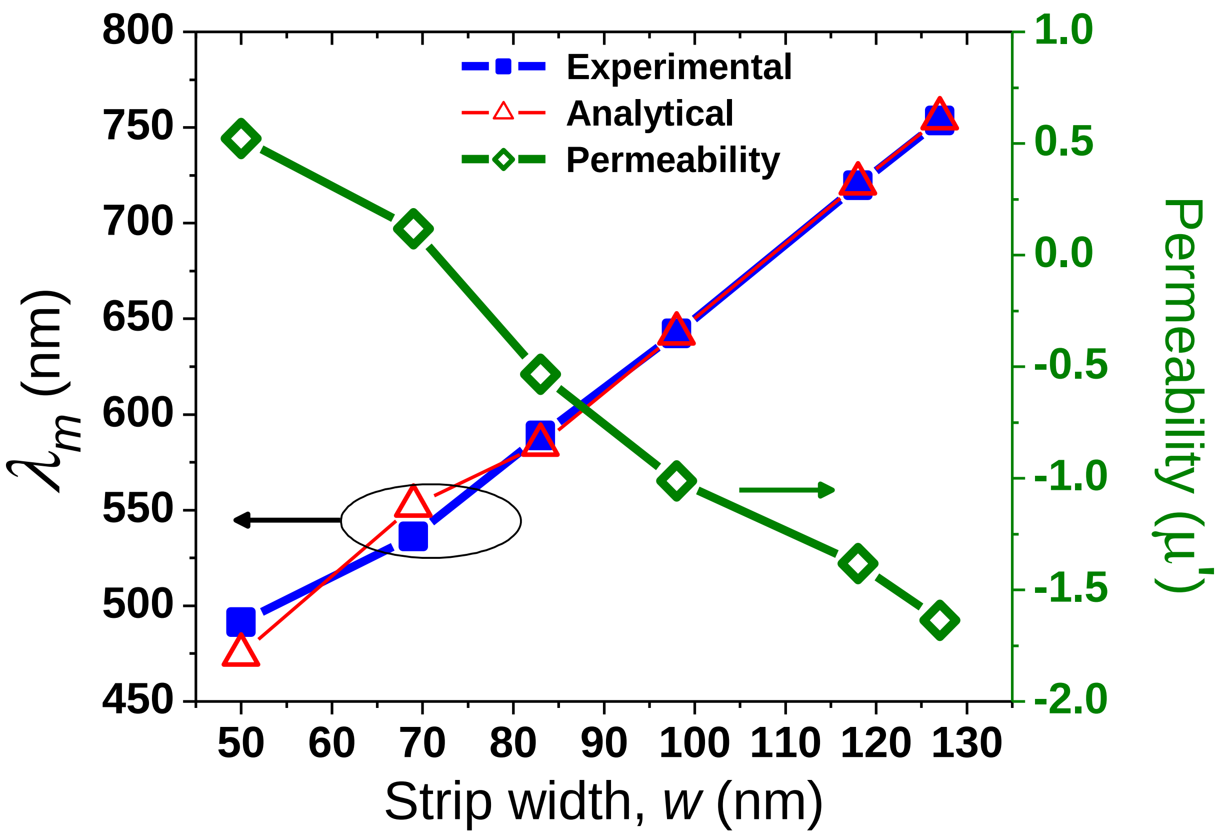
Podolskiy, Sarychev & Shalaev, *JNOPM* (2002) - $\mu < 0$ & $n < 0$

Lagar’kov, Sarychev PRB (1996) - $\mu > 0$

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



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

Cai, et al OE (2007)

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

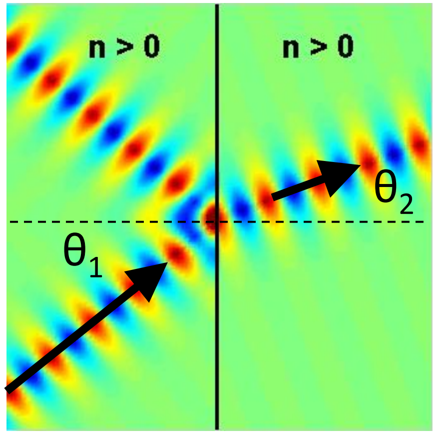
Pendry, the one who whipped up the recent boom of NIM researches

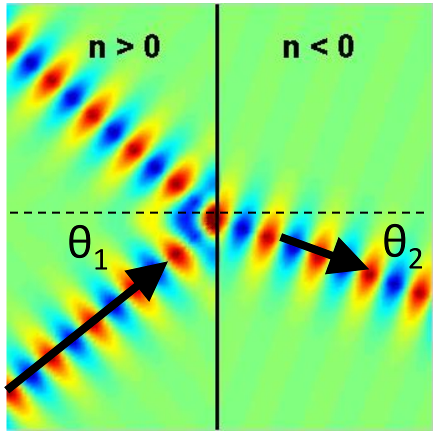
Perfect lens (2000)
EM cloaking (2006)

Sir John Pendry

Others: Sivukhin. Agranovich,…

Metamaterials with Negative Refraction





- **Refraction:** $$n^2 = \varepsilon\mu$$ $$n = \pm\sqrt{\varepsilon\mu}$$
- **Figure of merit:** $$F = |n'|/n''$$

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

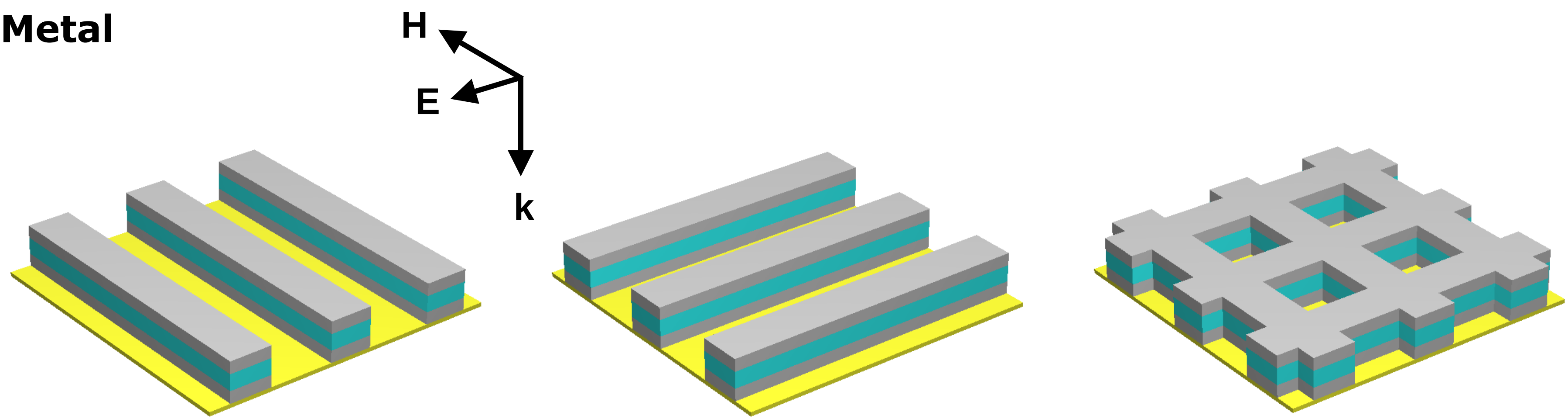
Single-negative:
$n < 0$, when ε′ < 0 whereas μ′ > 0 (F is low)

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

Negative Permeability and Negative Permittivity

Dielectric

Metal



Nanostrip pair (TM)

μ < 0 (resonant)

Nanostrip pair (TE)

ε < 0 (non-resonant)

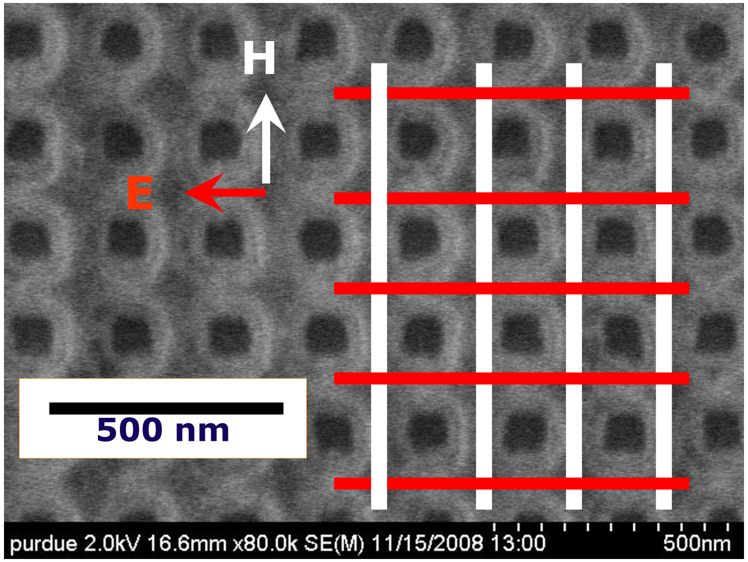
Fishnet

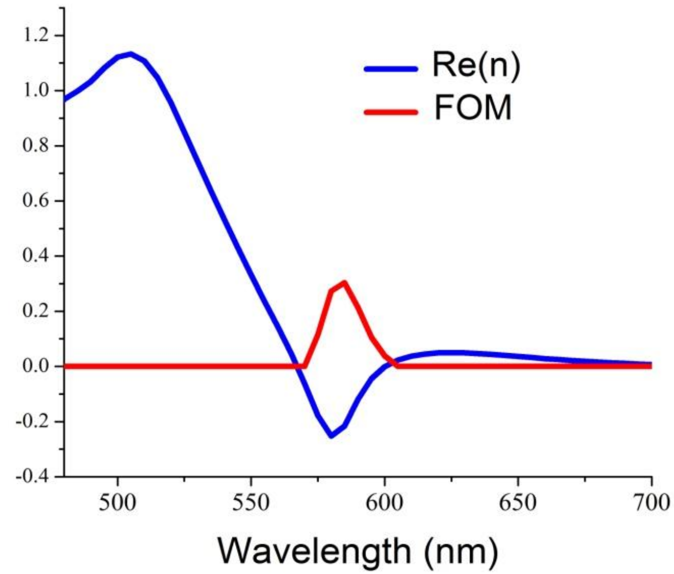
ε and μ < 0

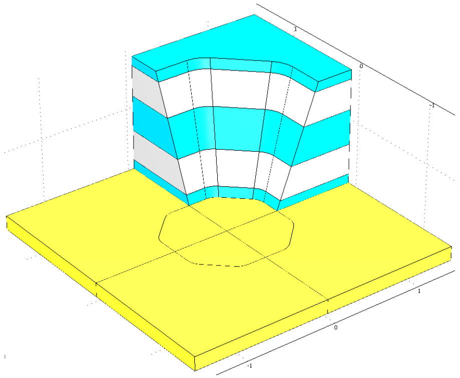
S. Zhang, et al., PRL (2005)

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

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

Xiao et al, OL (2009)

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Negative Refractive Index in Optics

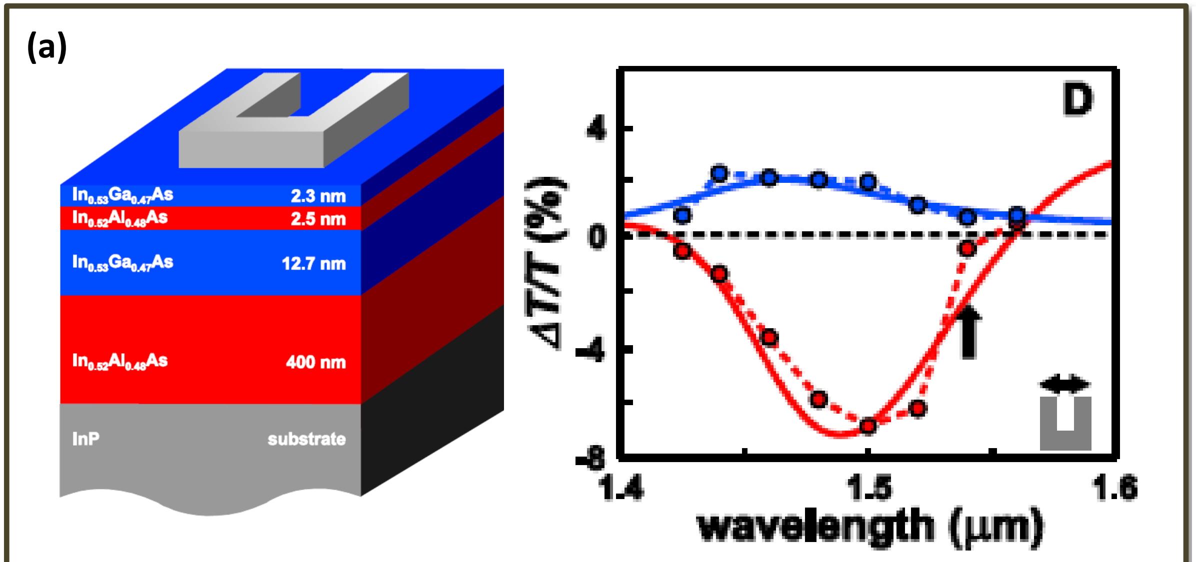
Year and Research group	*1st time posted and publication*	*Refractive index, n′*	*Wavelength, λ*	*Figure of Merit F=|n′|/n″*	*Structure used*
2005					
Purdue	April 13 (2005) arXiv:physics/0504091 Opt. Lett. (2005)	–0.3	1.5 μm	0.1	Paired nanorods
UNM & Columbia	April 28 (2005) arXiv:physics/0504208 Phys. 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

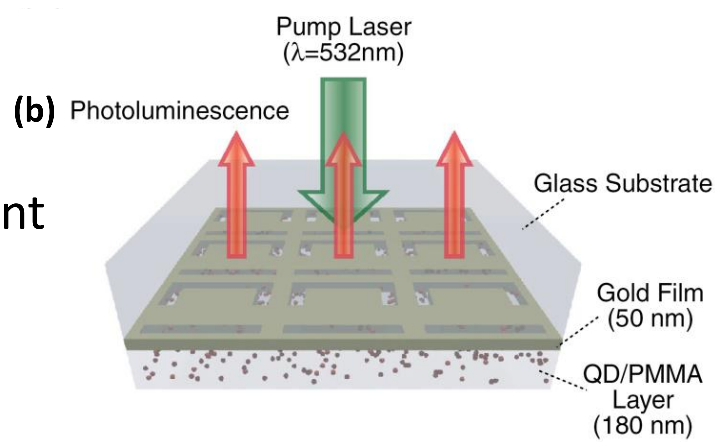
CalTech (Atwater): negative refraction in the visible for MIM waveguide SPPs (2007)

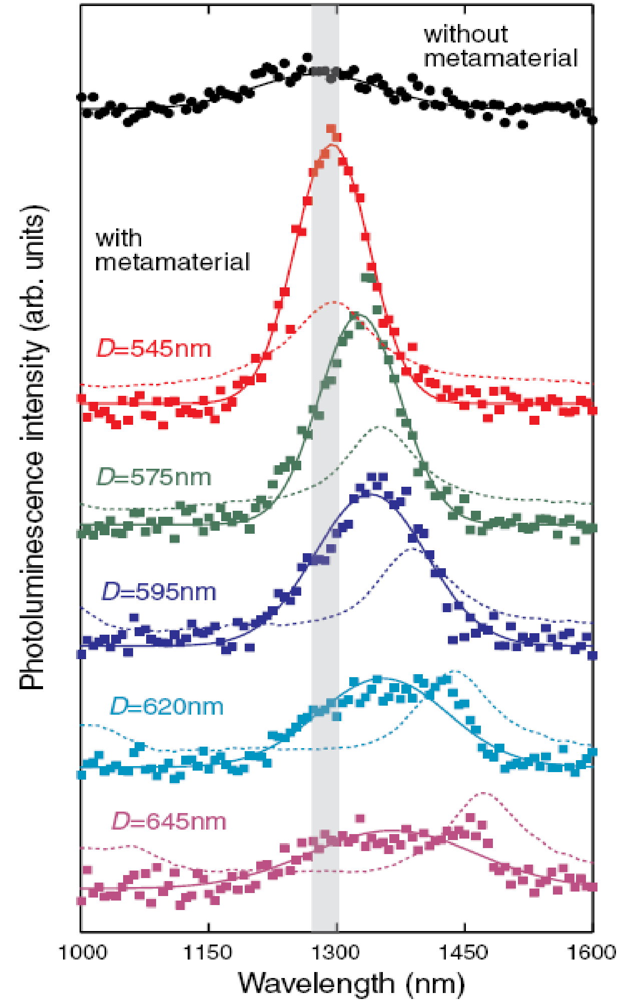
Active Negative-Index Metamaterials

Active Metamaterials (Experiments)

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





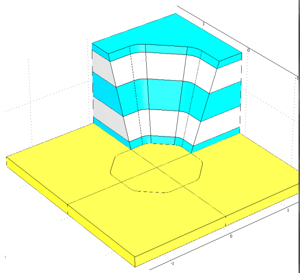


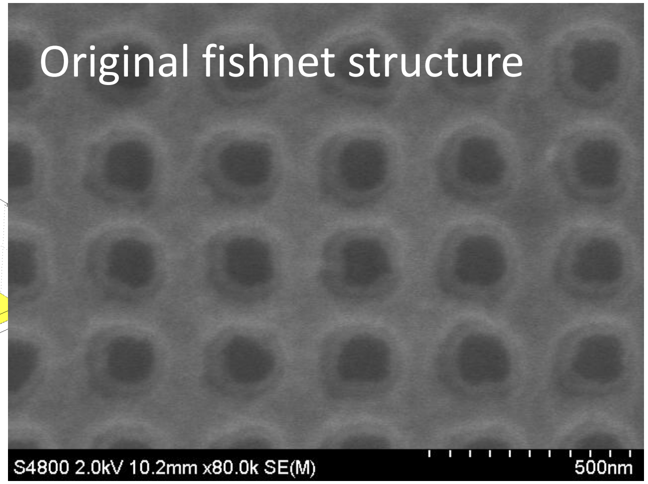
Multifold Enhancement of Quantum Dot Luminescence in Plasmonic Metamaterials

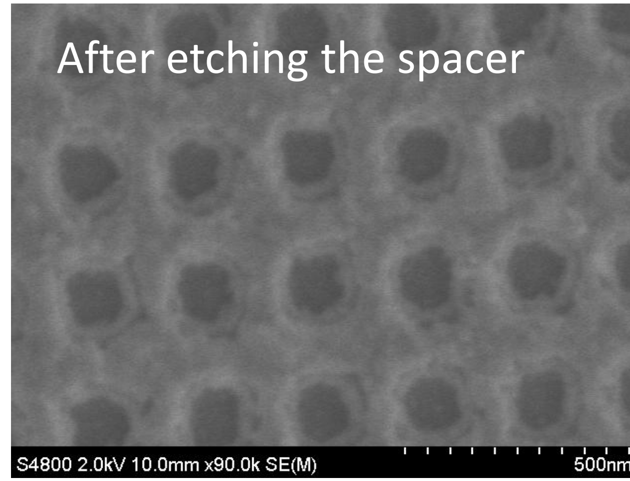
(a) N. Meinzer, et al, OE (2010) (Wegener group)

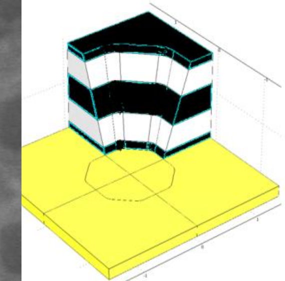
(b) K. Tanaka, et al, PRL (2010) (Zheludev group)

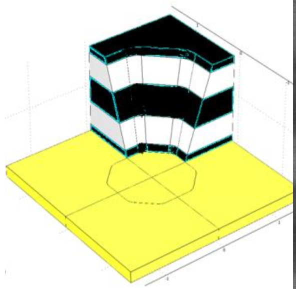
FESEM Images

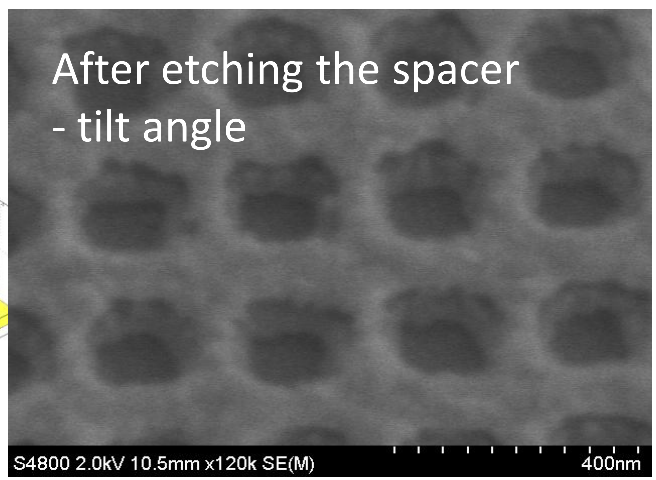


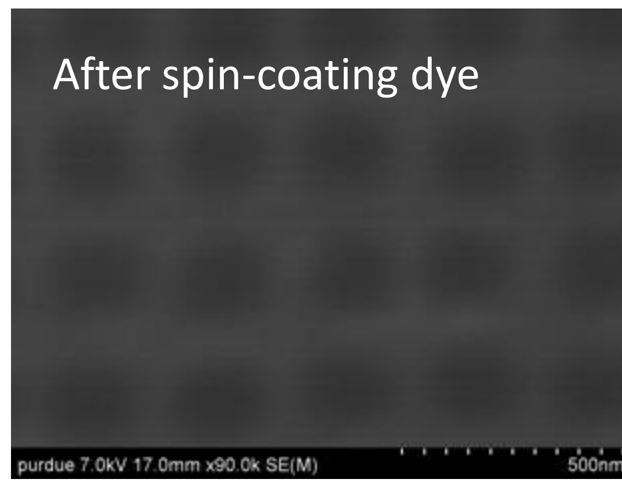


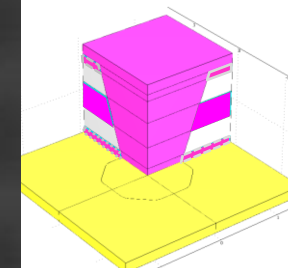








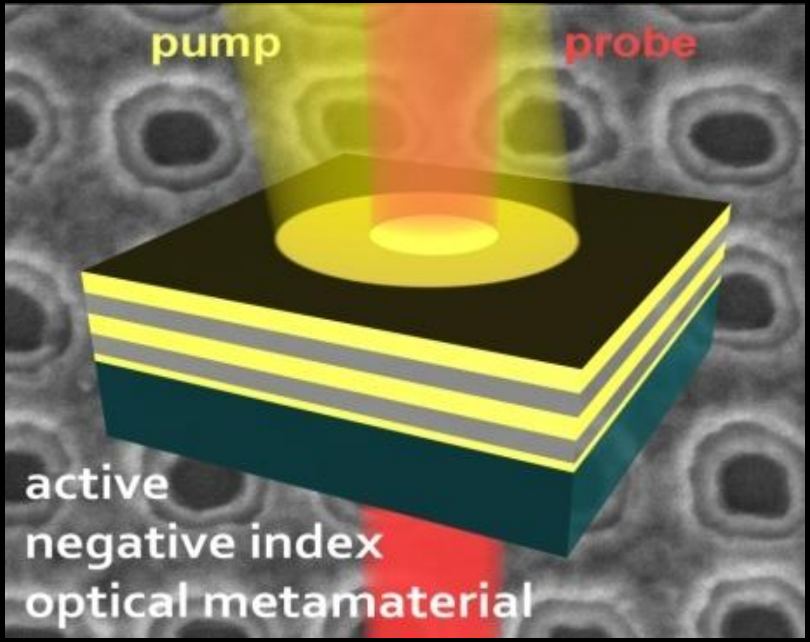


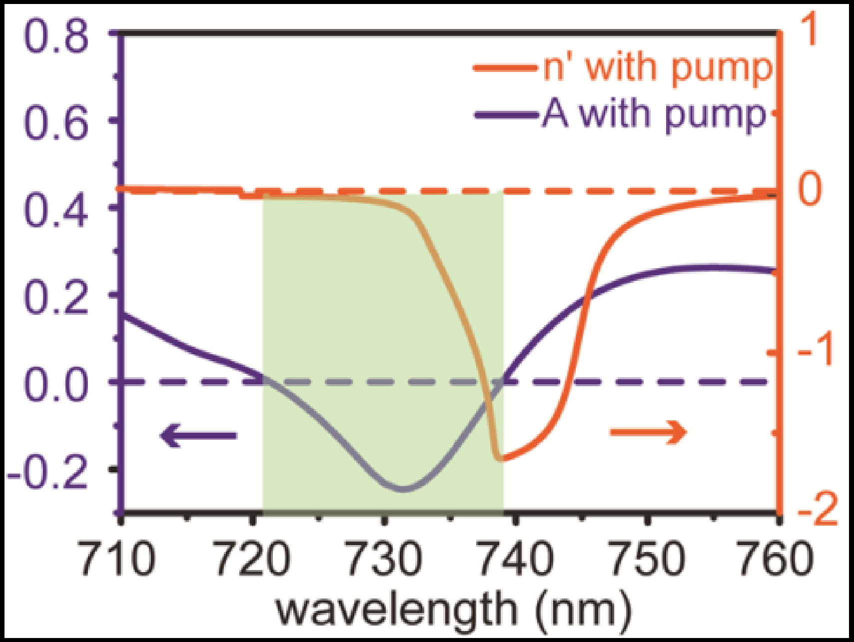


Al_2O_3 Rh800/SU-8 Air Silver

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)

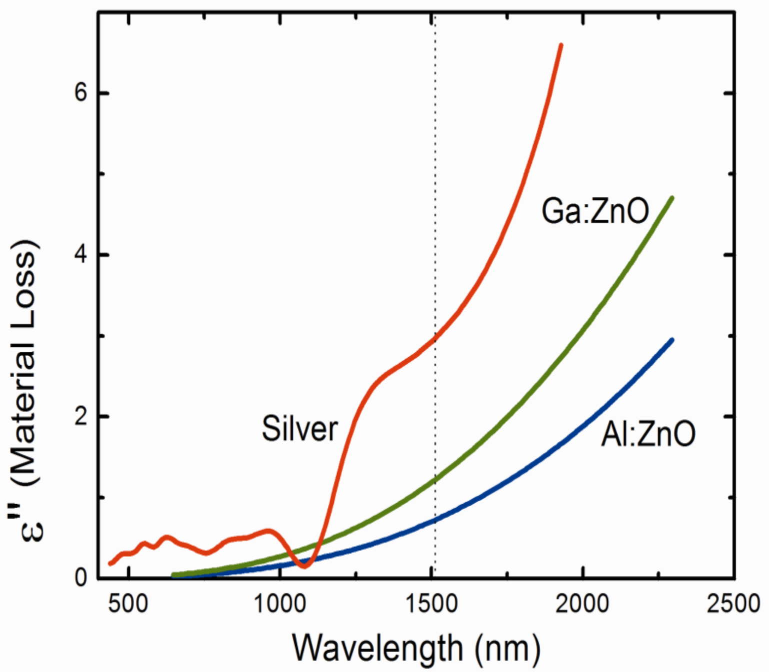
See also M. I. Stockman, PRL v. 106, 156802 (2011)

Toward Better Materials & Fabrication

(Boltasseva group)

Alternative Plasmonic Materials

Transparent Conductive Oxides



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

HMM Performance: Figure of merit for TiN

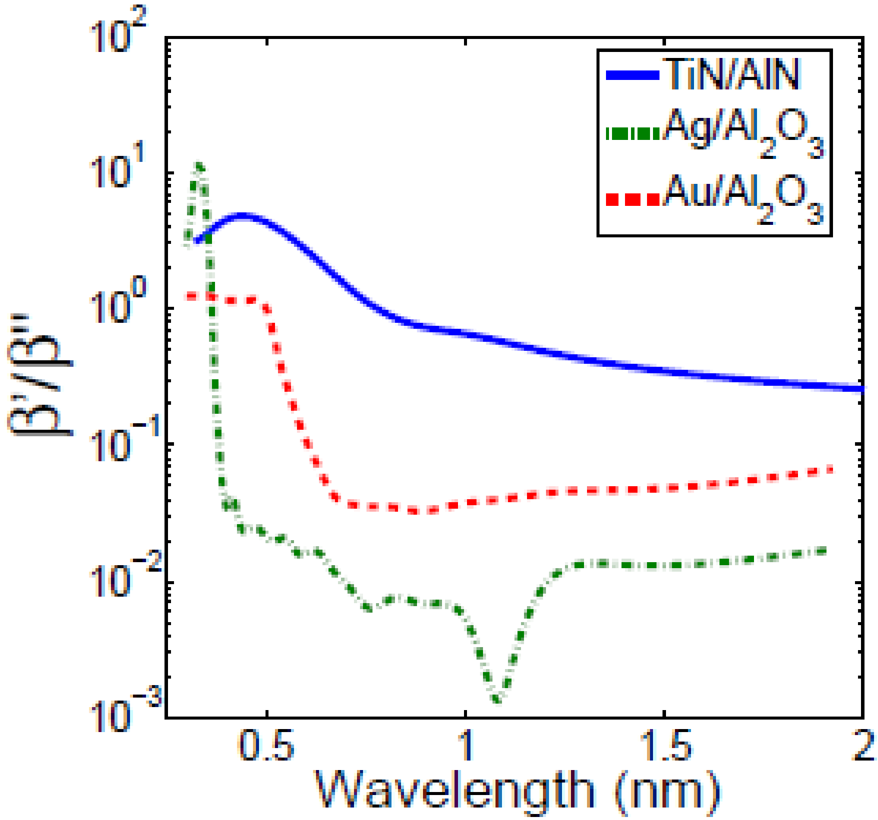


Figure-of-merit of HMMs formed by alternating, sub-wavelength layers of TiN/AlN, Ag/alumina and Au/alumina

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

What is the Best Material for…

LSPR

SPP & Waveguides

NIMs

Transform. Optics

ENZ

TCOs

Noble Alkali Alloys

Noble Metals

MetaMaterials?

Different Applications
Different figures-of-merit

Alkali Metals

Metal Nitrides

Graphene

Other Metals

What is the Best Material for…

LSPR: Au, Ag, TCOs

SPP Wvgds: Ag, Au, Nitrides

NIMs: Ag, Au, Na

Transform. Optics: TCOs

ENZ: TCOs

TCOs

Noble Alkali Alloys

Noble Metals

Metamaterials?

Different Applications
Different Materials

Alkali Metals

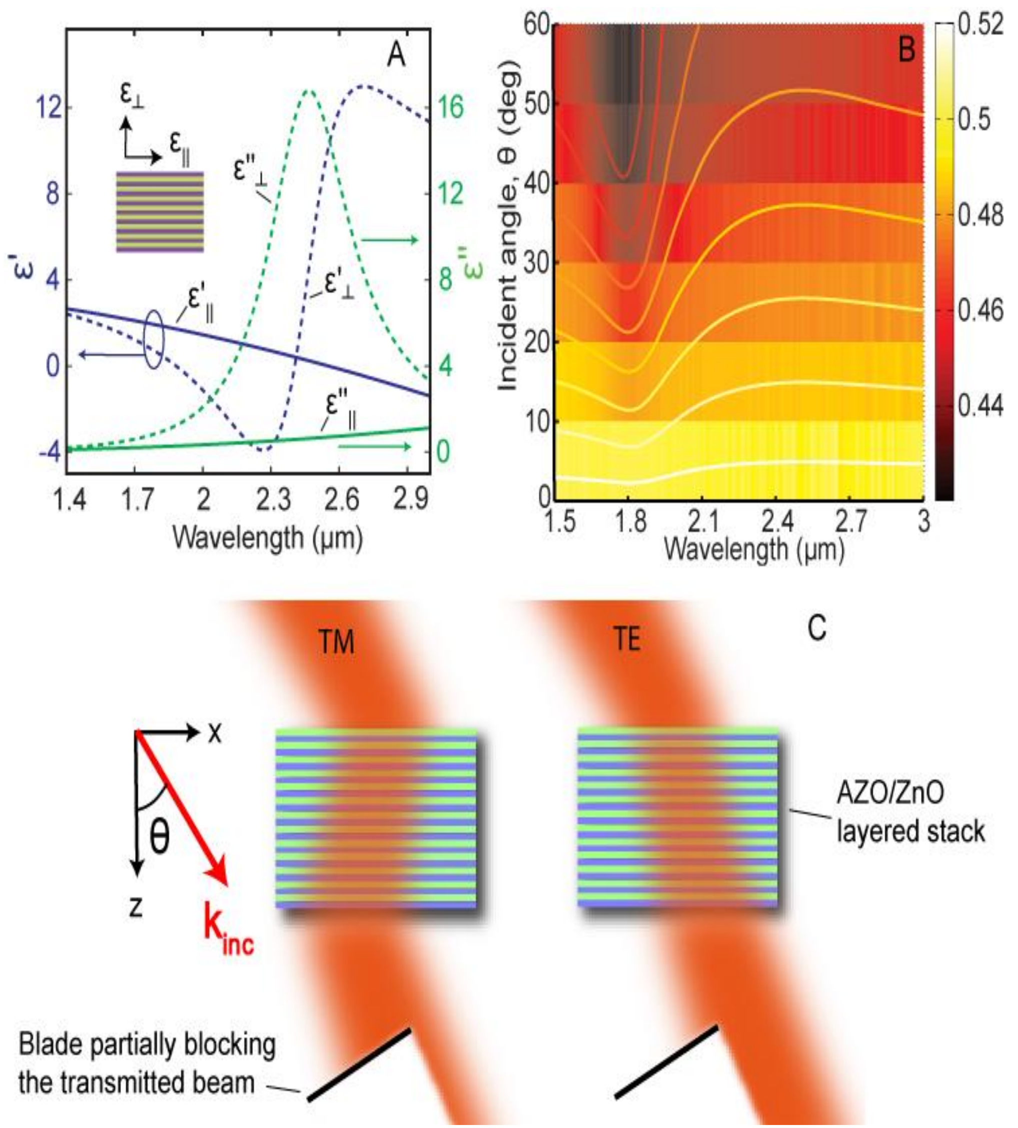
Metal Nitrides

Graphene

Other Metals

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. (Boltasseva /Shalaev groups)

Progress in large-scale & 3D fabrication

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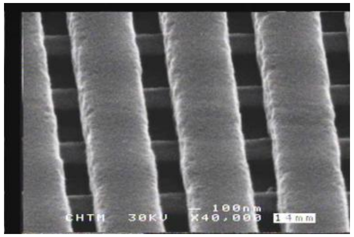
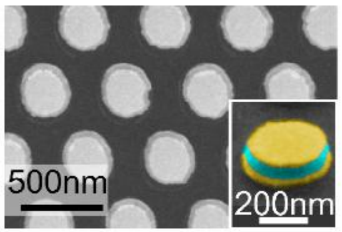
[Interference Lithography]

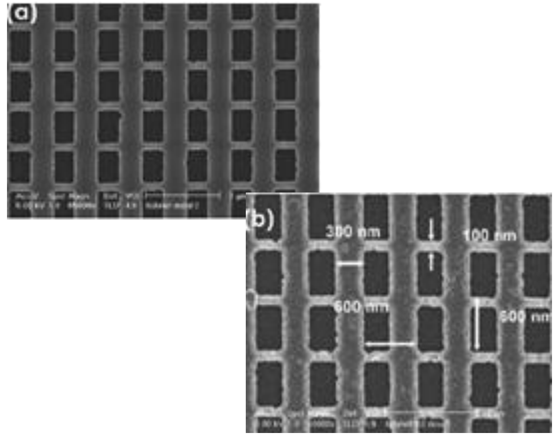


Z. Ku & SRJ Brueck, Opt. Exp. **15**, 4515 (2007)



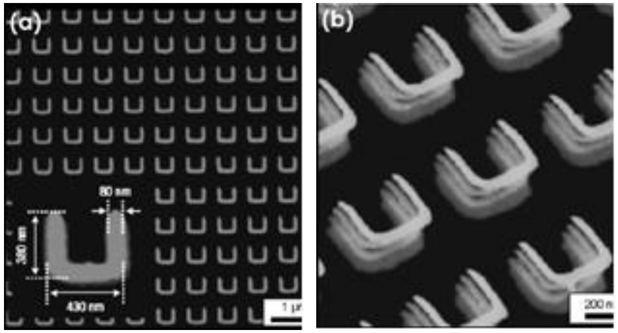
Nils Feth et. al, Opt. Exp. **15**, 501 (2007) (Wegener group)

[Nanoimprint Lithography]



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

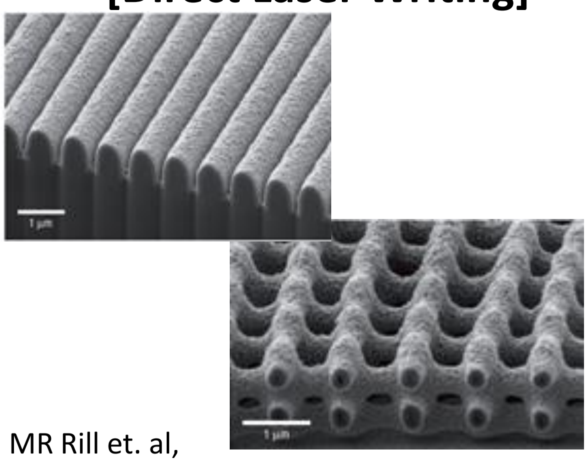
[Building layer-by-layer]



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

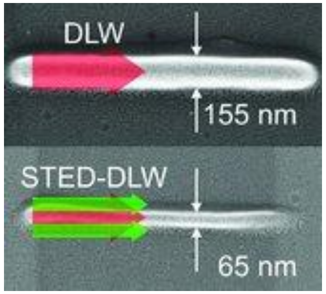
3D

[Direct Laser Writing]



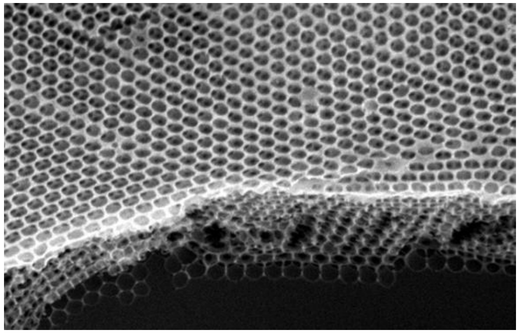
MR Rill et. al,
Nat. Mater. **5**,743 (2008) (Wegener group)

[STED-Direct Laser Writing]



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

[Self-assembly]

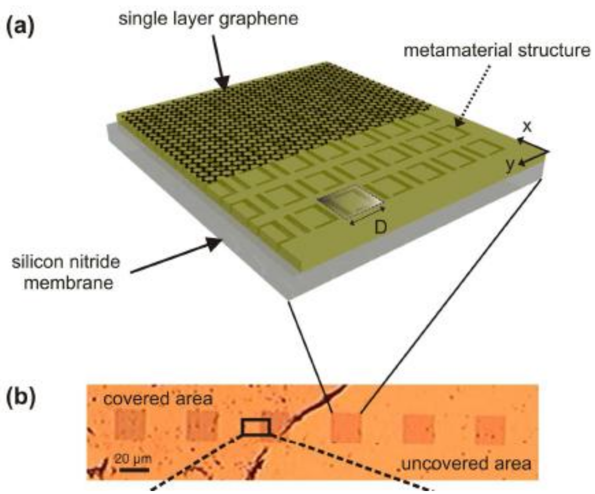


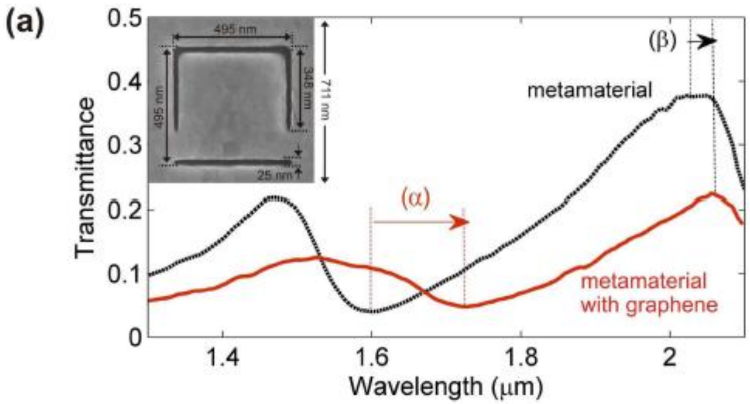
JF Galisteo et. al, J. Opt. A **7**, 244 (2005)

Metamaterials for Sensing

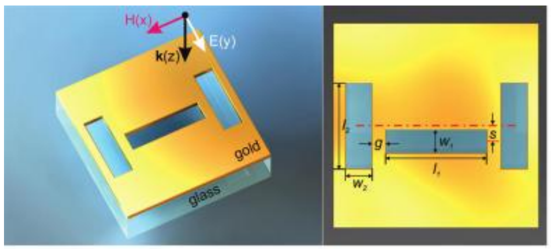
Metamaterials for Sensing

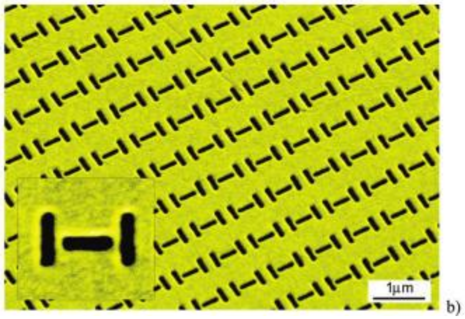
<Graphene+metamaterial for sensing>

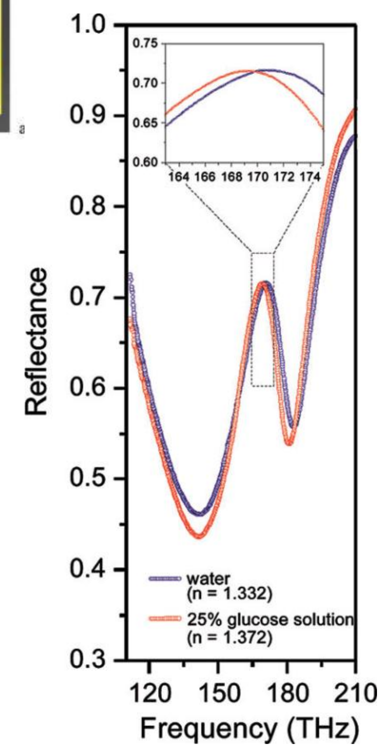




<EIT metamaterial for sensing>



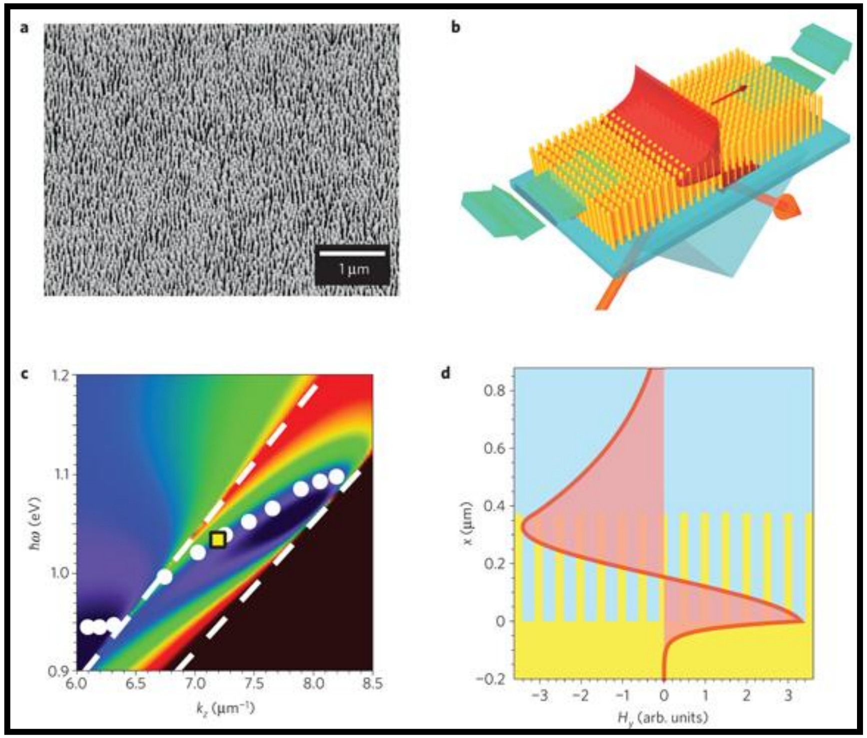


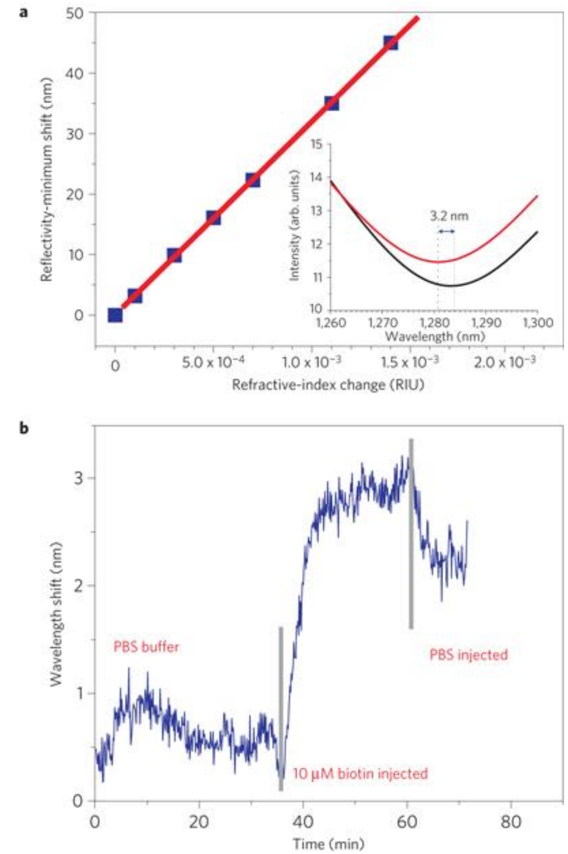


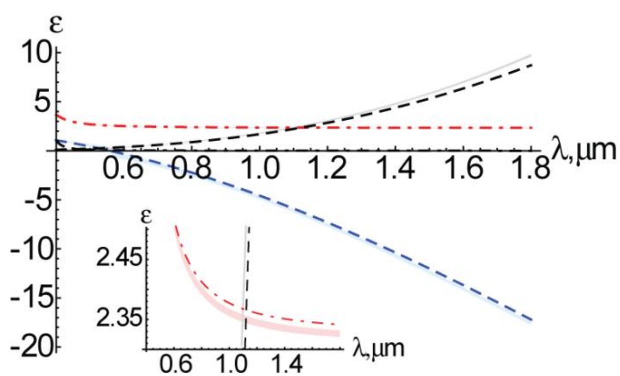
N. Papasimakis, et al, OE (2010) (Zheludev group)

N. Liu, et al, NL (2010) (Giessen group)

Hyperbolic Metamaterials for Biosensing



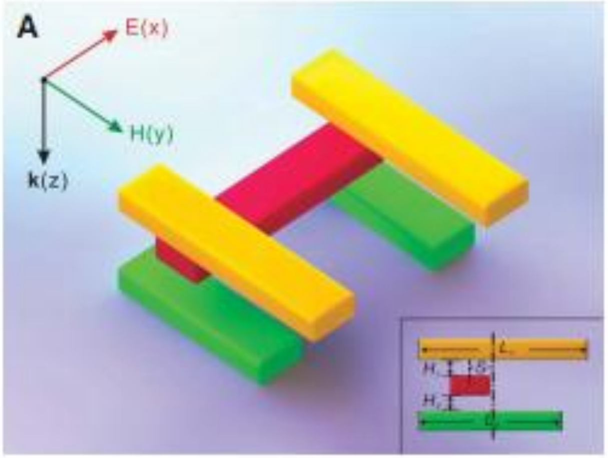




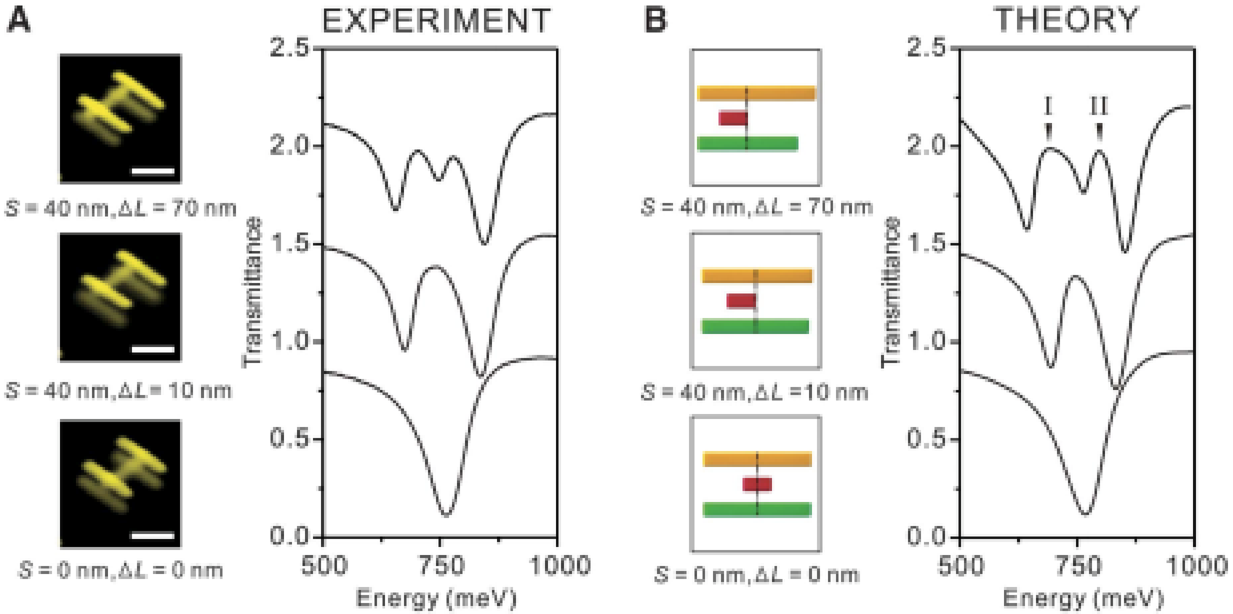
More than <u>100 times </u>sensitive than other LSP based sensors

A. Kabashin, et al, Nature Materials (2009) (Zayats group)

3D Plasmon Rulers



Induce one broad dipolar resonance and two narrow quadrupolar resonances for high precision sensing



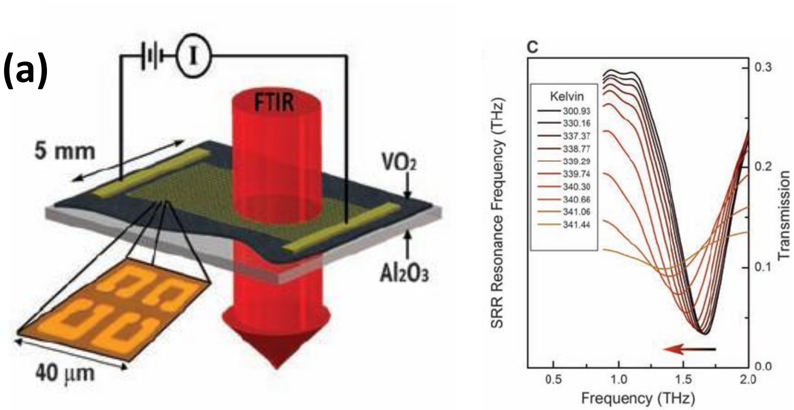
N. Liu, et al, Science (2011) (Giessen /Alivasatos groups)

Tunable, Ultrafast & Nonliear Metamaterials

Tunable MMs with Phase Change Components

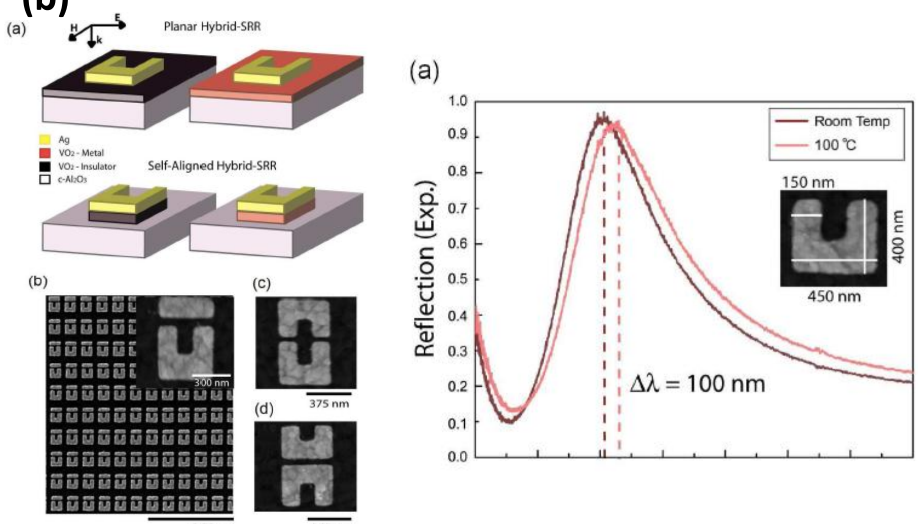
Electircally controllable memory with VO_2

(a)

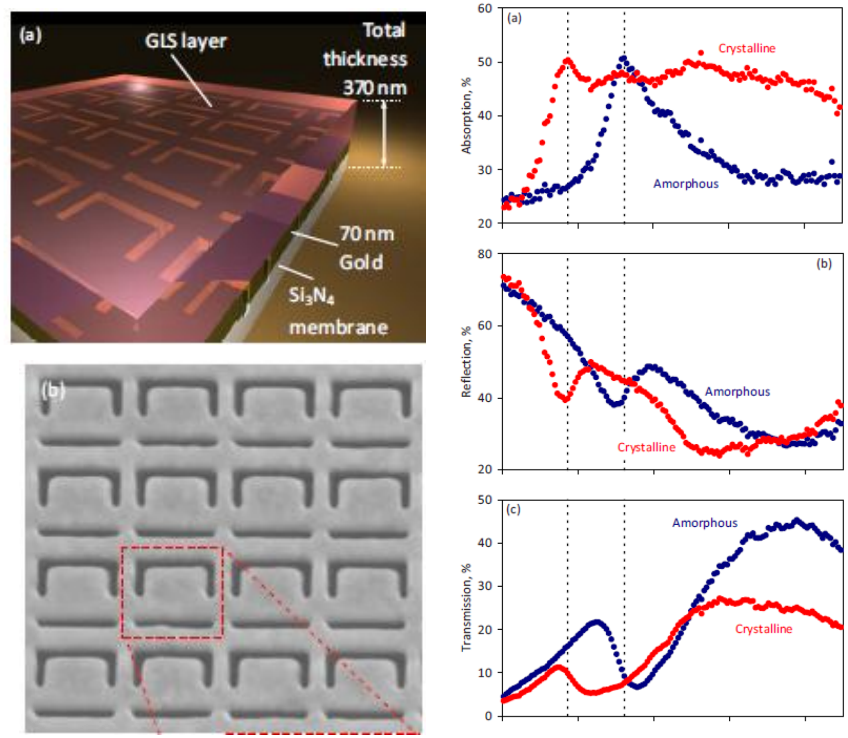


NIR tunability with VO_2

(b)



(c) **Tunability with ChG**



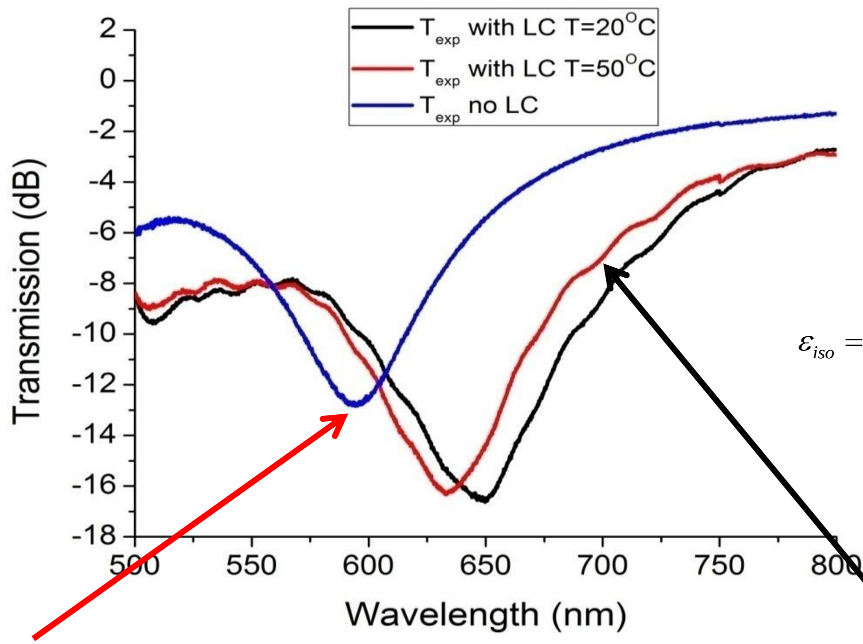
THz range – Willie Padilla

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

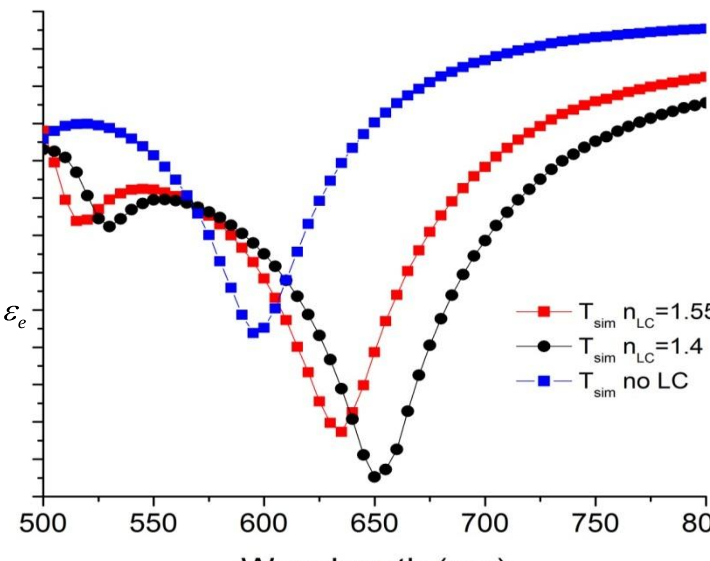
(b) M. Dicken, et al, OE (2009) (Atwater group)

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

Tunable Metamaterials



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



(Isotropic)

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

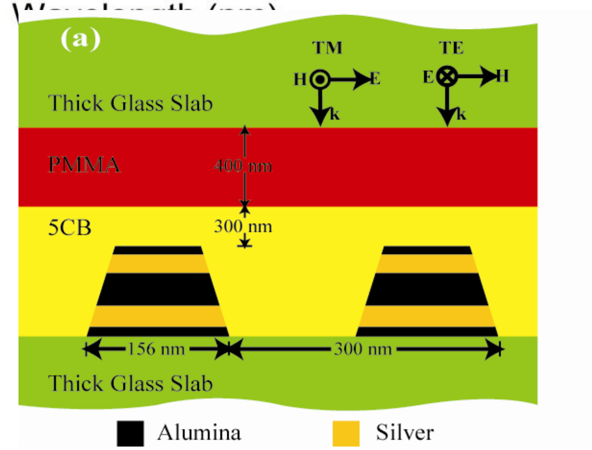
Phase transition

Δn=0.17

T>T$_e$

(Nematic)

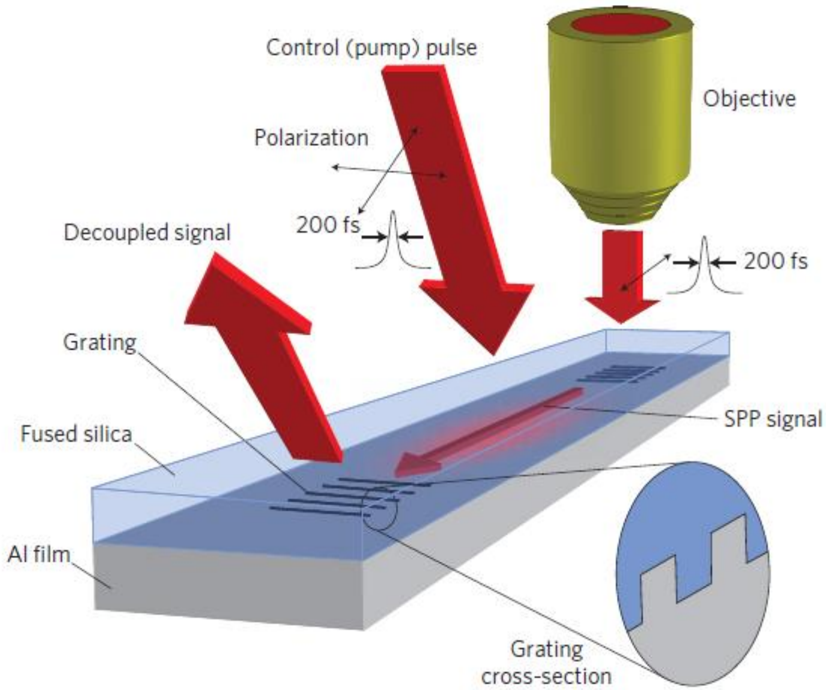
$$n_{eff} = n_e$$

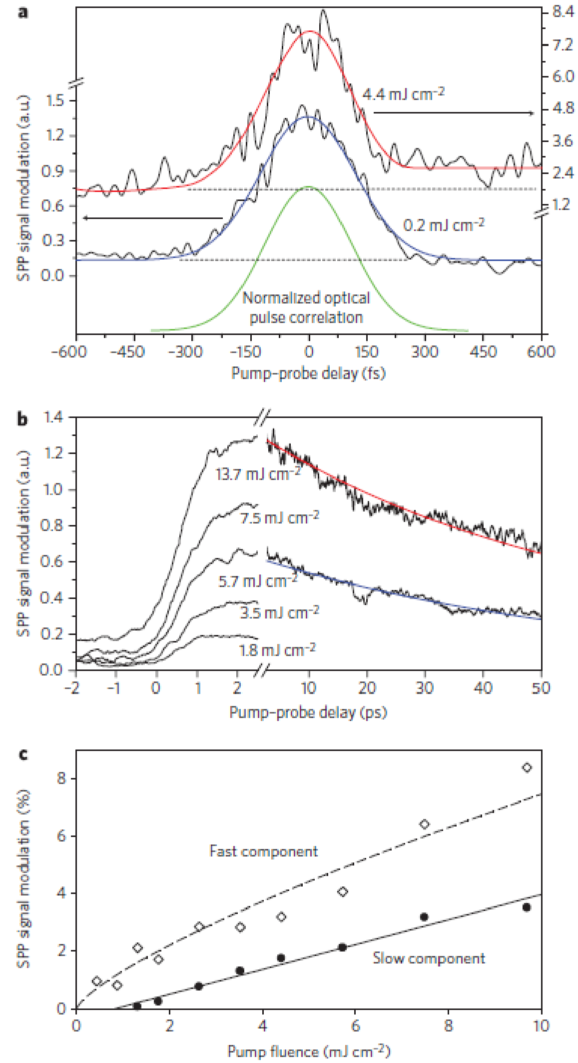


S. Xiao, et al, APL (2009)

also work by Zheludev group: phase-changing dielectrics

Ultrafast Active Plasmonics





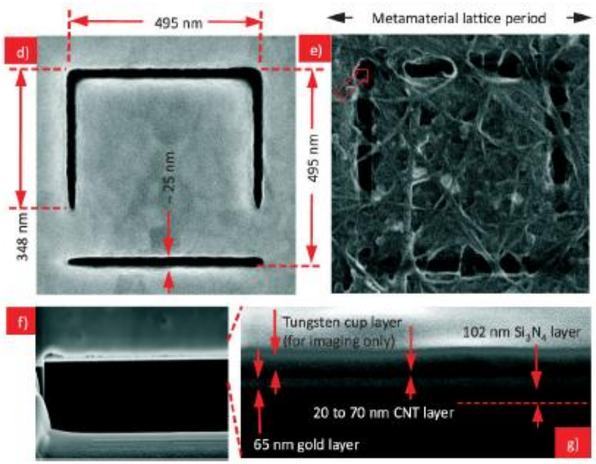
- SPP propagation influenced by optical pump
- Sub-ps control on SPPs

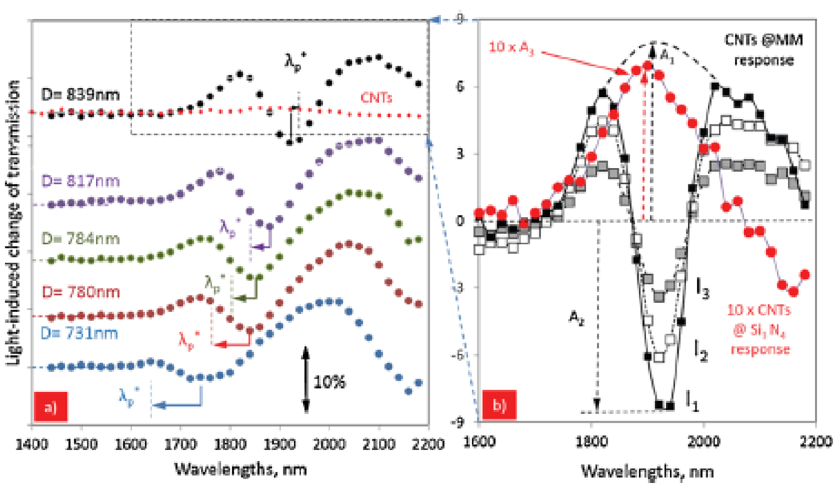
K. MacDonald, et al, Nature Photonics (2008) (Zheludev group and Stockman)

Nonlinear Metamaterials

Carbon nanotubes + MM

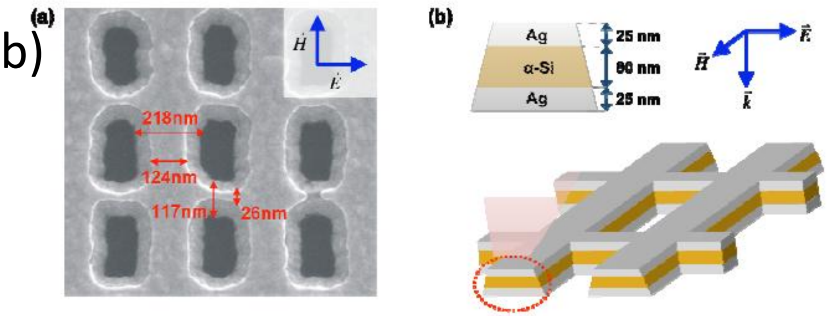
(a)

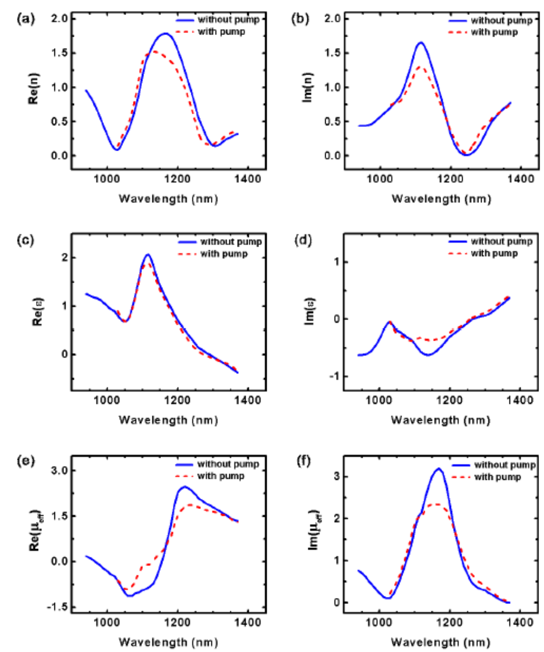




a-Si+ MM

(b)



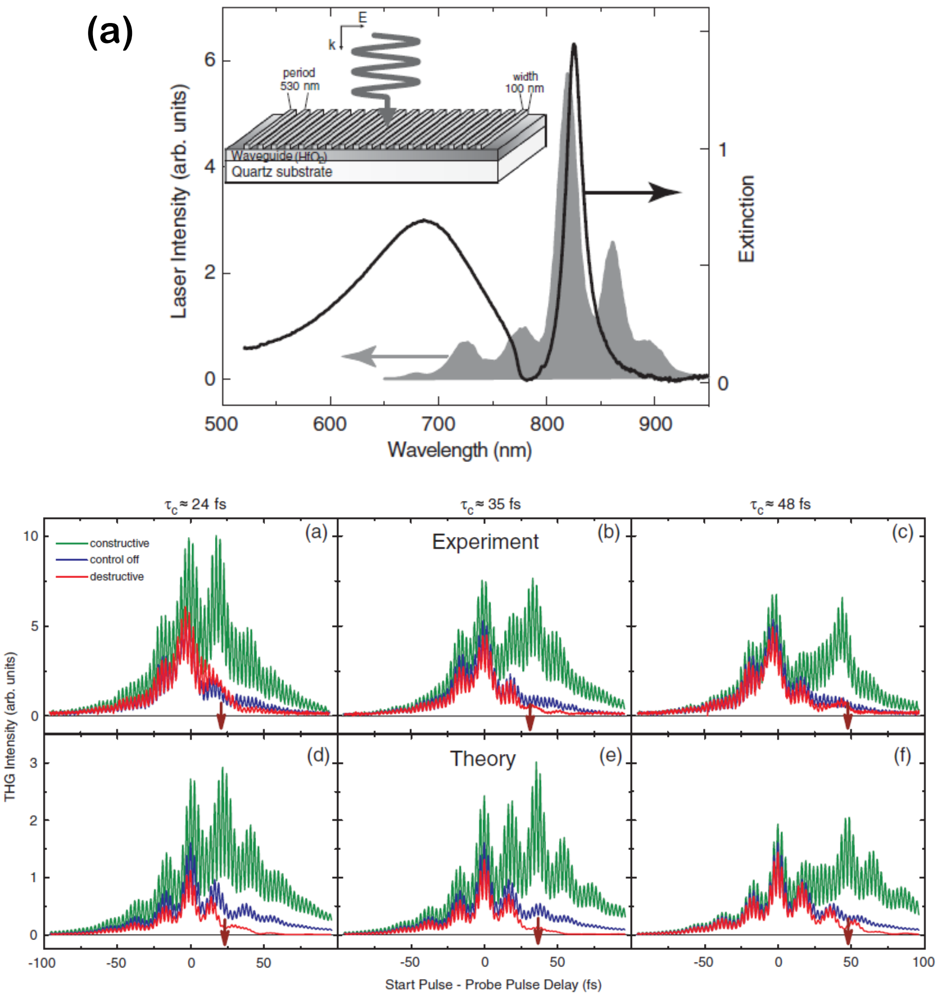


(a) N. Papasimakis, et al, PRL (2010) (Zheludev group)

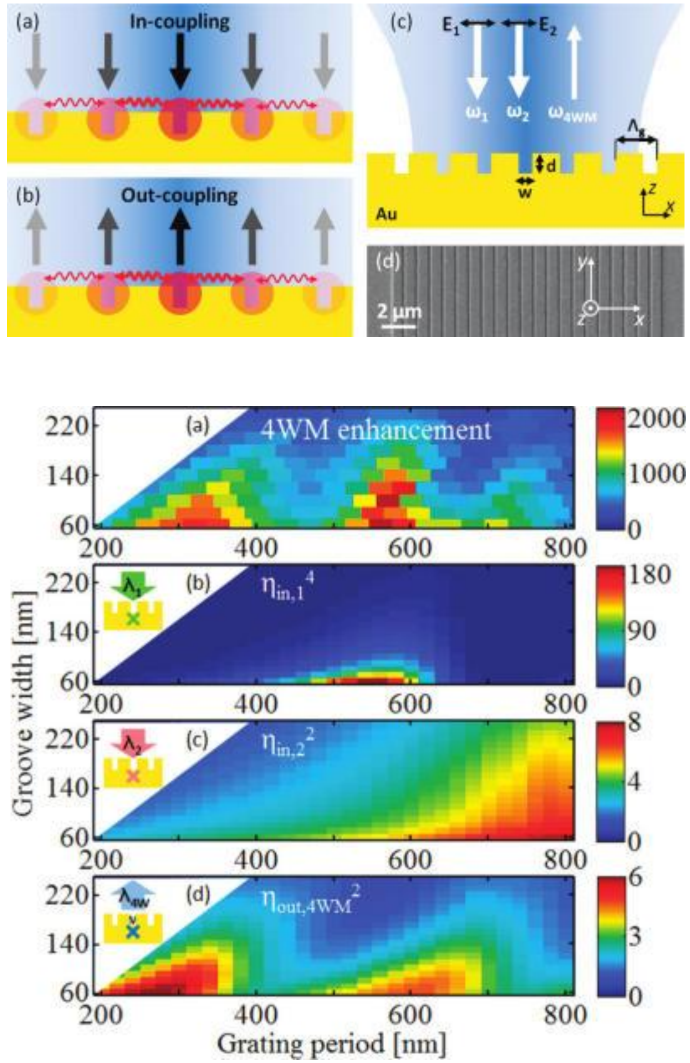
(b) D. Cho, et al, OE (2009) (Shen/Zhang groups)

Four-Wave Mixing in Metamaterials

(a)



(b)

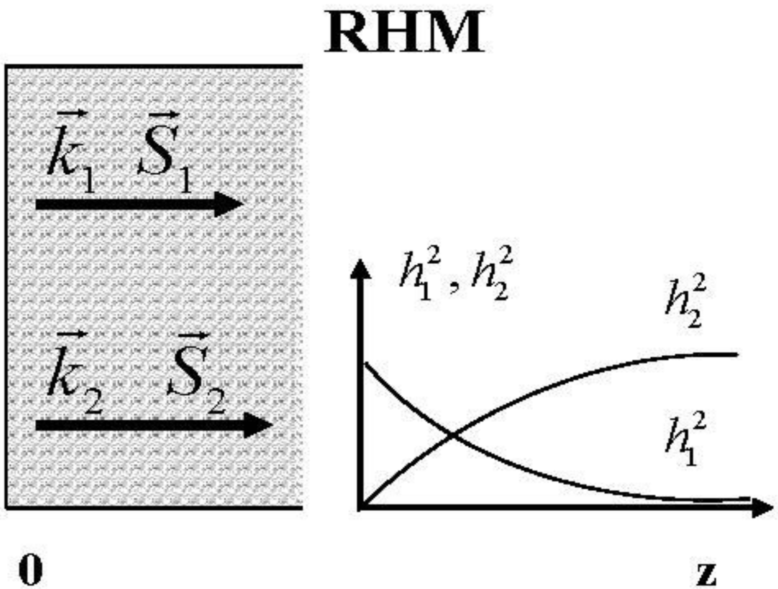


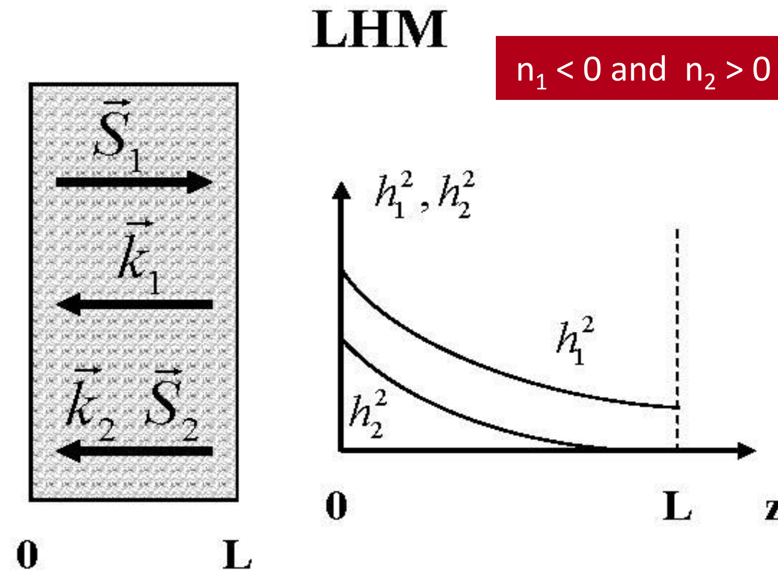
(a) T. Utikal, et al, PRL (2010) (Gissnen/Stockman group)

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

Backward Waves in Nonlinear NIMs

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





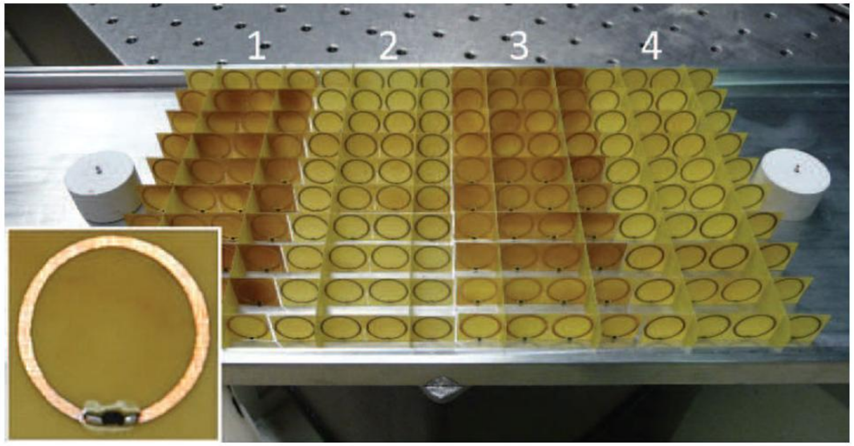
$n_1 < 0$ and $n_2 > 0$

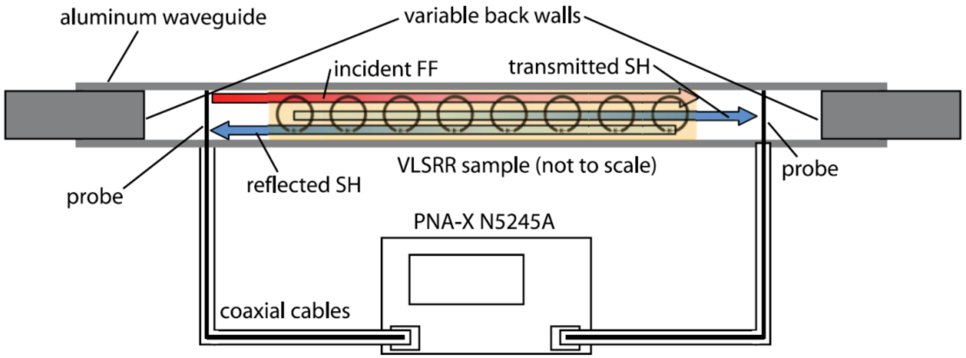
Manley-Rowe Relations

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

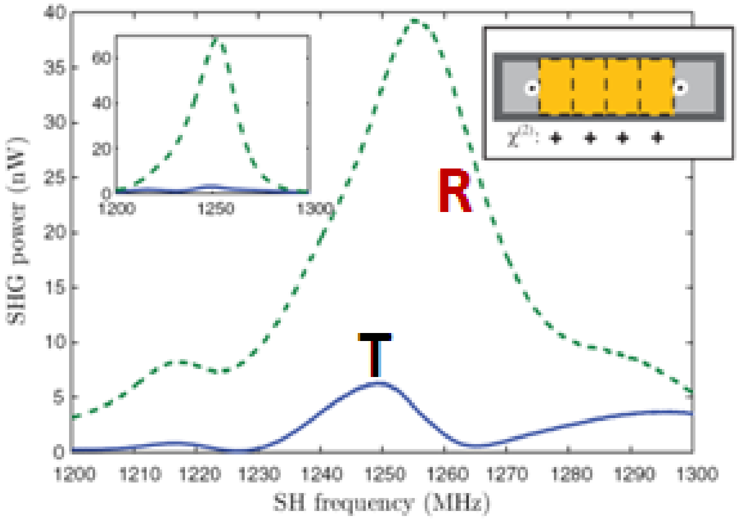
Phase-matching: $\varepsilon_1 = -\varepsilon_2, k_2 = 2k_1$ $\Rightarrow$ $h_1^2(z) - h_2^2(z) = C$

Second Harmonic generation in a Phase-Matched NIM





Experimental setup



R. SH enhancement
(nonlinear optical mirror)

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

Quantum Optics with Metamaterials:

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

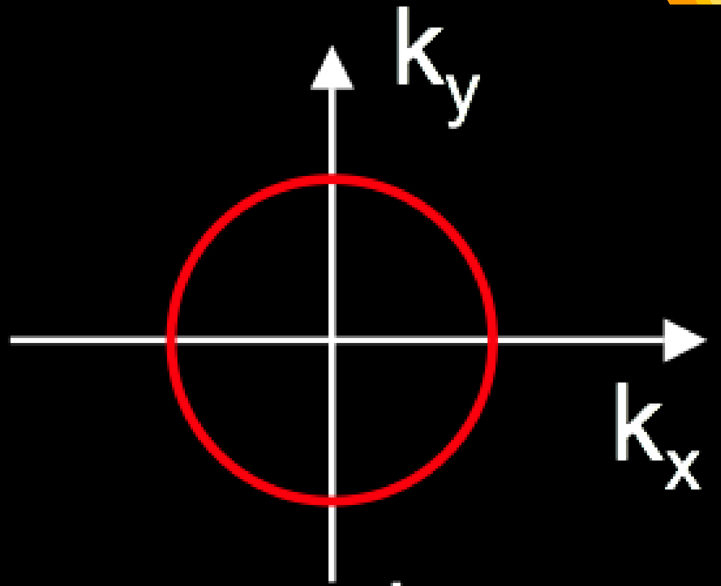
Hyperbolic Dispersion

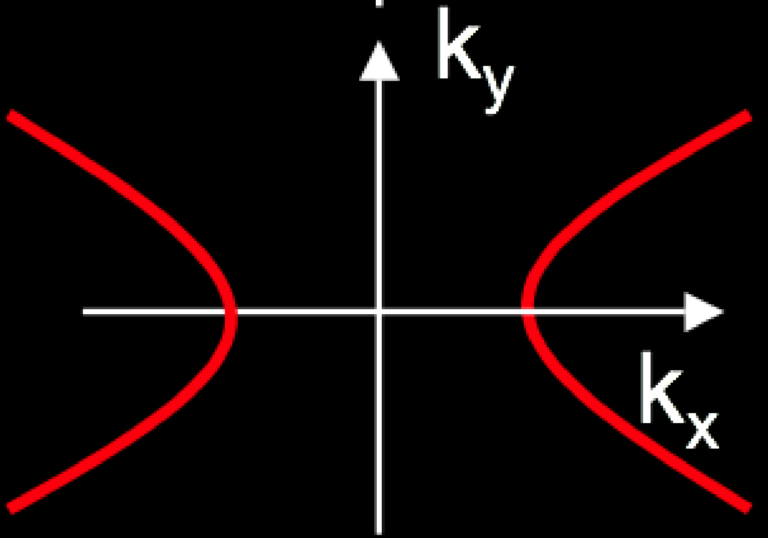
"Regular" dielectric

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

"Strongly Anisotropic" media

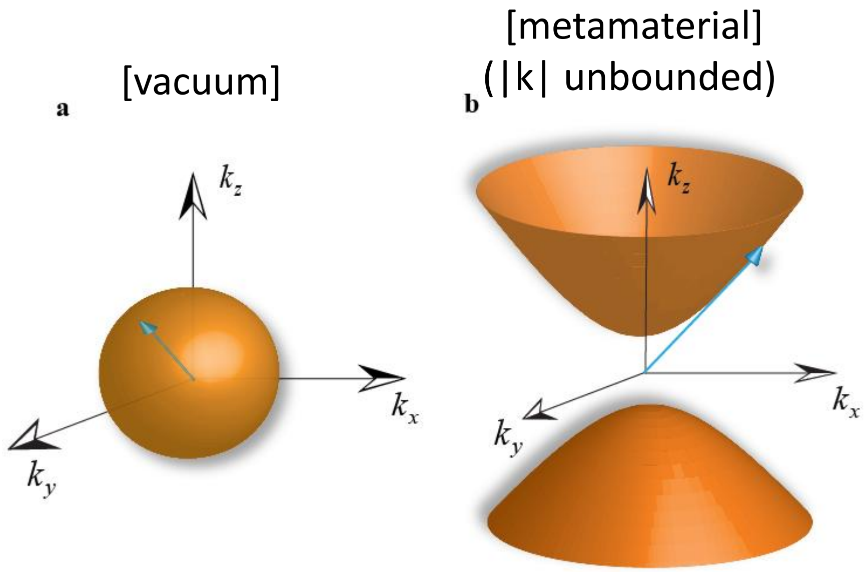
$$\frac{k_x^2}{\epsilon_y} + \frac{k_y^2}{\epsilon_x} = \frac{\omega^2}{c^2}$$

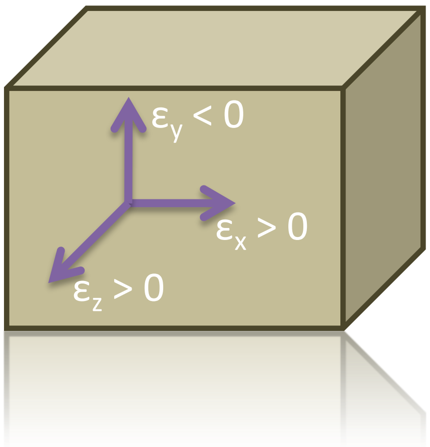




Special case of "Indefinite Media", D. Smith, et al. (2003)

PDOS in Hyperbolic Metamaterial?





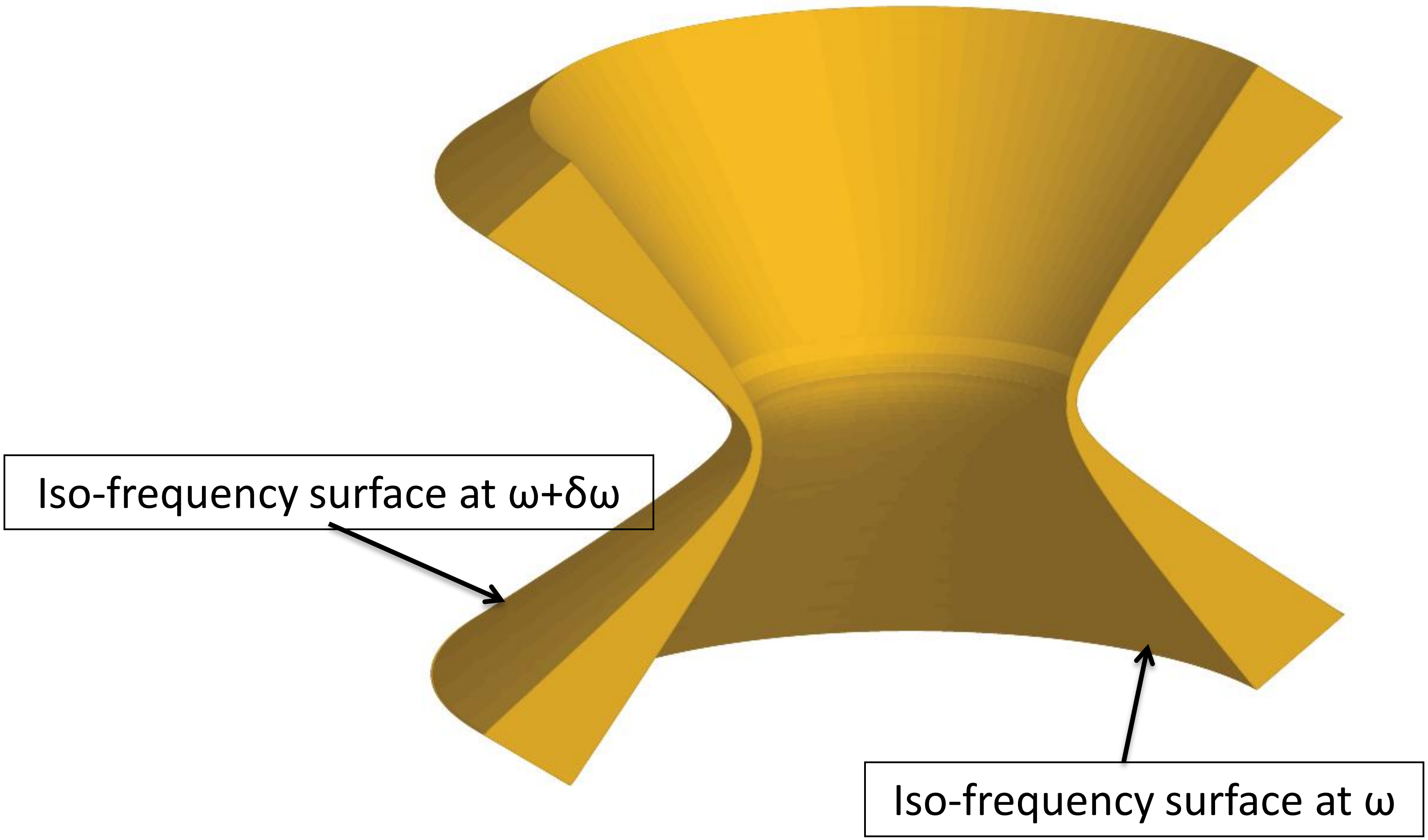
Singularity in density of states!!!!

Hyperbolic dispersion supports high spatial wavevectors compared to vacuum

Large contribution to DOS from the "high k" states (think beyond imaging!)

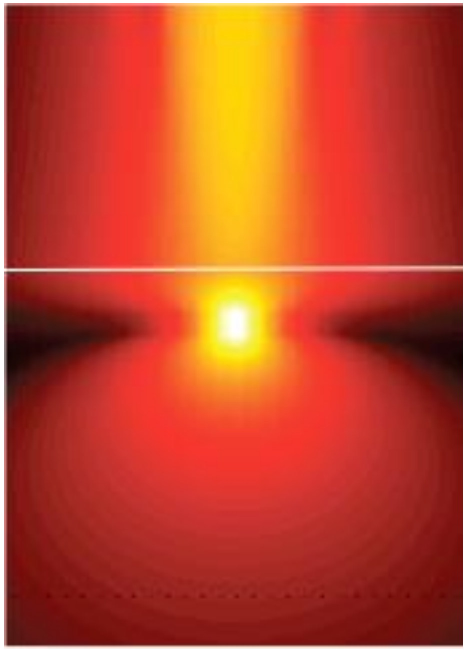
Theory: E. Narimanov, Z. Jacob, and I. Smolyaninov

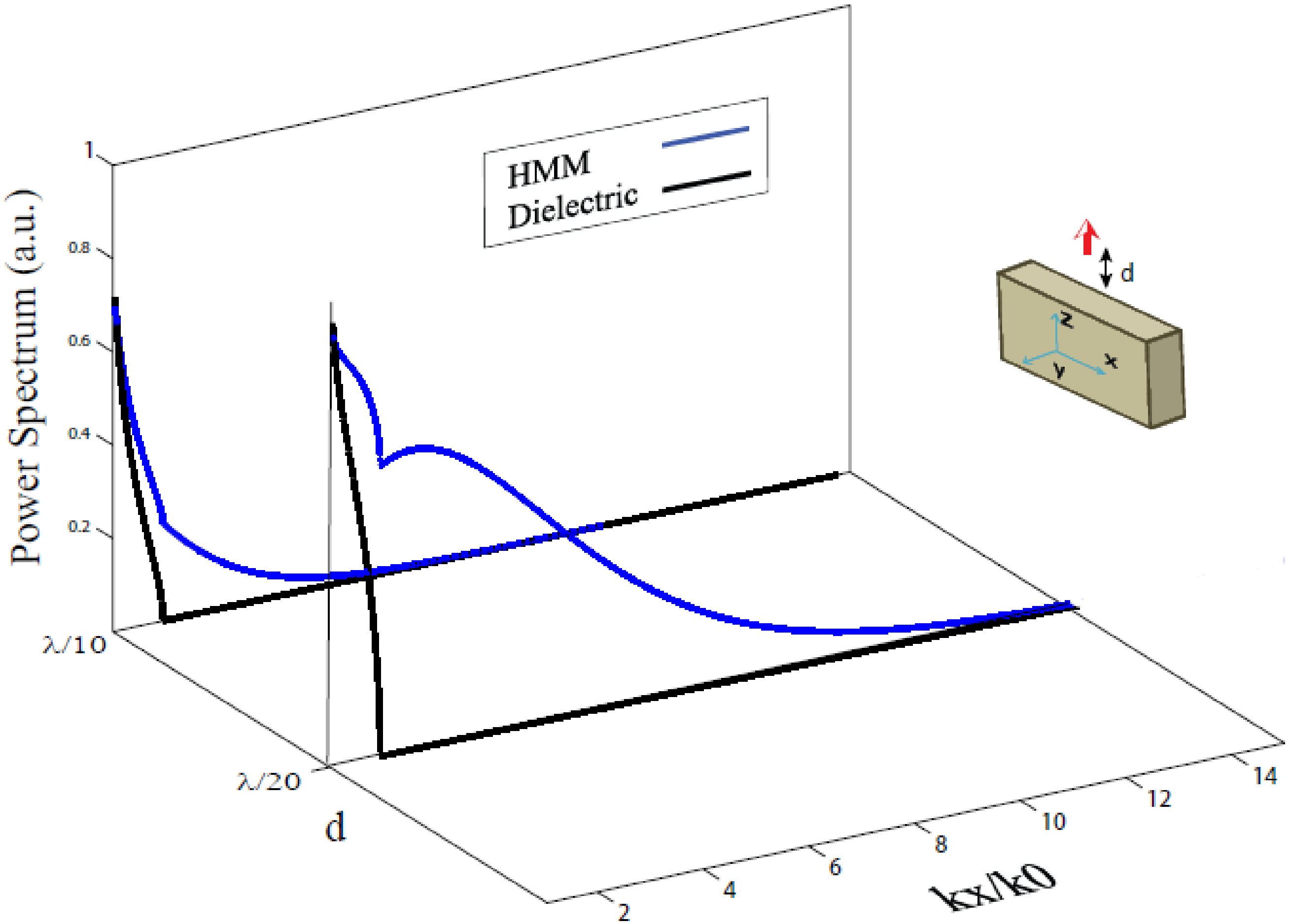
Photonic Density of States (PDOS)



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

Emission Power Spectrum



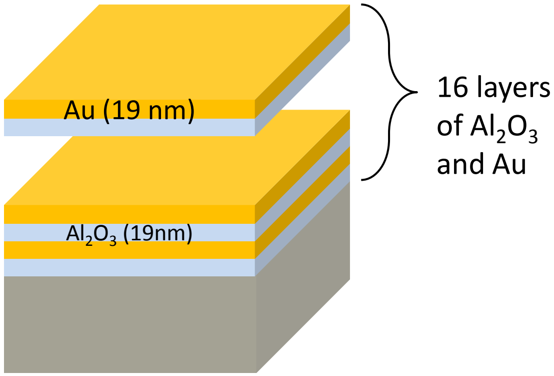


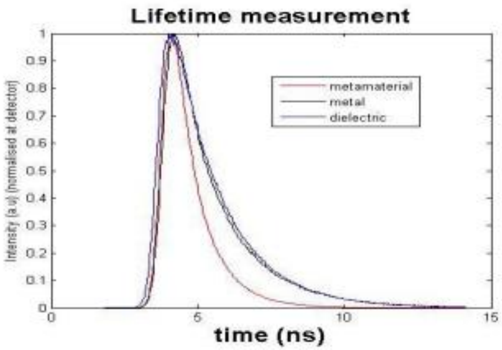
Calculation Methods: $\Gamma = \dfrac{P}{\hbar\omega}$: Ford and Weber (1984)

QED: Hughes group (2009)

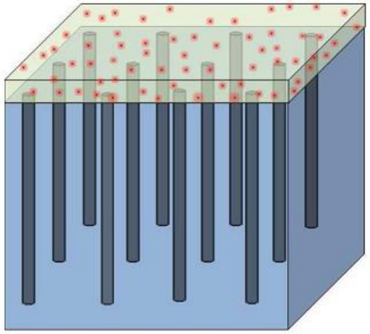
HMMs: Type I and Type II

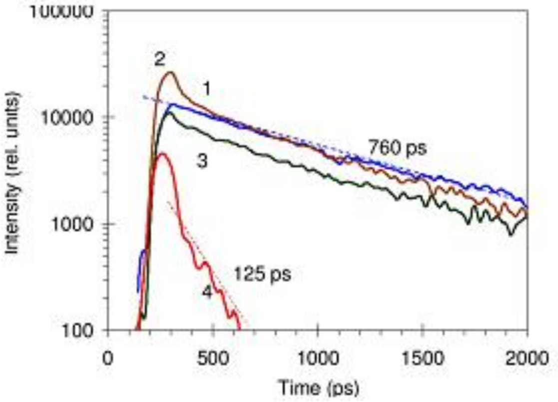
Design 1. Shalaev's group:
Stacked metal-dielectric layer
$\varepsilon_x, \varepsilon_y < 0, \varepsilon_z > 0$
$\varepsilon_\perp = 12.5+0.5i$
$\varepsilon_{||} = -8.2+0.9i$
Applied Physic B 2010





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





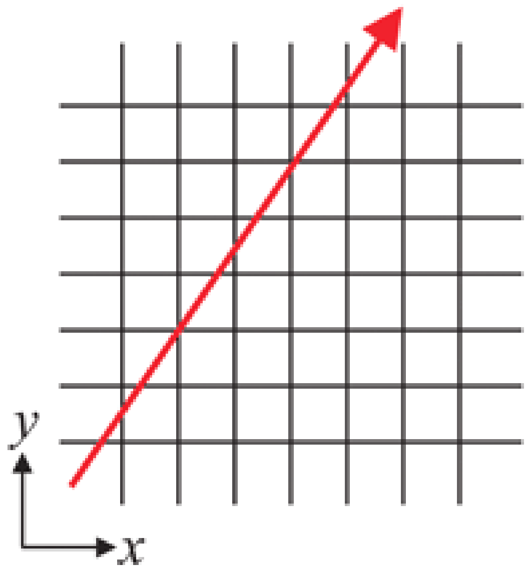
Transformation Optics

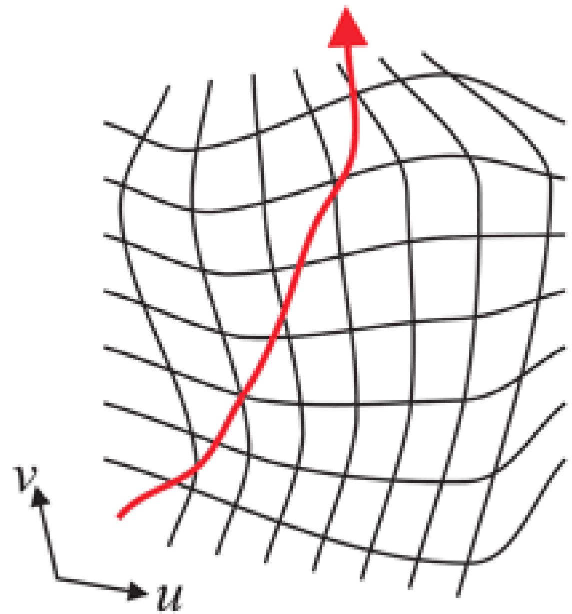
V. M. Shalaev, Transforming Light, Science (2008)

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

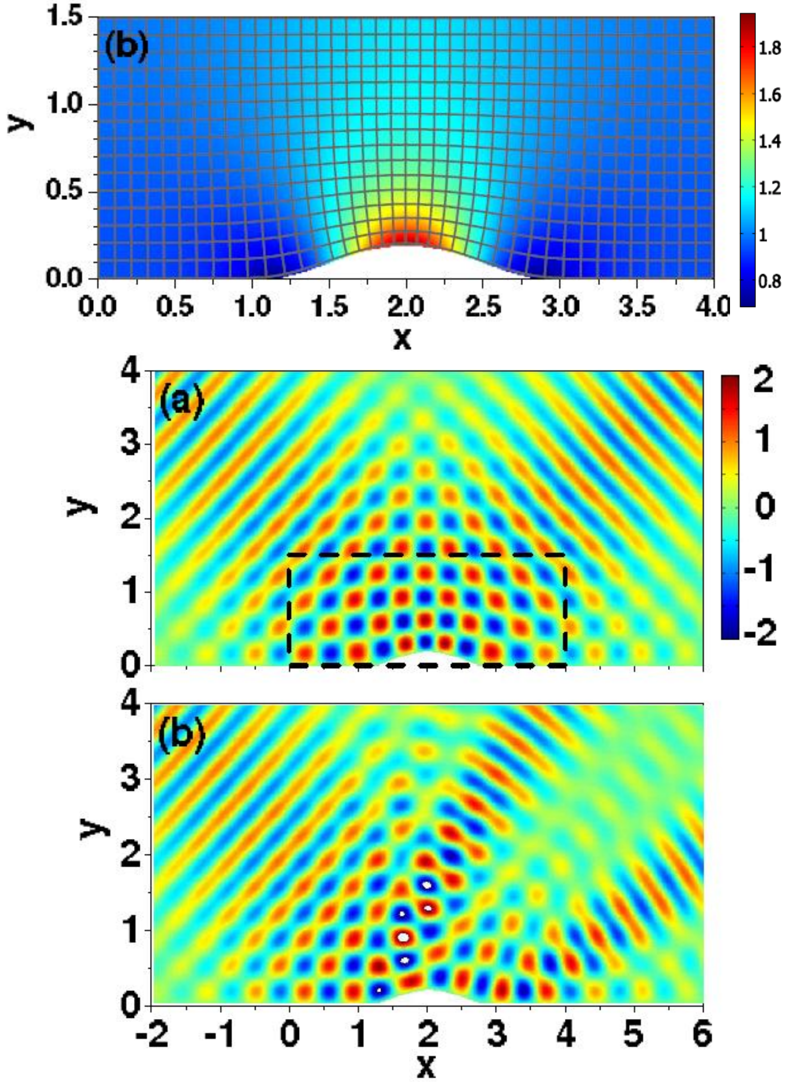
Distorted field line
in distorted coordinate

Spatial profile of ε & μ tensors determines the distortion of ordinates

Seeking for profile of ε & μ to make light avoid particular region in space — optical cloaking

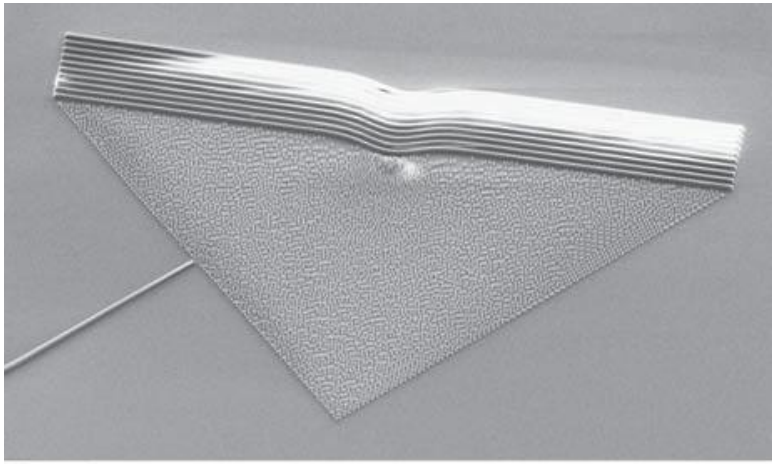
J. Pendry et al., Science (2006)
U. Leonhard, Science (2006)
A. Greenleaf et al. (2003)
L. Dolin, Izv. VUZ, 19614

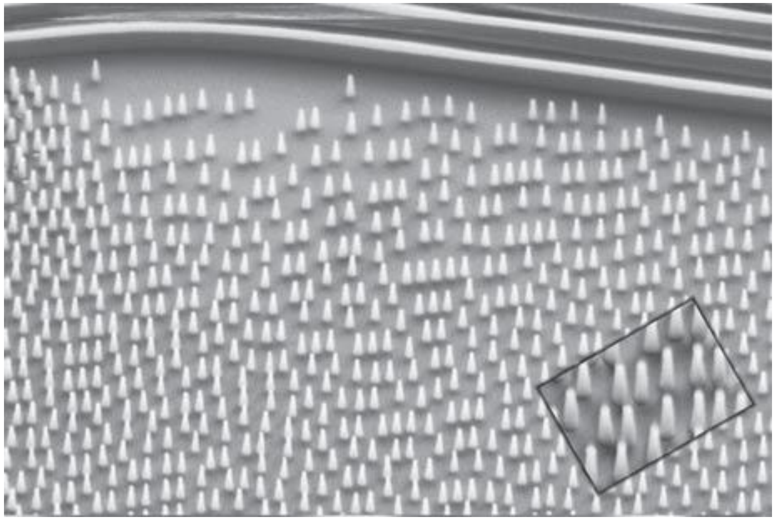
Invisible Carpet

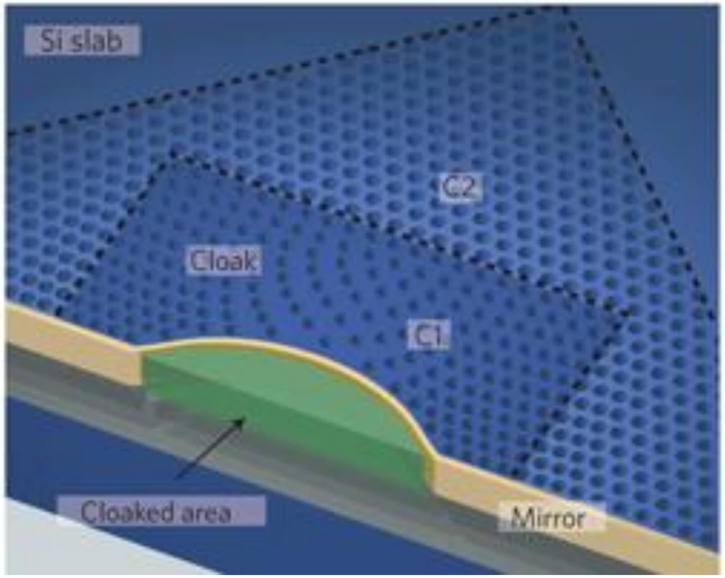


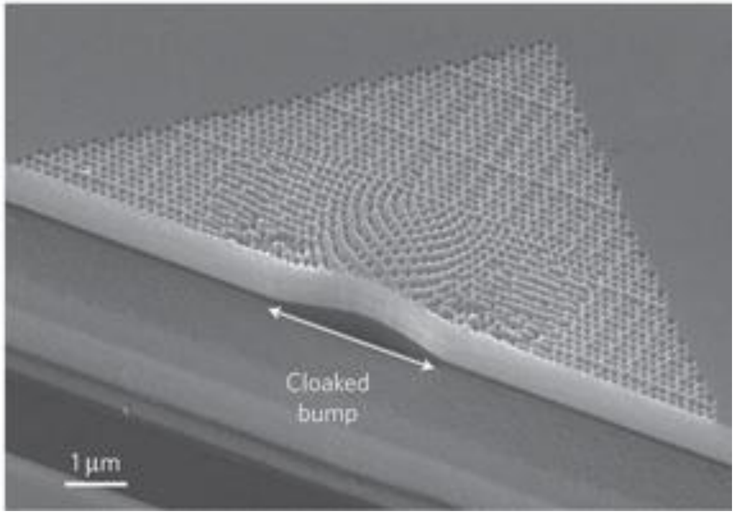
picture from discovery.com

J. Li and J. Pendry, PRL. (2008)







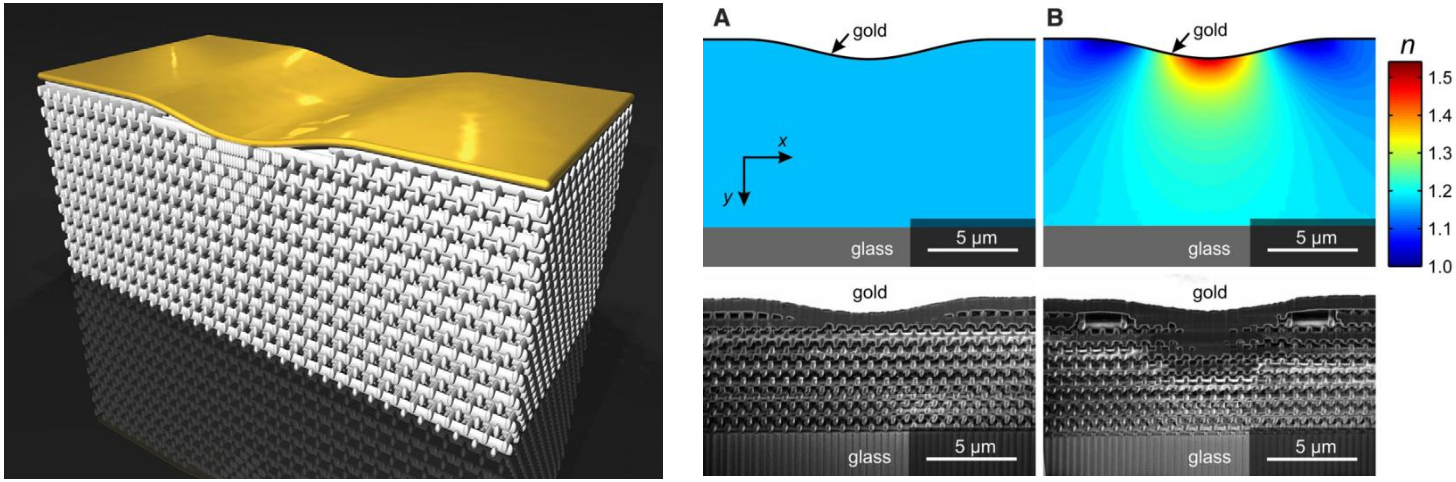


L. Gabrielli, et al, Nature Photonics (2009)
(Lipson group)

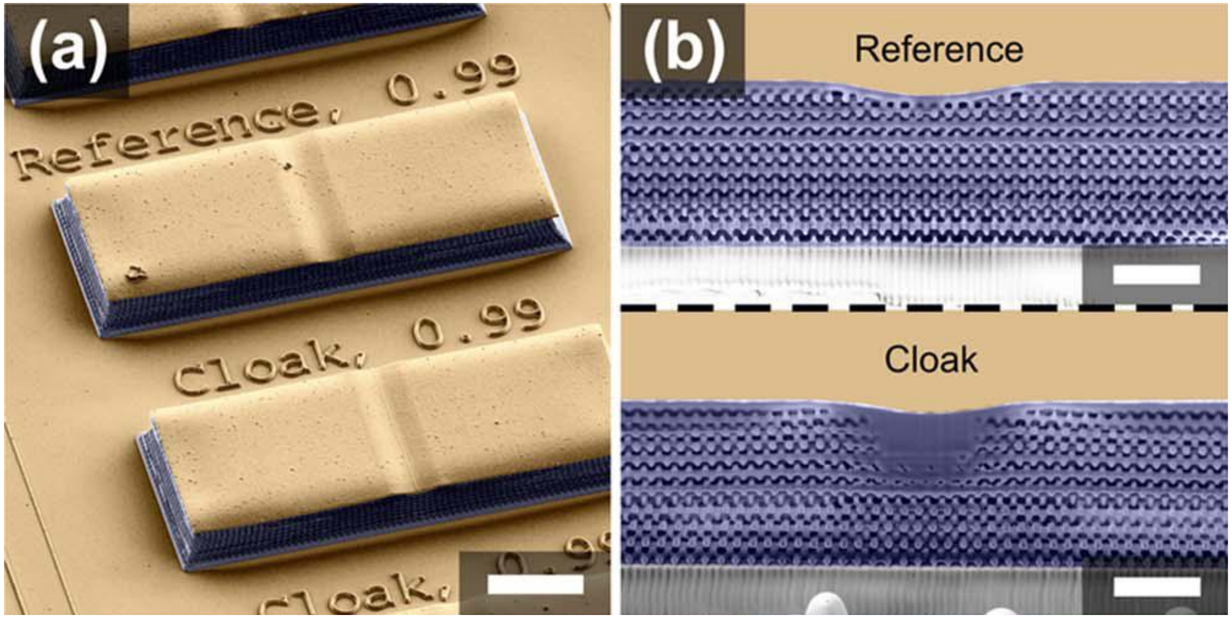
J. Valentine, et al, Nature Materials (2009)
(Zhang group)

3D carpet cloaking

(a)



(b)



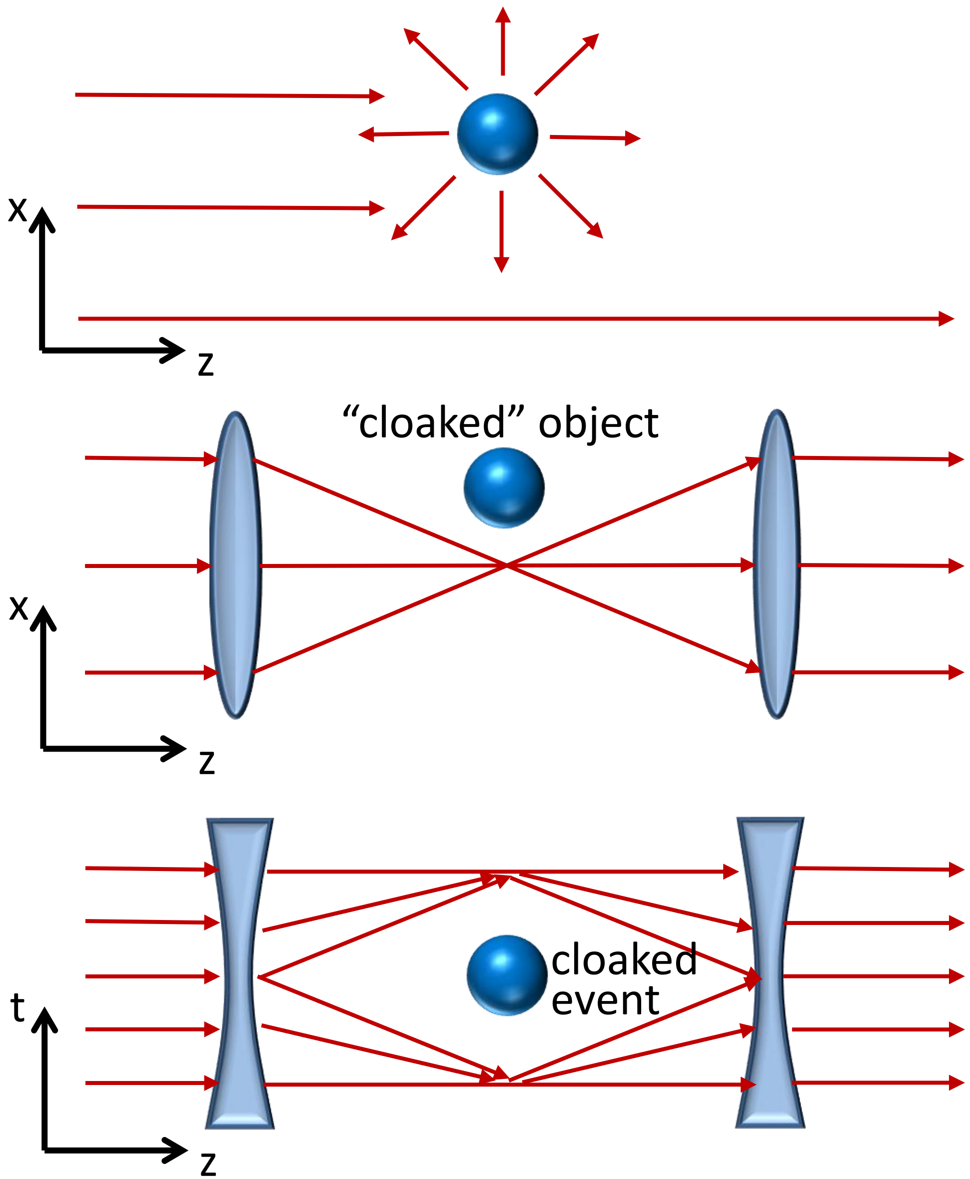
stimulated-emission-depletion (STED)-inspired direct laser writing was used

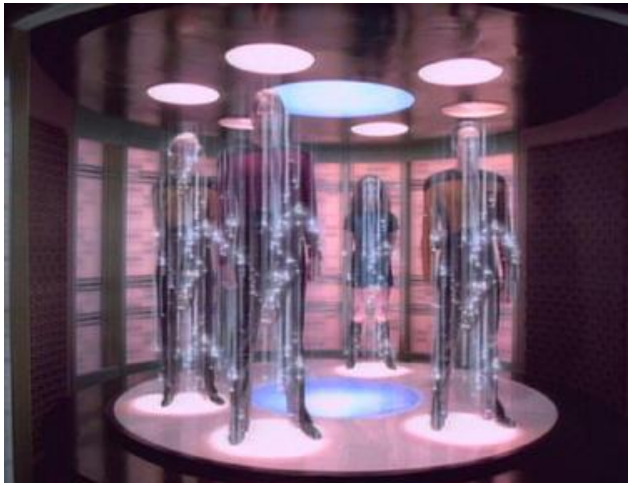
Rod spacing
Science: 800 nm
OL: 350 nm

Operating wavelength
Science: 1.4 ~ 2.7 μm
OL: 650 ~ 900 nm

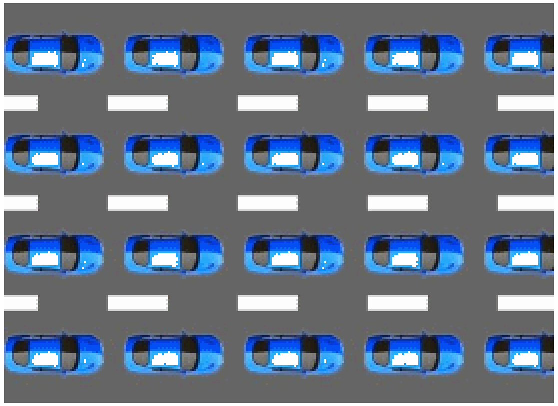
(a) T. Ergin, et al, Science (2010) (Wegener group)
(b) Opt. Lett. (2011) (Wegener group)

Space-time Cloak Theory

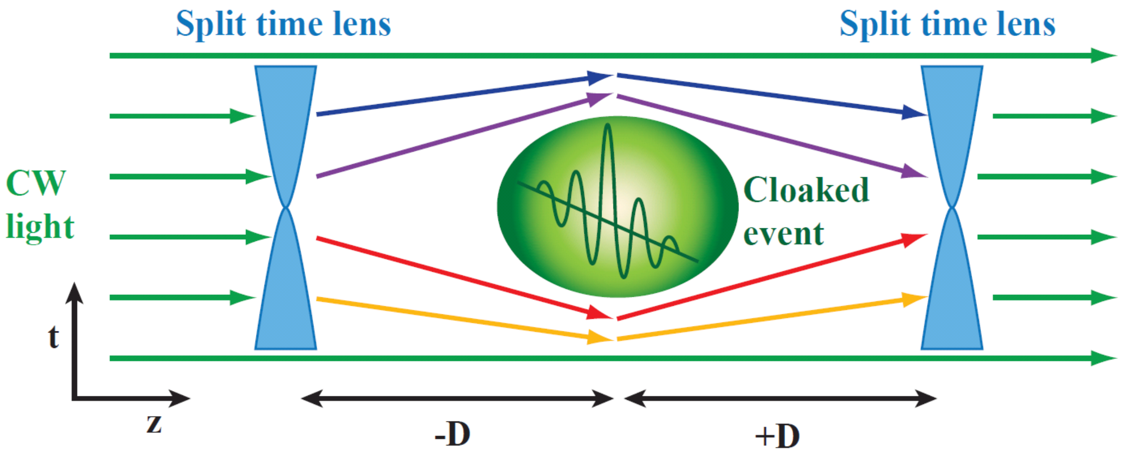


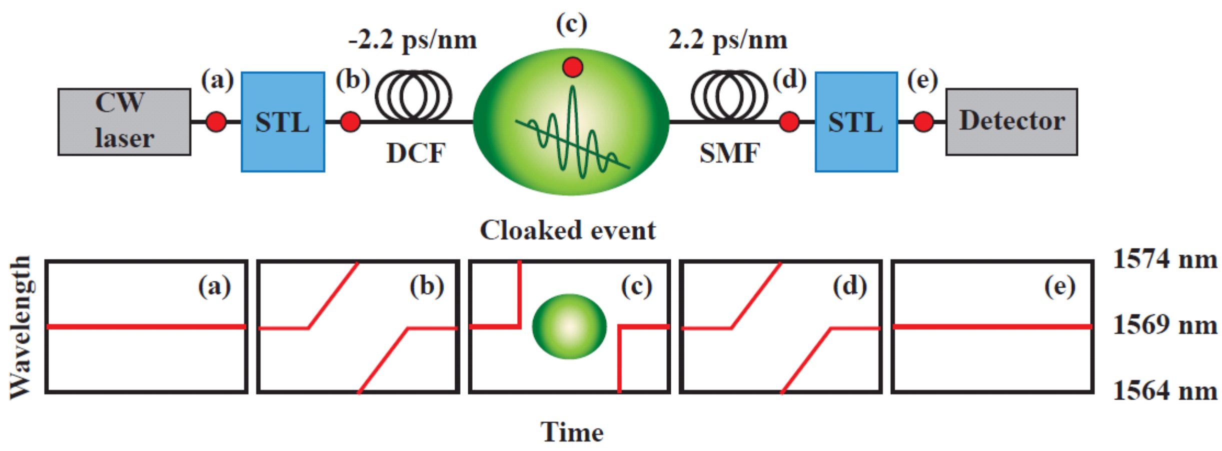


Star Trek transporter

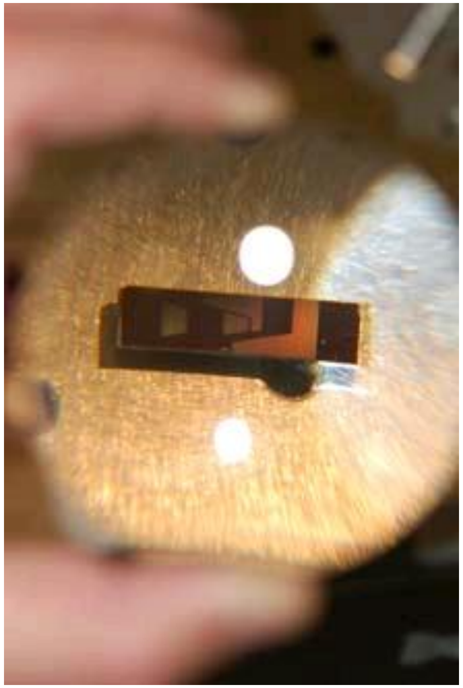


M. McCall, et al, Journal of Optics (2011)





Time Lens



M. Fridman, et al, Arxiv:1107.2062 (2011) (Gaeta group)

Outline

- Electrical Metamaterials (Plasmonics): A Route to Nanophotonics
- Artificial Optical Magnetism in Metamaterials
- Optical Negative-index Metamaterials
- Active and Loss-Free Metamaterials
- Toward Better Materials & Fabrication
- Negative-Refraction in Semiconductor-based Metamaterials
- Metamaterials for Sensing
- Tunable, Ultrafast, and Nonlinear Metamaterials
- Quantum Metamaterials
- Transformation Optics and Cloaking

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