Thanks to my Team

Vladimir M. Shalaev
Purdue University

Transforming Light with Metamaterials:
A New Paradigm for the Science of Light

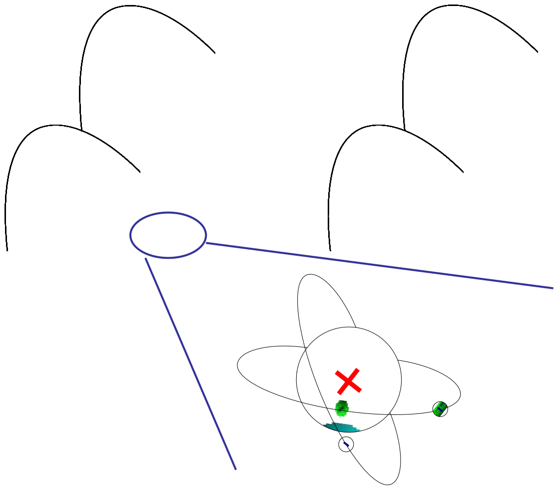
OUTLINE

- Intro to metamaterials
- Electrical metamaterials for nanoplasmonics & nanophotonics (nanoantennae and world's smallest nanolaser)
- Magnetic metamaterials
- Negative refractive index
- Superlens
- Transformation Optics & Optical Cloaking

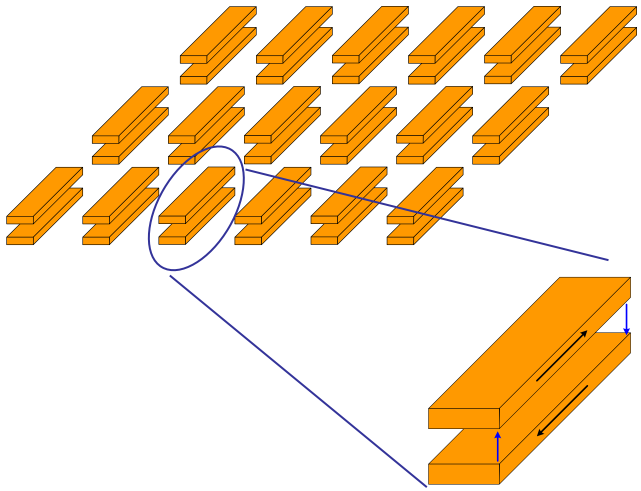
What is a metamaterial?

Metamaterial is an arrangement of artificial structural elements, designed to achieve electromagnetic properties unattainable with natural materials

μετα = meta = beyond (Greek)



A natural material with its atoms



A metamaterial with artificially structured "atoms"

Photonic crystals *vs.* Optical metamaterials: connections and differences

0 —— 1 —— ∞ → a/λ

$a \ll \lambda$.
Effective medium description using Maxwell equations with μ, ε, n, Z

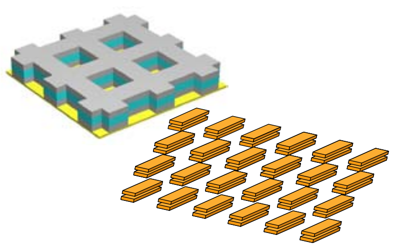
Example:
Optical crystals
Metamaterials

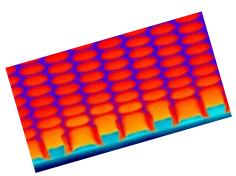
$a \sim \lambda$.
Structure dominates. Properties determined by diffraction and interference

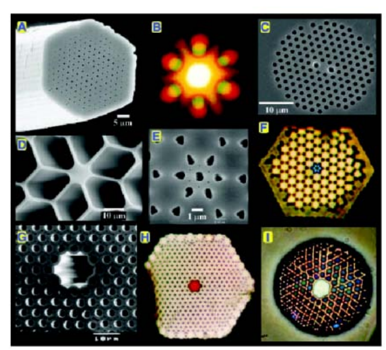
Example:
Photonics crystals
Phased array radar
X-ray diffraction optics

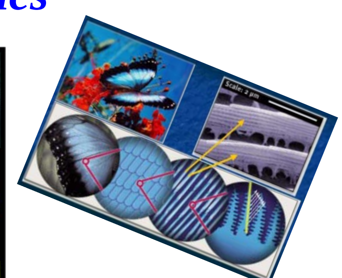
$a \gg \lambda$.
Properties described using geometrical optics and ray tracing

Example:
Lens system
Shadows



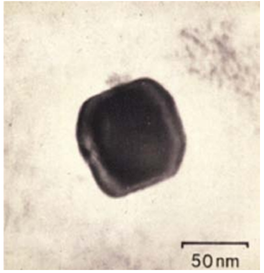






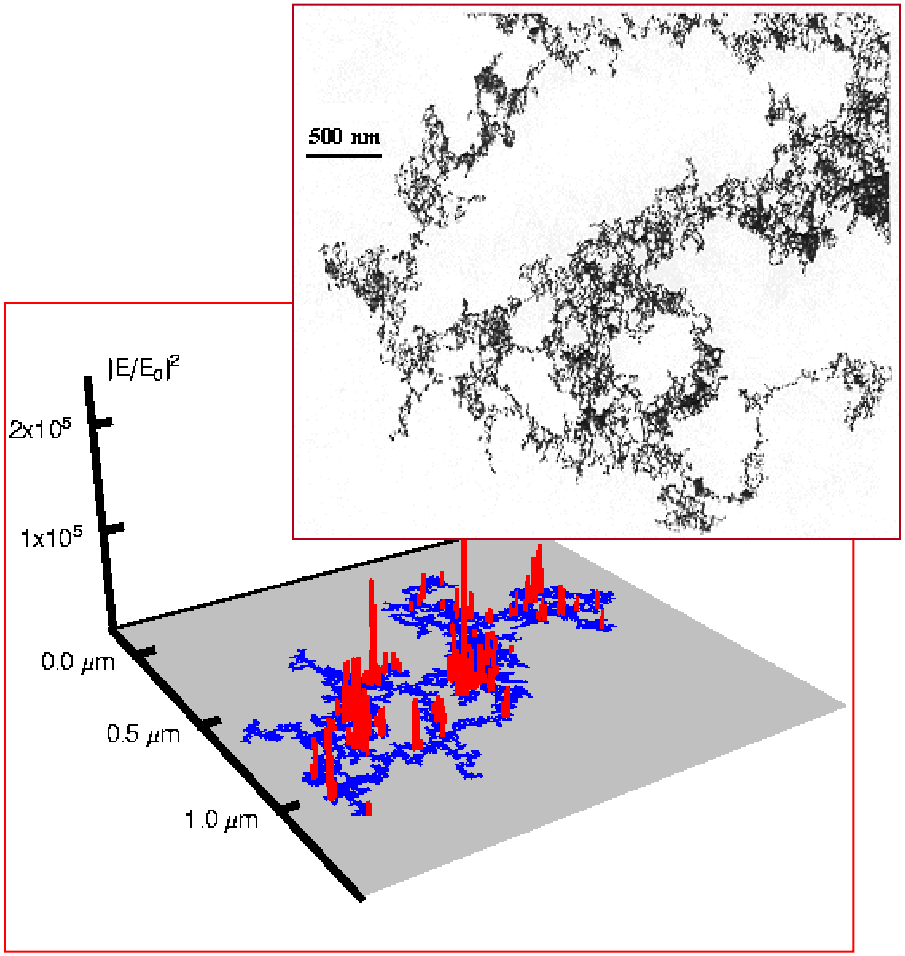
Metamaterials: Artificial periodic structures?

Lycurgus Cup (4th century AD)



Ancient (first?) random metamaterial (carved in Rome!) with gold nano particles

"Hot-spots" in fractals

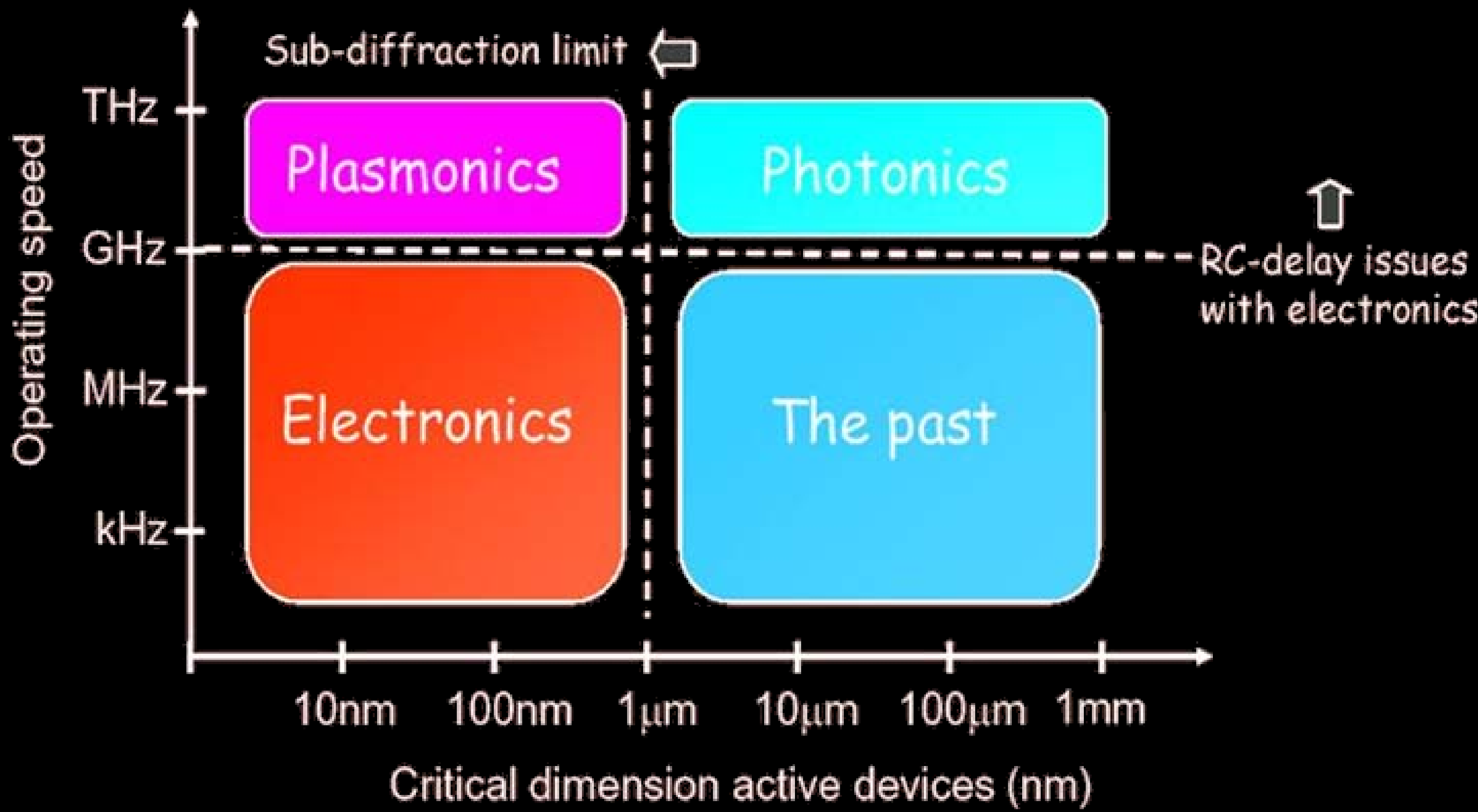


Shalaev, Nonlinear Optics of Random Media: Fractals and Composite Films, Springer, 2000

Electrical Metamaterials: a Route to Nanophotonics

Why nanophotonics needs plasmonic/electric ε-MMs ?

Operating regimes of different technologies

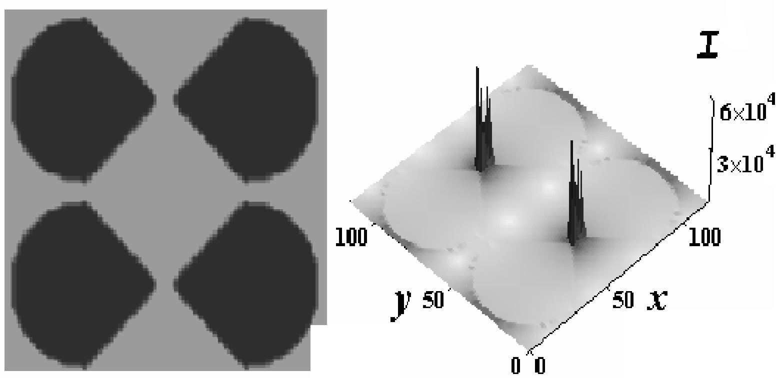


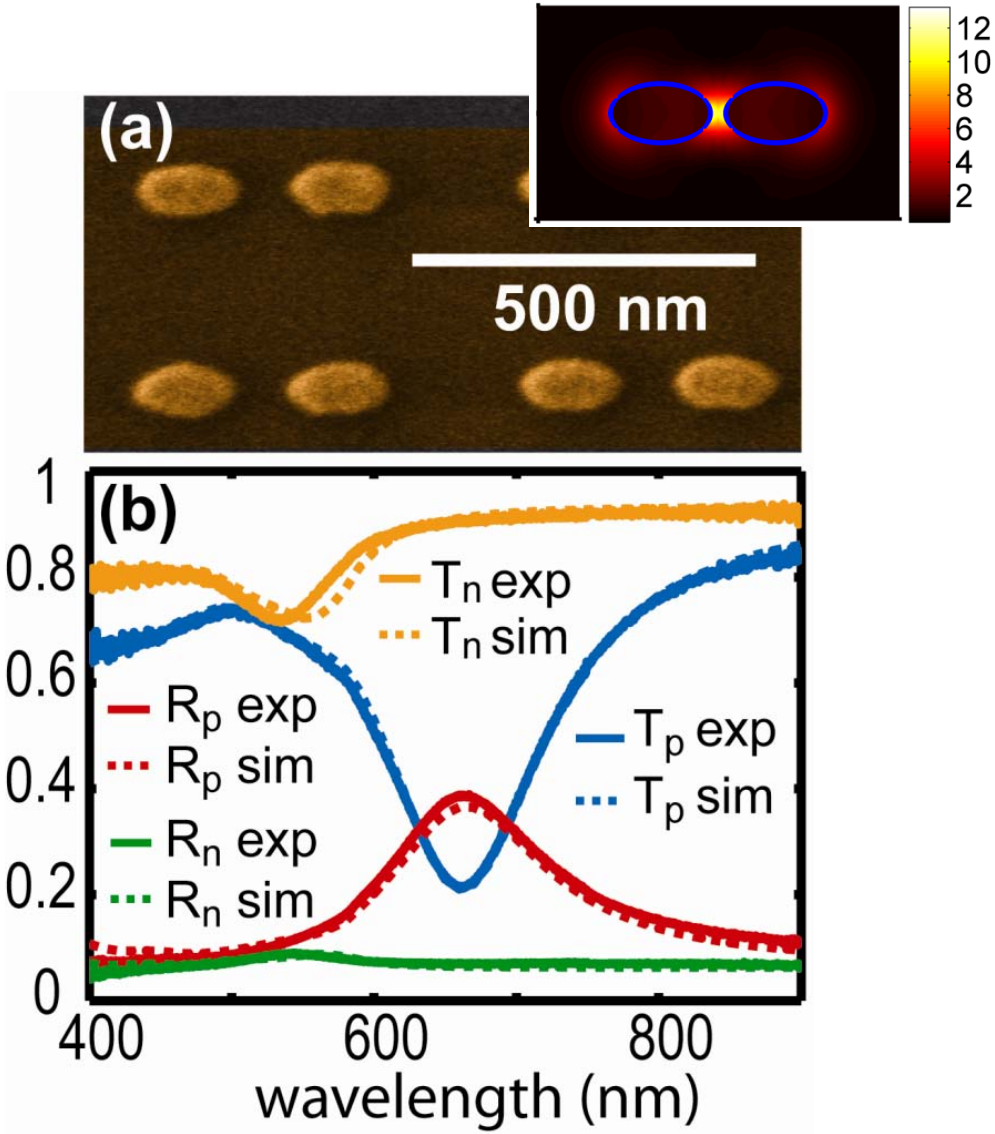
- Plasmonics: improved synergy between electronic and photonic devices
- Plasmonics: size of electronic components
- Plasmonics: operating speed of photonic networks

Courtesy of M. Brongersma

Optical Antennae as Electrical Metamaterials: Focusing Light to Nanoscale

Bow-tie antennas



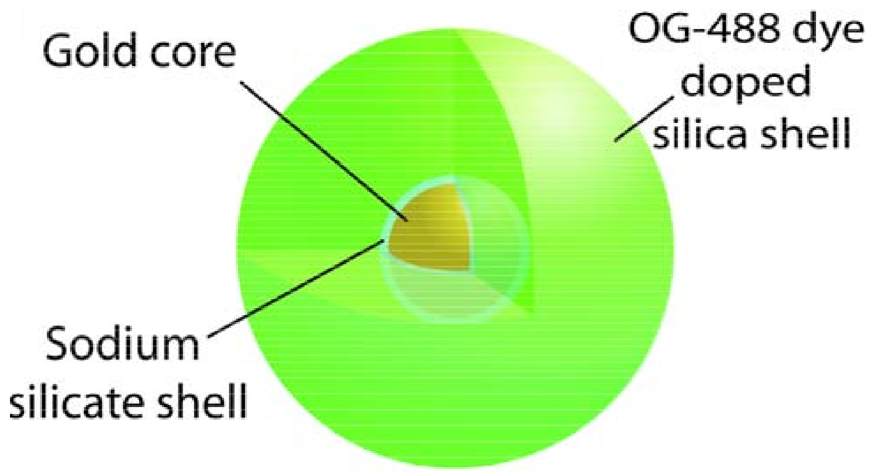


LC-nanophotonics

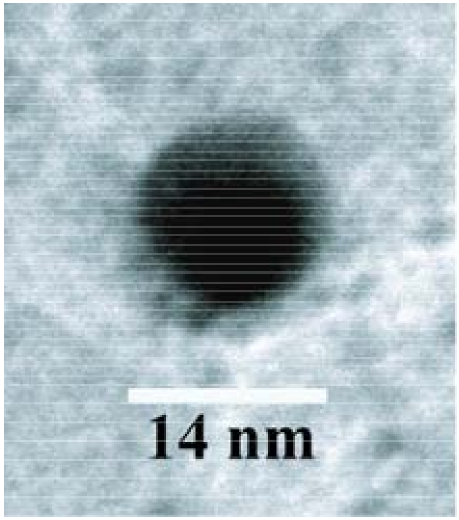
<u>Applications:</u>
Nano-laser, sensor, Nanophotonic circuits

Optical Nanolaser Enabled by SPASER (NSU-Purdue-Cornell)

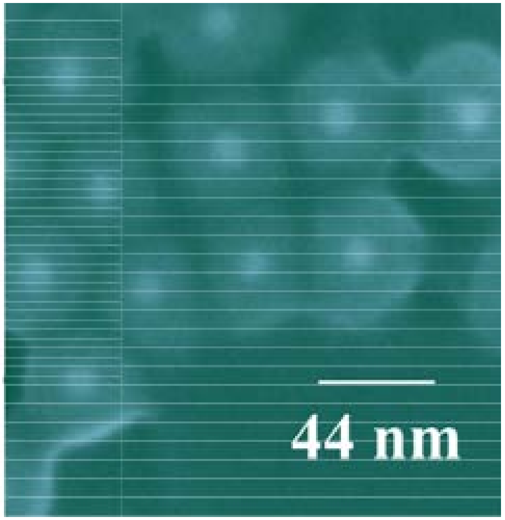
Hybrid Nanoparticle



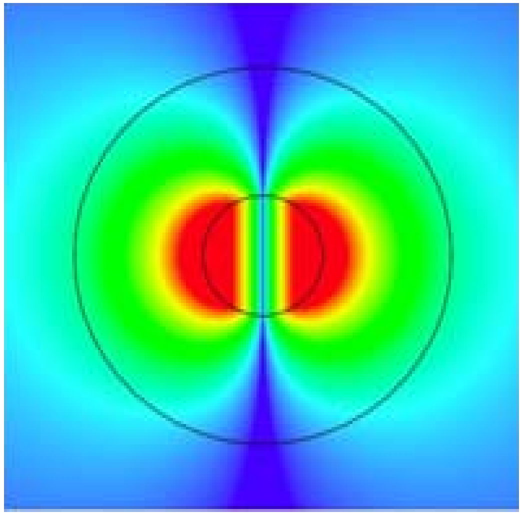
Au core



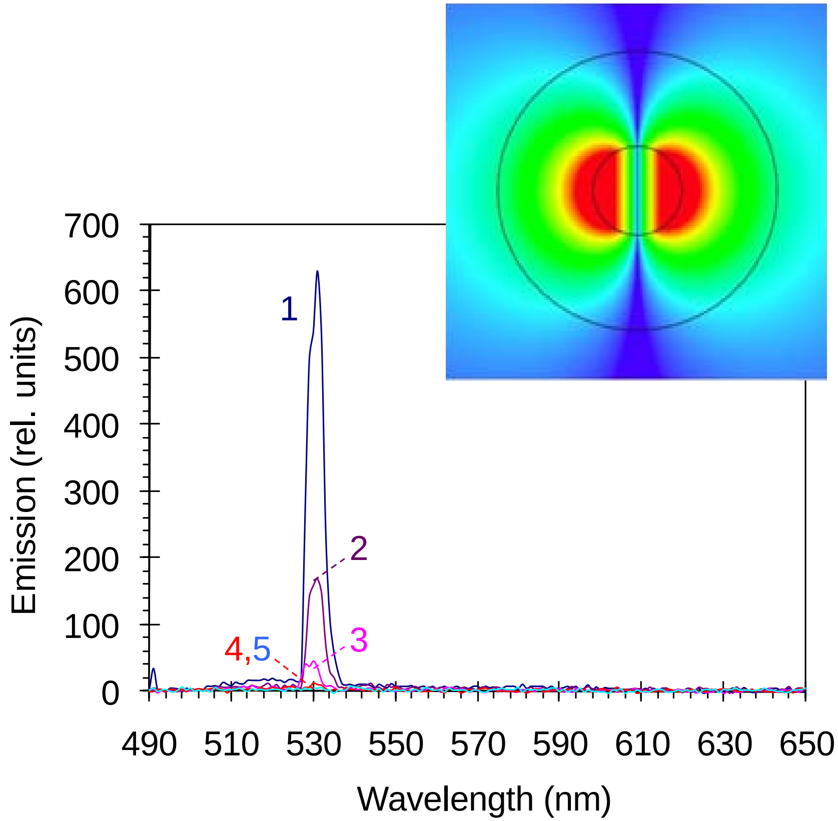
Au/silica/dye NPs

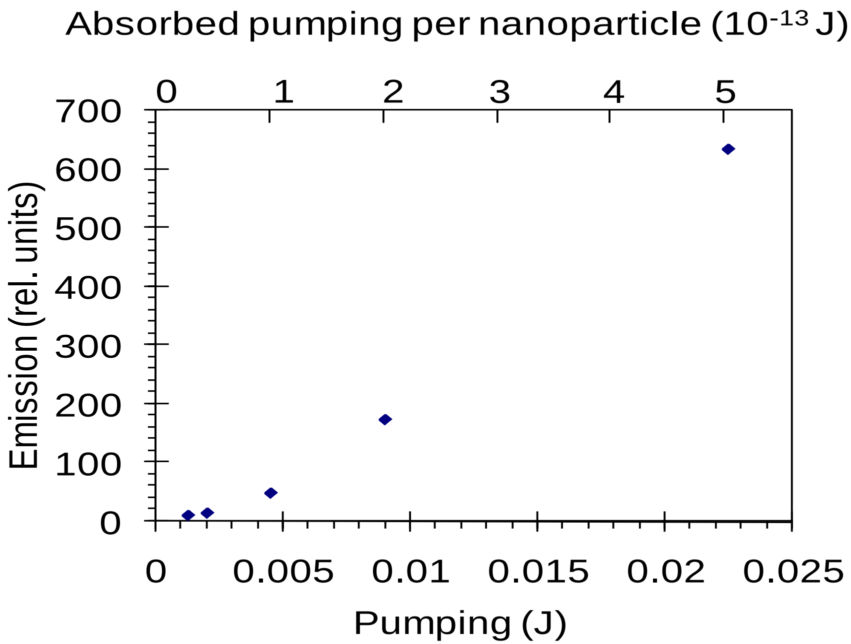


SPASER mode



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





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

Noginov, et al, Nature (2009)

Magnetic Metamaterials for the Optical Range

Absence (or very weak: $\mu \approx 1$) Optical Magnetism in Nature

Magnetic coupling to an atom: ~ $\mu_B = e\hbar / 2m_e c = \alpha e a_0$ **(Bohr magneton)**

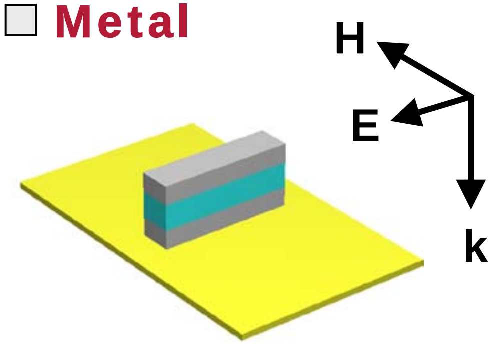
Electric coupling to an atom: ~ $e a_0$

Magnetic effect / electric effect $\approx \alpha^2 \approx (1/137)^2 < 10^{-4}$

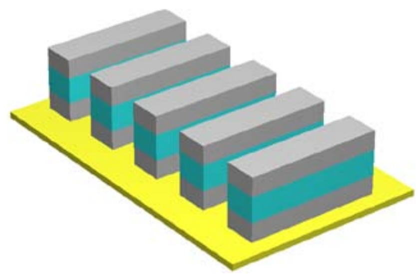
> **"… the magnetic permeability μ(ω) ceases to have any physical meaning at relatively low frequencies…there is certainly no meaning in using the magnetic susceptibility from optical frequencies onwards, and in discussion of such phenomena we must put μ=1."**
>
> **Landau and Lifshitz, ECM, Chapter 79**

Artificial Magnetic Metamaterials for Visible

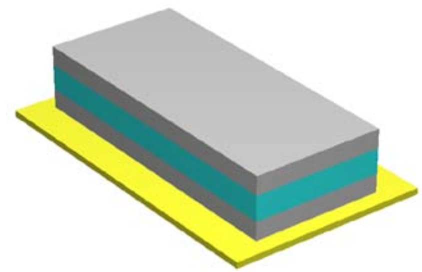
- Dielectric
- Metal



Nanorod pair



Nanorod pair array

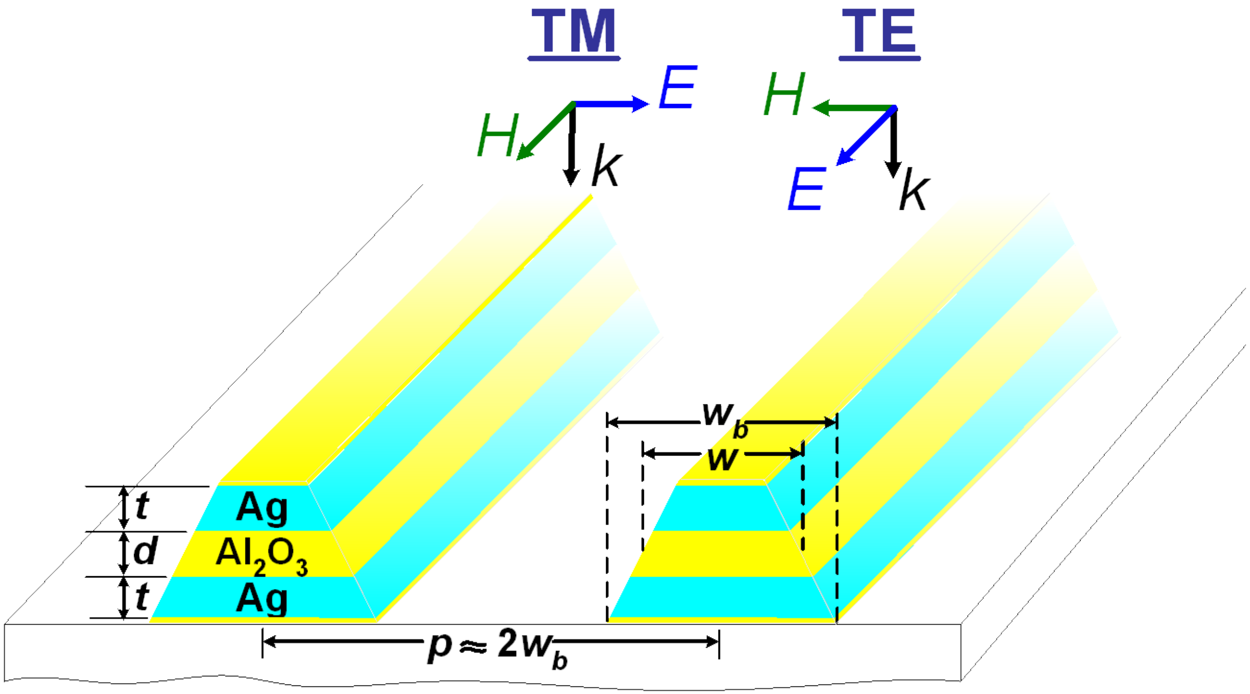


Nanostrip pair

Nanostrip pair has a much stronger magnetic response

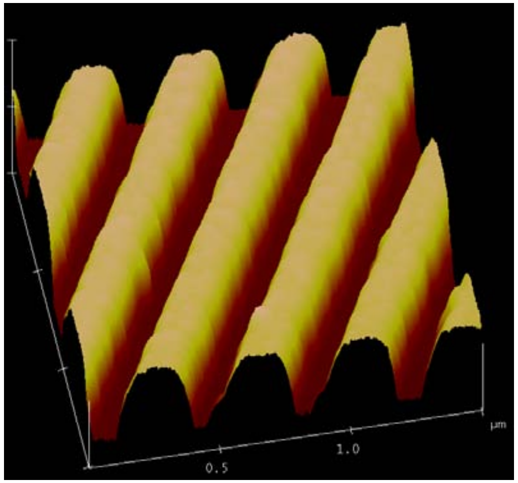
Podolskiy, Sarychev & Shalaev, *JNOPM* (2002) - μ < 0 & n < 0
Lagar'kov, Sarychev PRB (1996) - μ > 0
Kildishev et al, *JOSA B* (2006); Shvets et al (2006) – strip pairs
Zheludev et al (2001) – pairs of rods for chirality

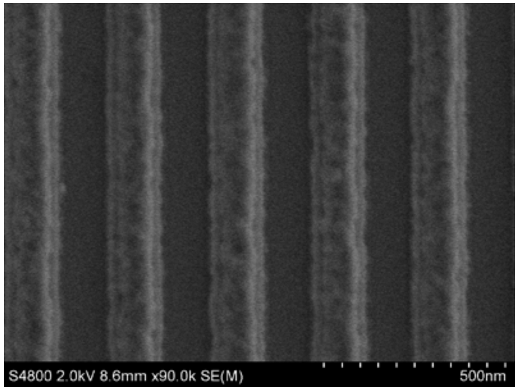
Artificial Magnetism for Visible



$t = 35 \quad nm \qquad d = 40 \quad nm \qquad p \approx 2w_b$

Width varies from 50 nm to 127 nm



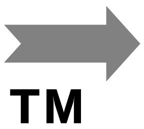


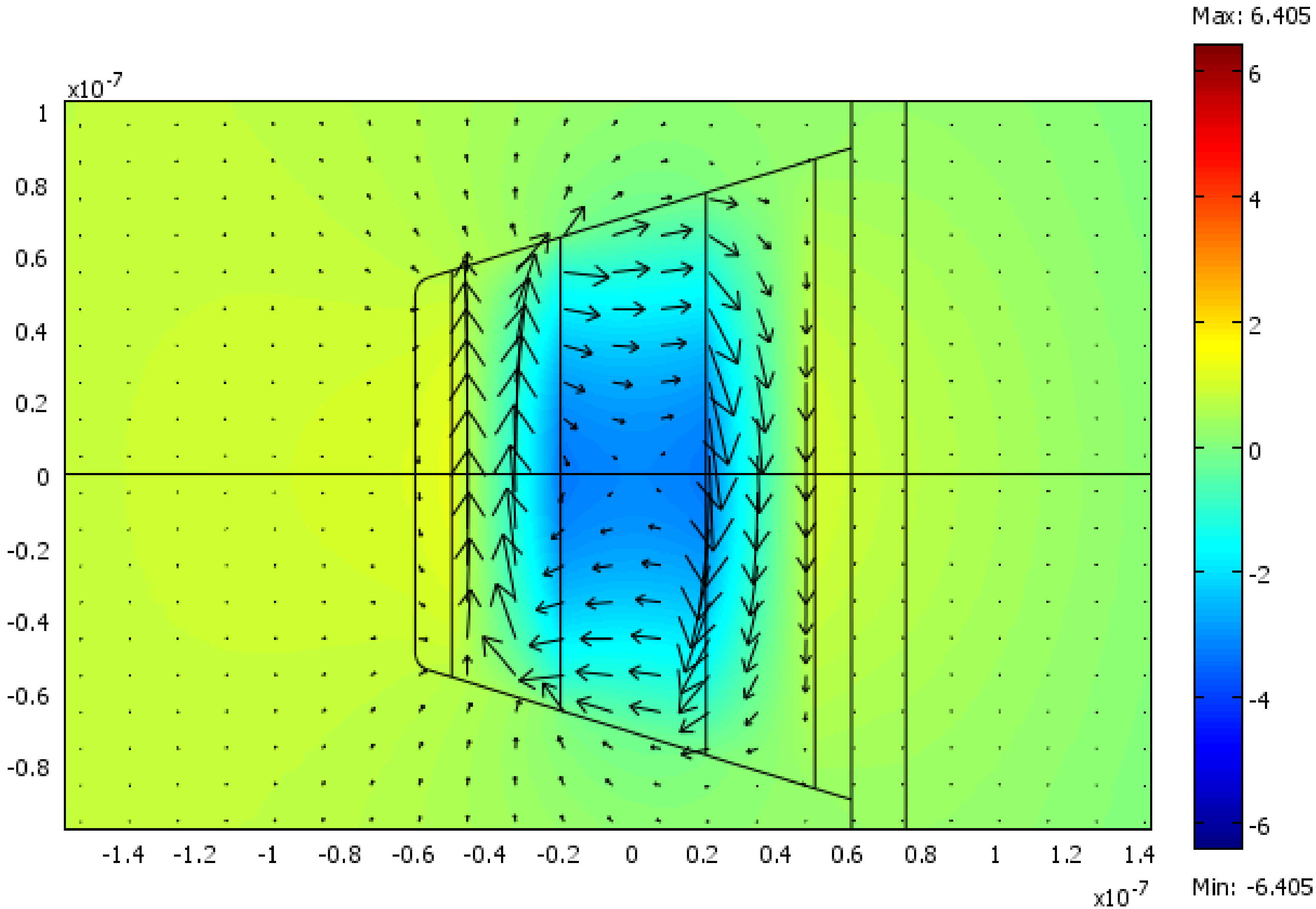
Purdue group

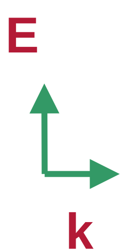
Yuan, et al., Opt. Expr., 2007 – red light

Cai, et al., Opt. Expr., 2007 – entire visible

Negative Magnetic Response in Visible

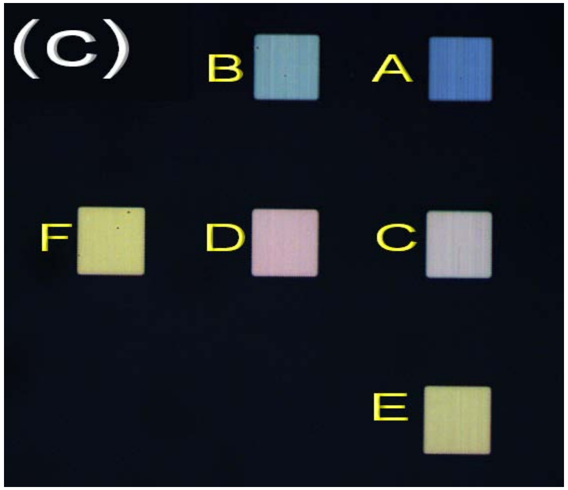




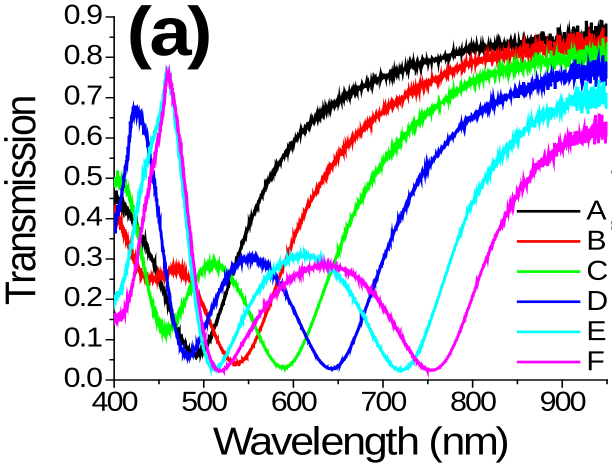


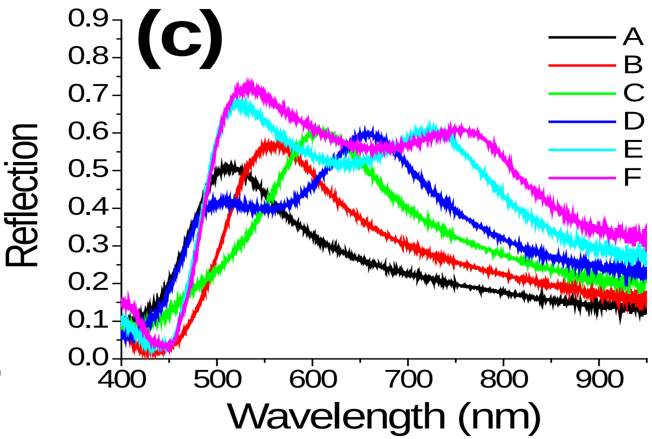
Metamagnetics with Rainbow Colors

Transmittance



Reflectance

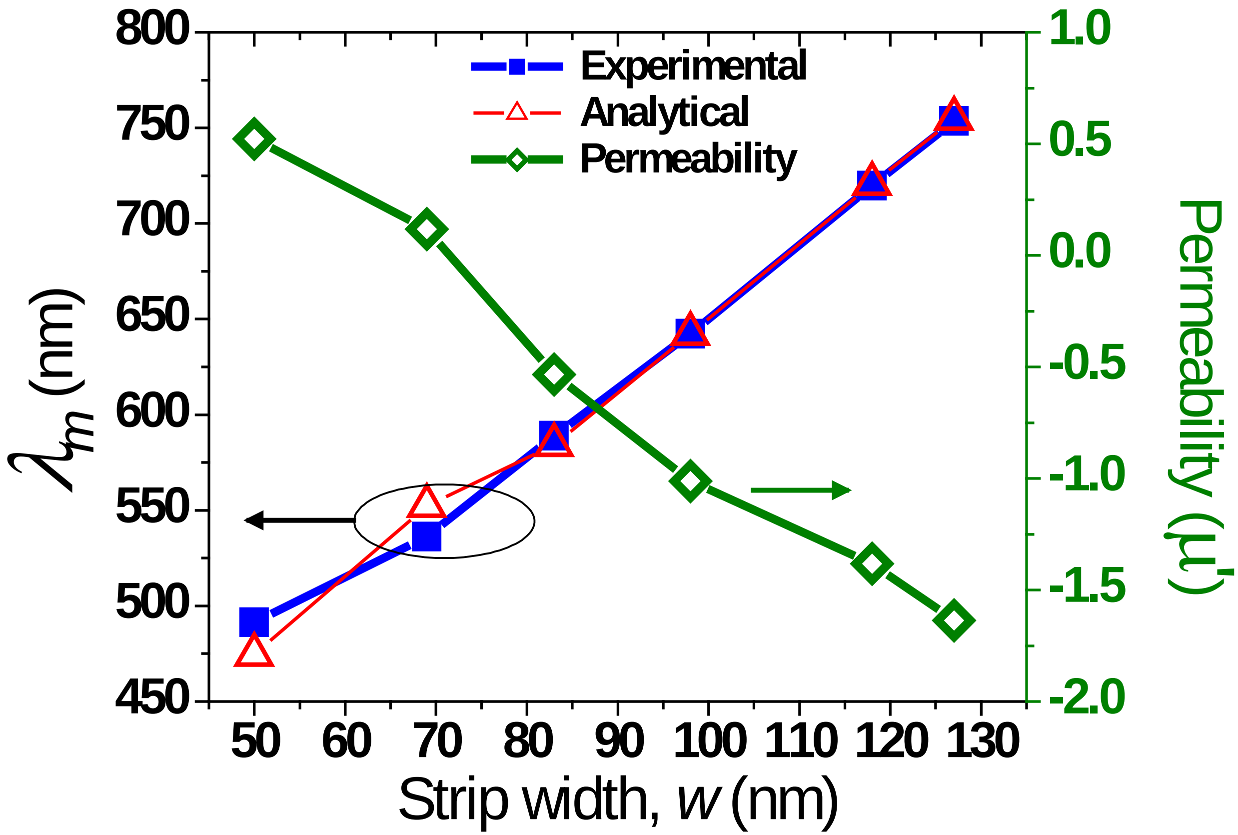




Sample #	***A***	***B***	***C***	***D***	***E***	***F***
Width *w* *(nm)*	**95**	**118**	**127**	**143**	**164**	**173**

Cai et al.
Opt. Exp., 2007

Visible Meta-Magnetics: from Red to Blue

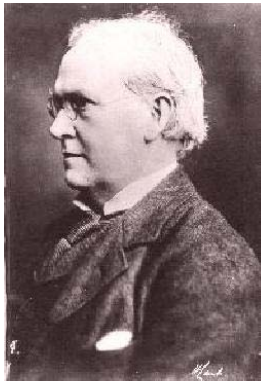


λ_m as a function of strip width "w": experiment vs. theory

Negative Refractive Index in Optics

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


L. I. Mandel'stam

Negative refraction and backward propagation of waves
Mandel'stam, 1945

V. G. Veselago

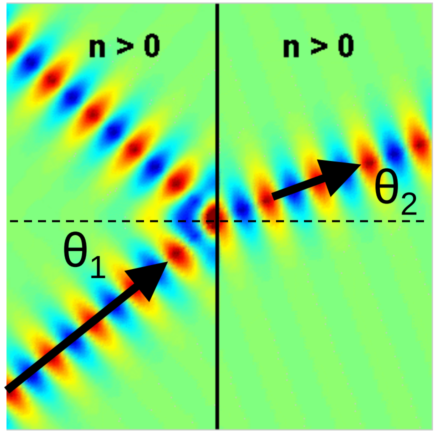
Left-handed materials: the electrodynamics of substances with simultaneously negative values of ε and μ
Veselago, 1968

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

Perfect lens (2000)
EM cloaking (2006)


Sir John Pendry

Metamaterials with Negative Refraction



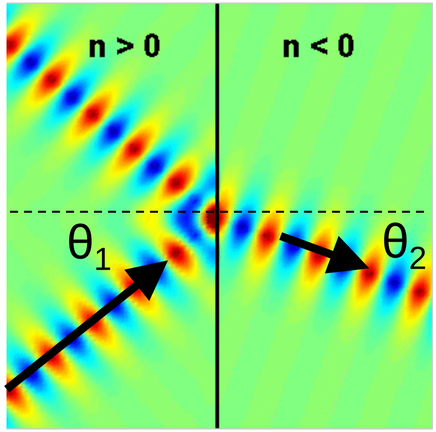
Refraction:

$$n^2 = \varepsilon\mu$$

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

Figure of merit
F = |n'| / n"

n < 0, if **ε′|μ| + μ′|ε| < 0**



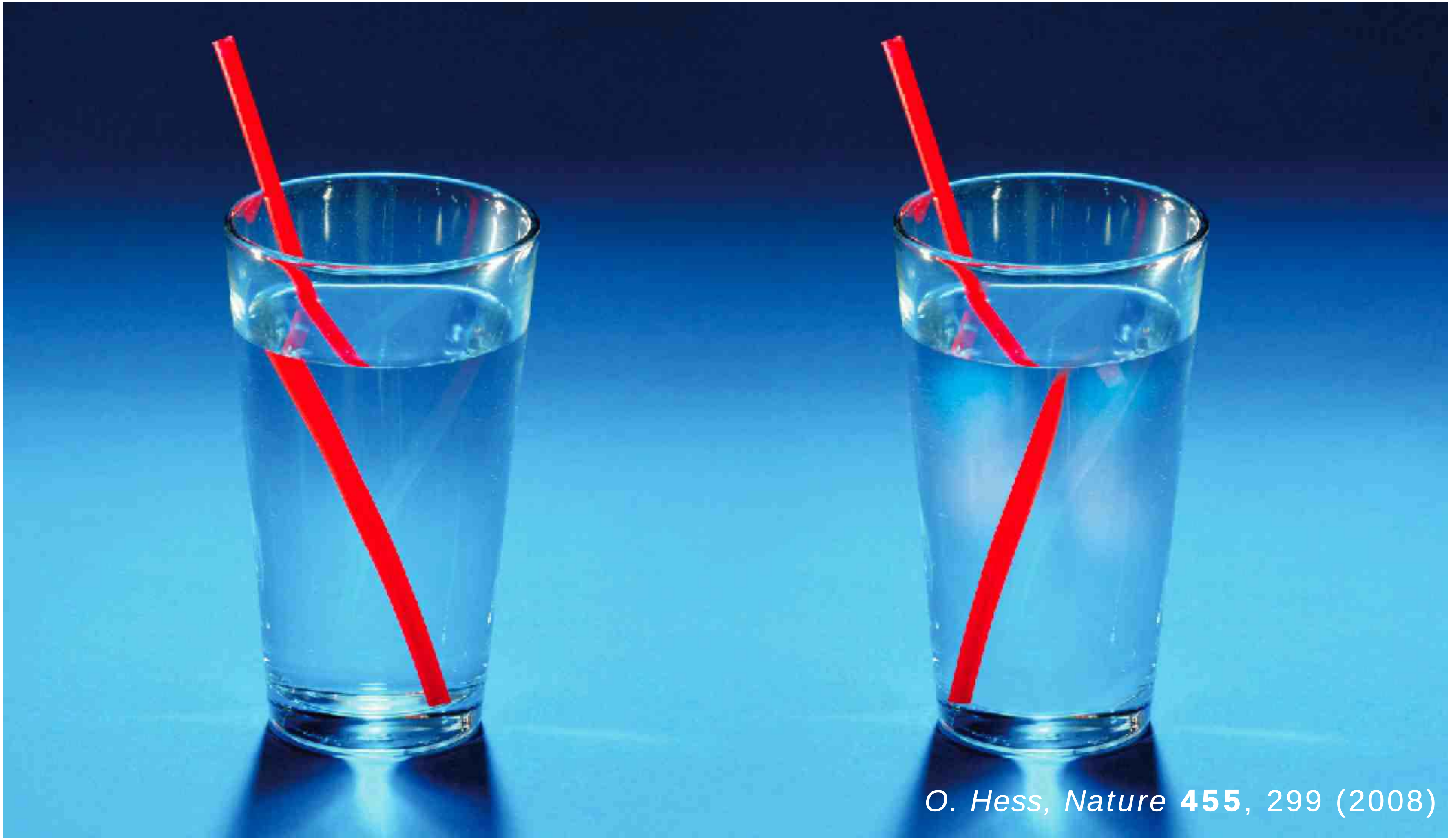
Single-negative:

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

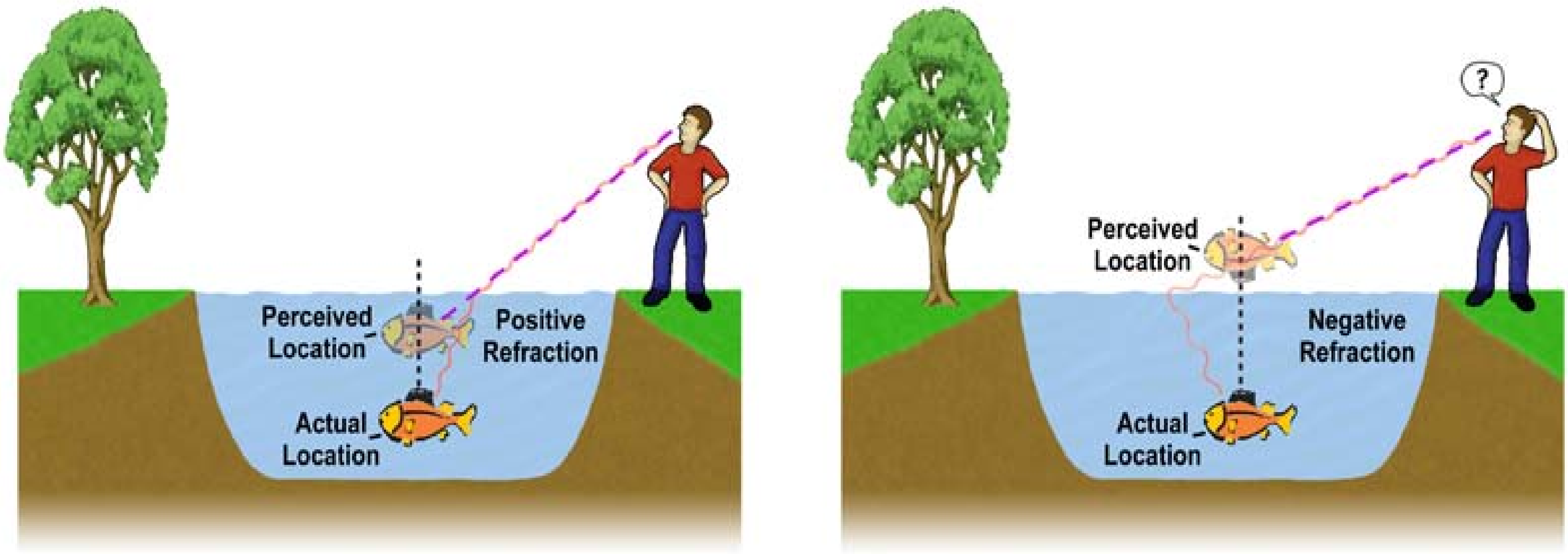
Double-negative:

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

Negative Refraction Effects



Negative Refraction Effects



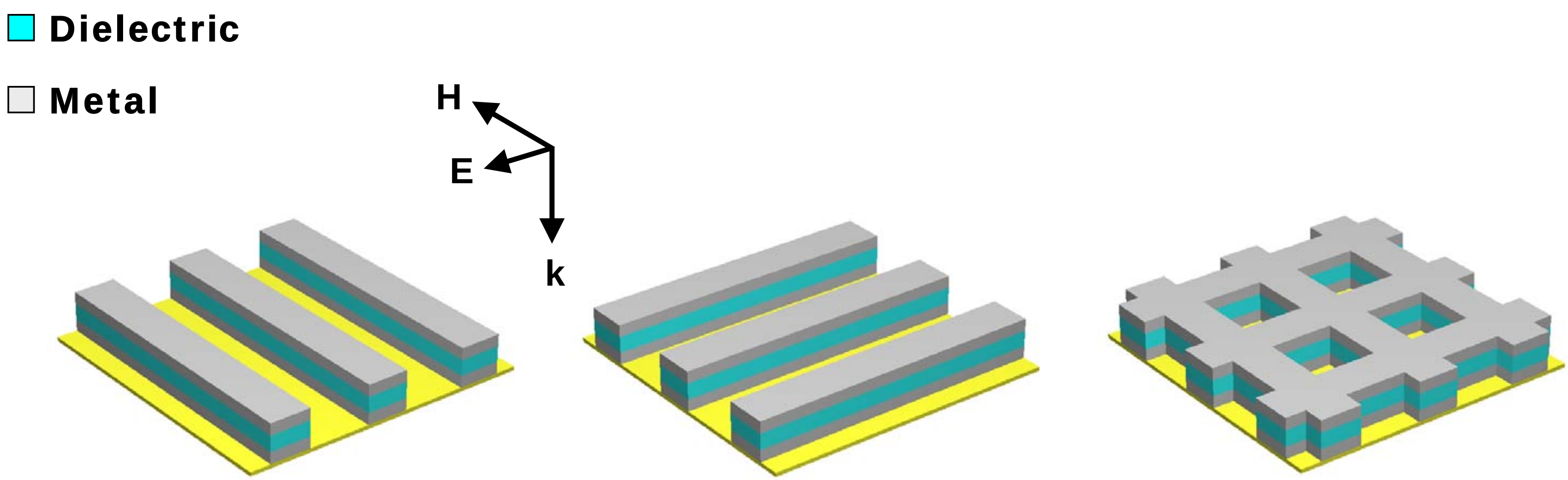
http://io9.com/5036183/secrets-of-the-metamaterials-that-will-make-you-invisible

Negative Refractive Index in Optics: State of the Art

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	In prep (2009)	-0.25	580nm	0.3	Nano-fishnet

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

Negative Permeability and Negative Permittivity



Nanostrip pair (TM)

μ < 0 (resonant)

Nanostrip pair (TE)

ε < 0 (non-resonant)

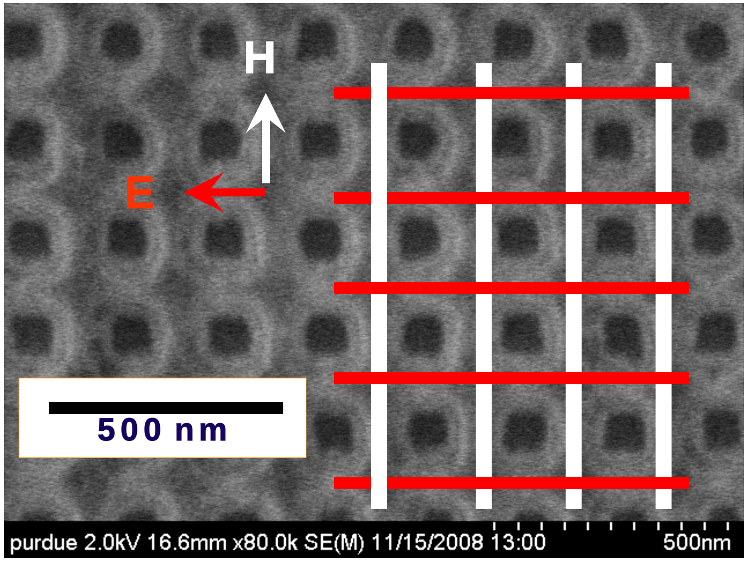
Fishnet

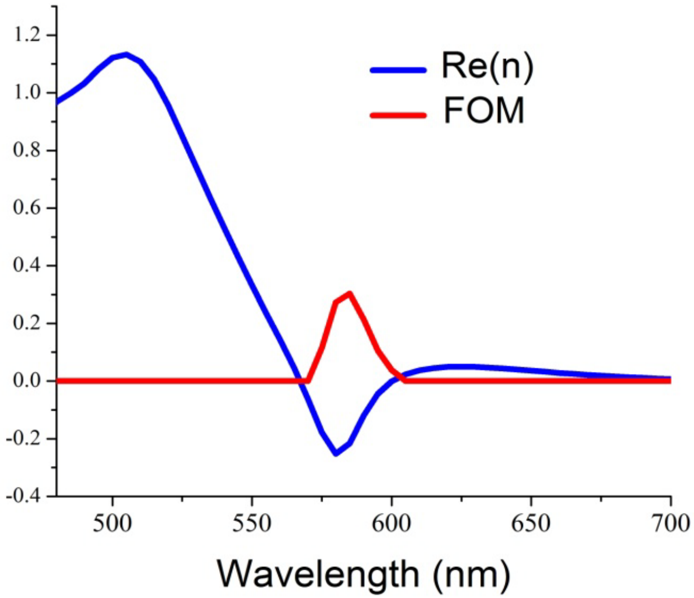
ε and μ < 0

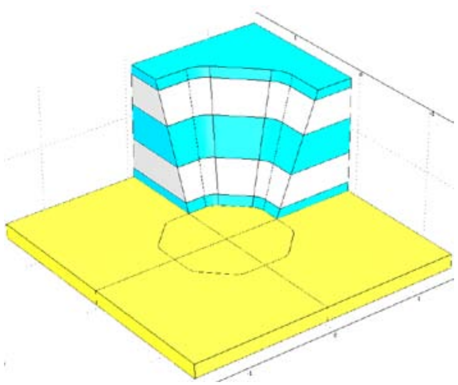
S. Zhang, et al., PRL (2005)

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

Superlens and Hyperlens

Super-resolution: Amplification of Evanescent Waves Enables sub-λ Image!

Waves scattered by an object have all the Fourier components $k_z = \sqrt{k_0^2 - k_x^2 - k_y^2}$

The propagating waves are limited to: $k_t = \sqrt{k_x^2 + k_y^2} < k_0$

To resolve features Δ, we must have $\lambda_t = 2\pi / k_t < \Delta, \quad \Delta < \lambda \Rightarrow \quad k_t = \sqrt{k_x^2 + k_y^2} > k_0, \quad k_z^2 < 0$

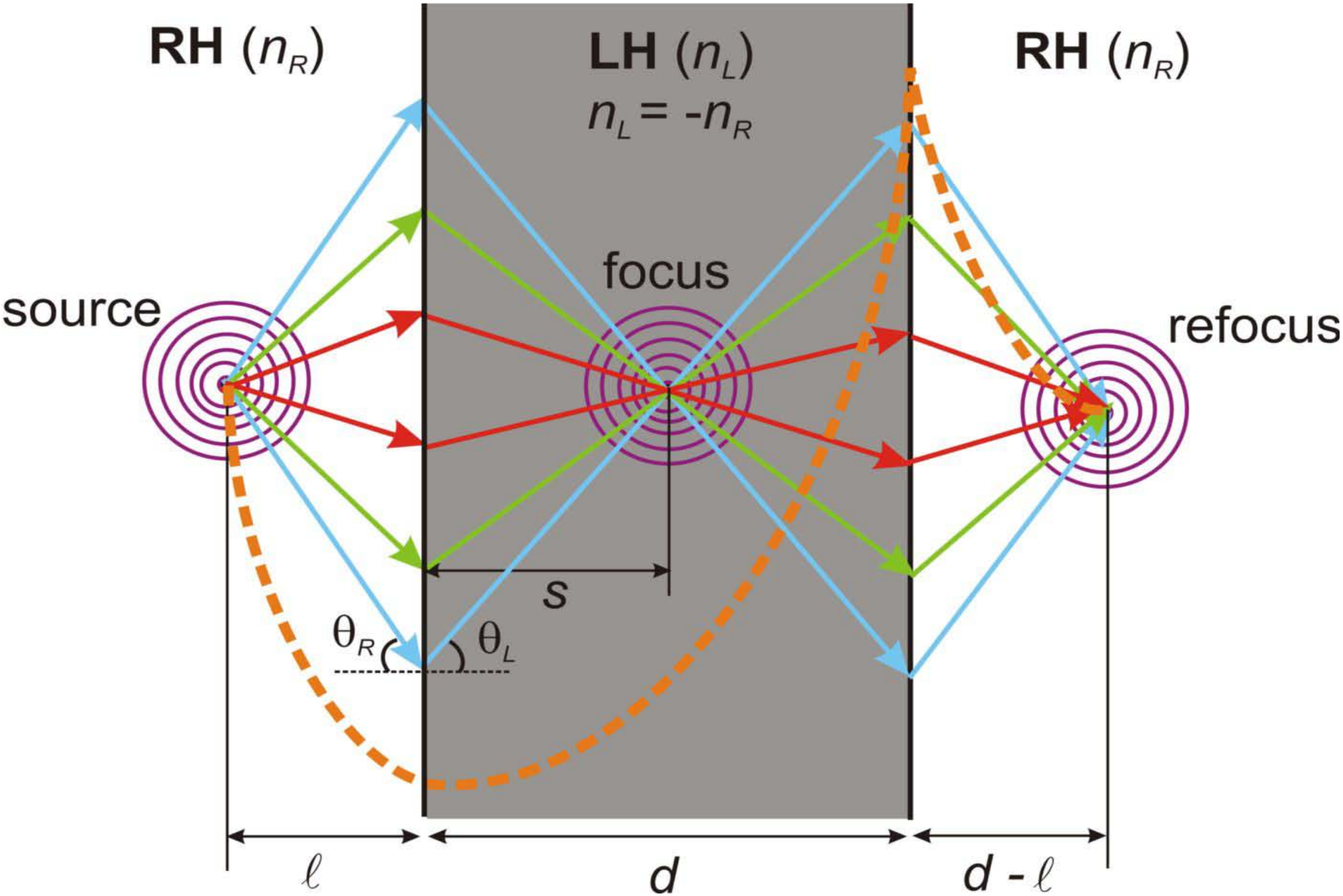
The evanescent waves are “re-grown” in a NIM slab and fully recovered at the image plane

Conventional lens

NIM slab lens

Pendry, PRL, 2000

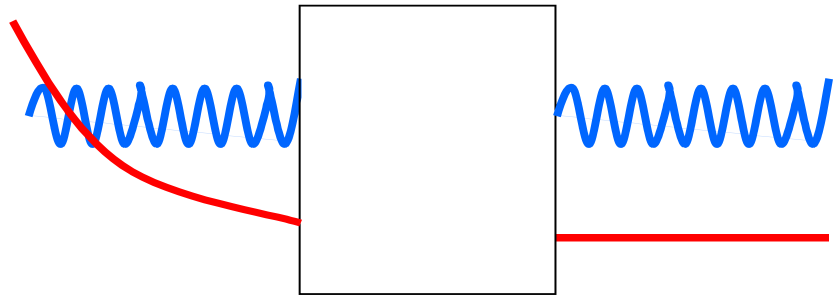
Amplification of Evanescent Waves Enables sub-λ Image



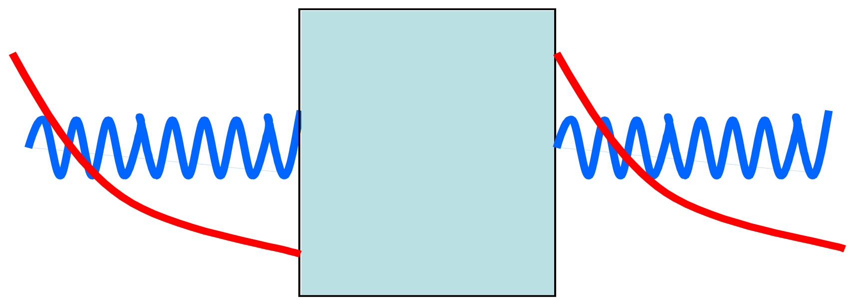
O. Hess, University of Surrey

Superlens High and Low

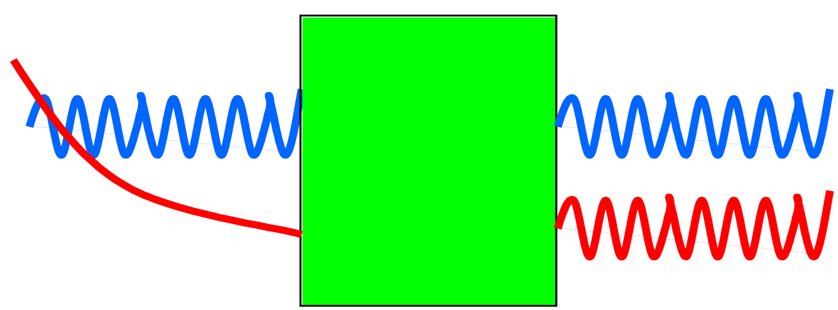
Ordinary Lens:
Evanescent field lost



Super Lens:
Evanescent field enhanced
but <u>decays away from the lens</u>
* LIMITED TO NEAR FIELD
* EXPONENTIALLY SENSITIVE TO DISORDER, LOSSES,...

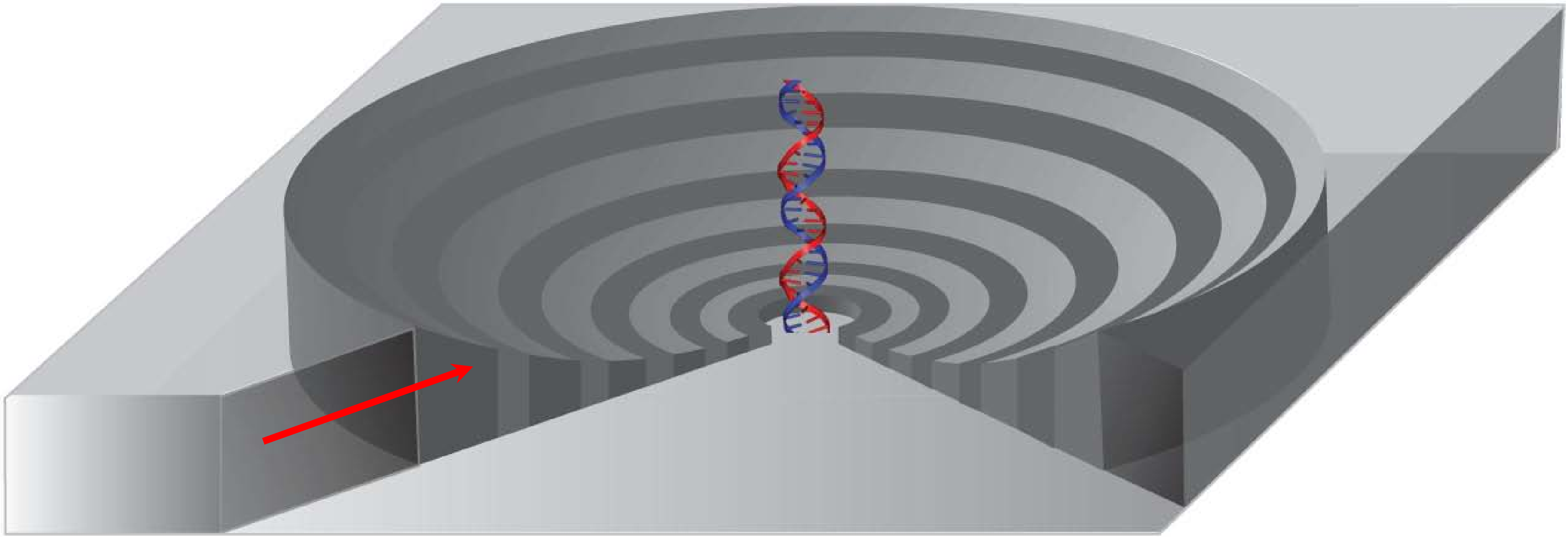


Hyper Lens:
Evanescent field <u>converted</u> to propagating waves
(that do not mix with the others)



Hyperlens

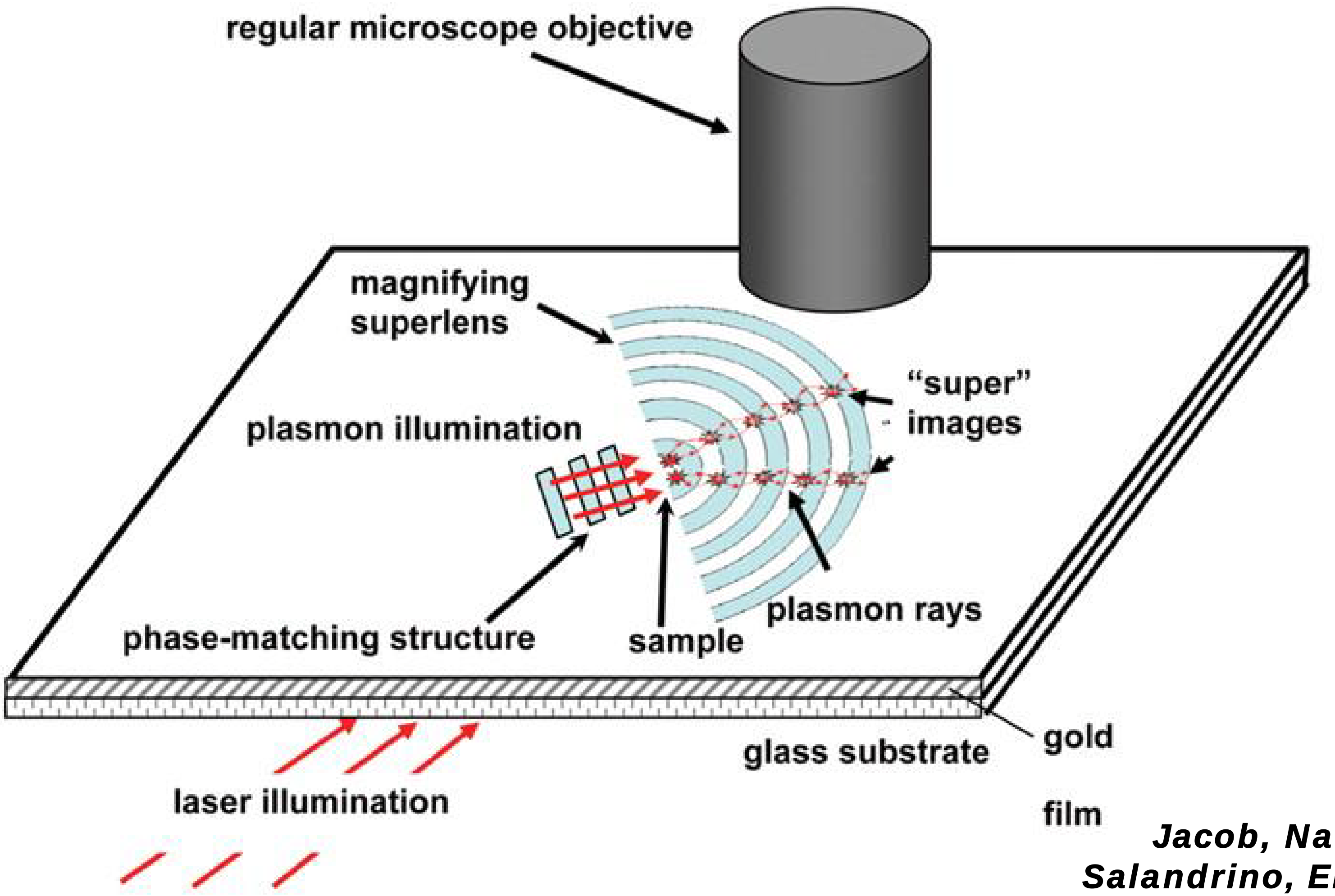
Converting evanescent components to propagating waves



Far-field sub-λ imaging

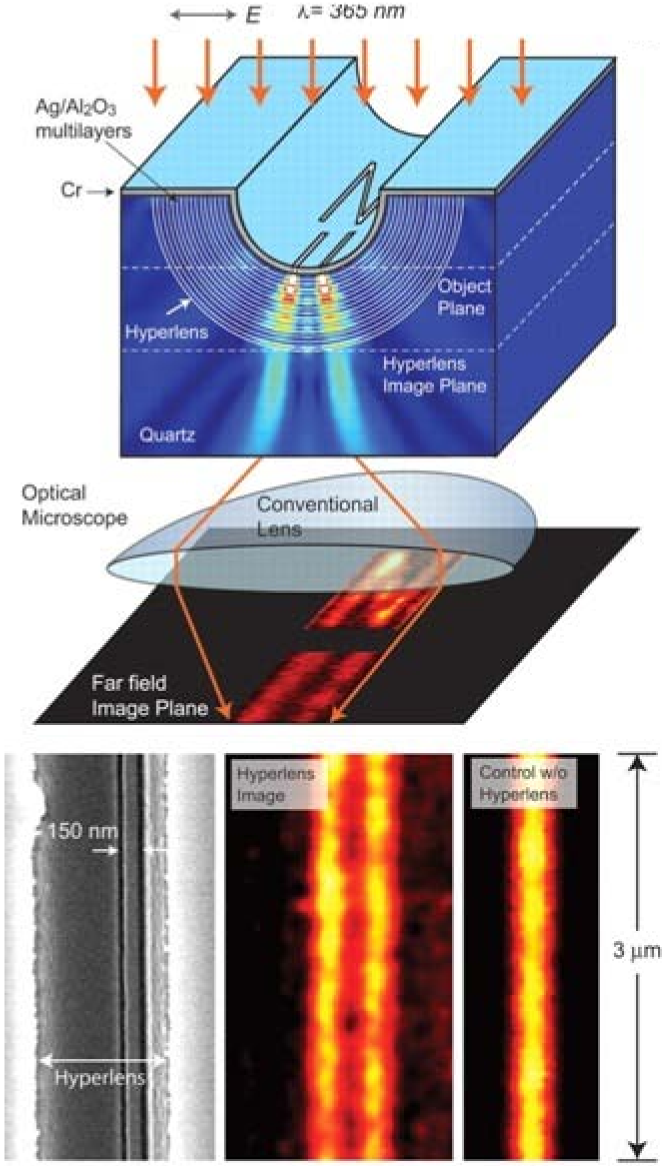
Narimanov et al; Engheta et al

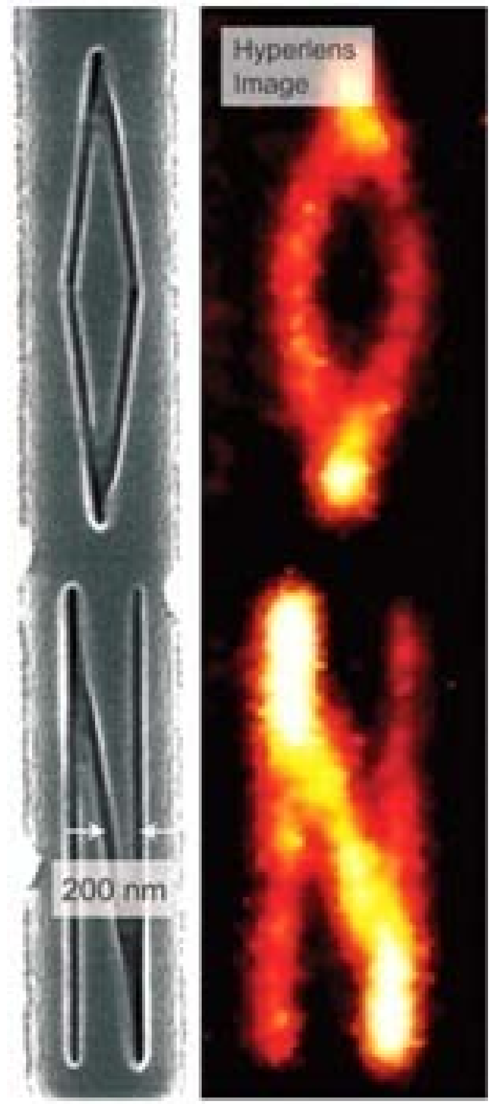
Optical Hyperlens

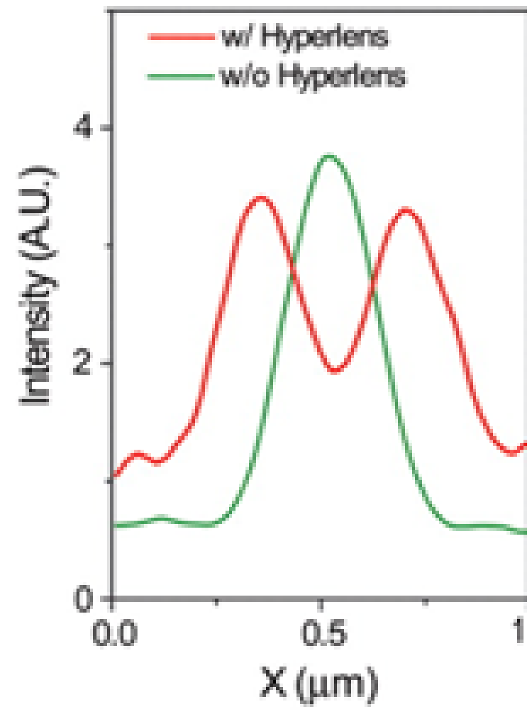


Theory:
Jacob, Narimanov, OL, 2006
Salandrino, Engehta, PRB, 2006
Experiment:
Smolyaninov et al., Science, 2007

Optical Hyperlens

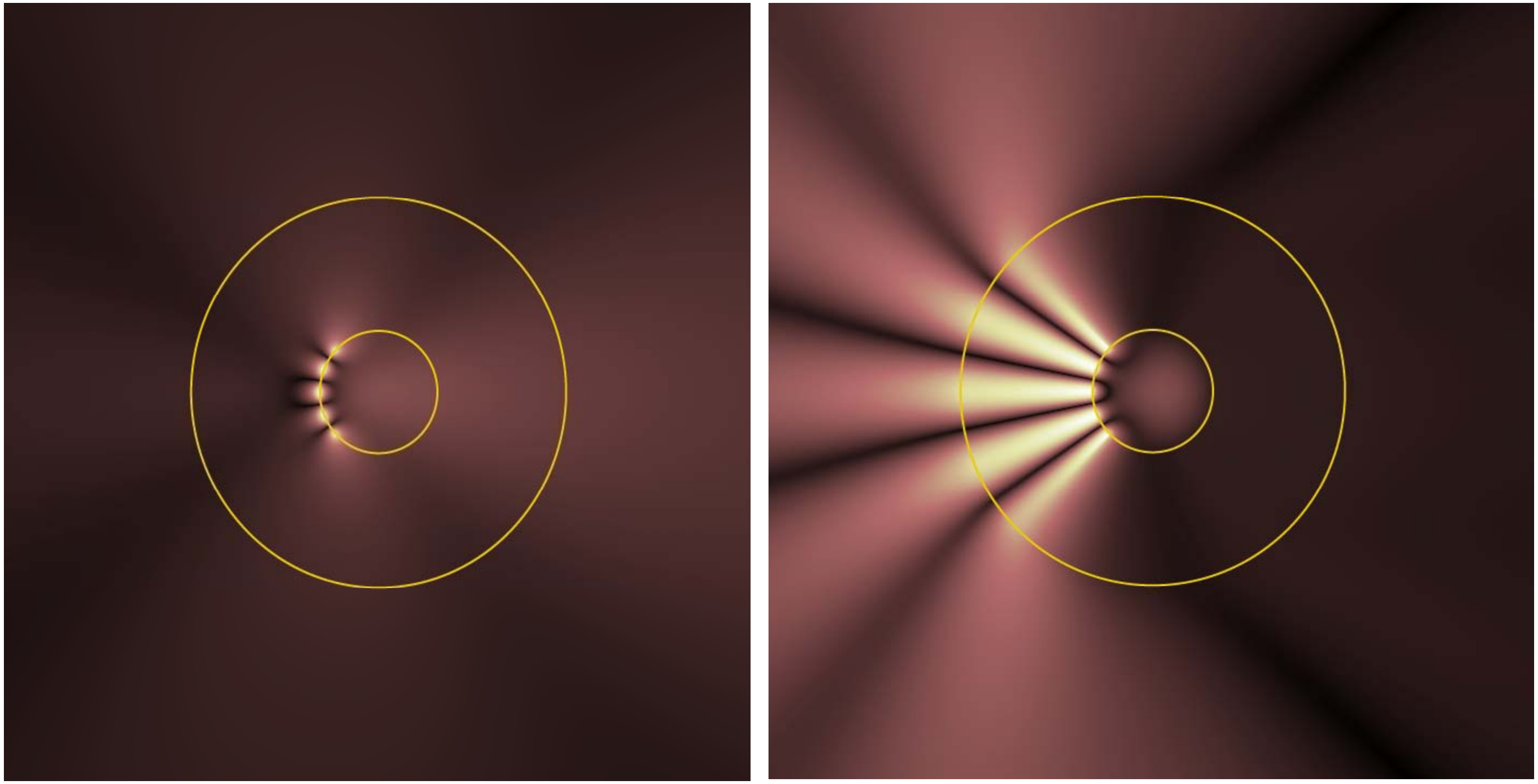






Z. Liu et al., Science, 2007

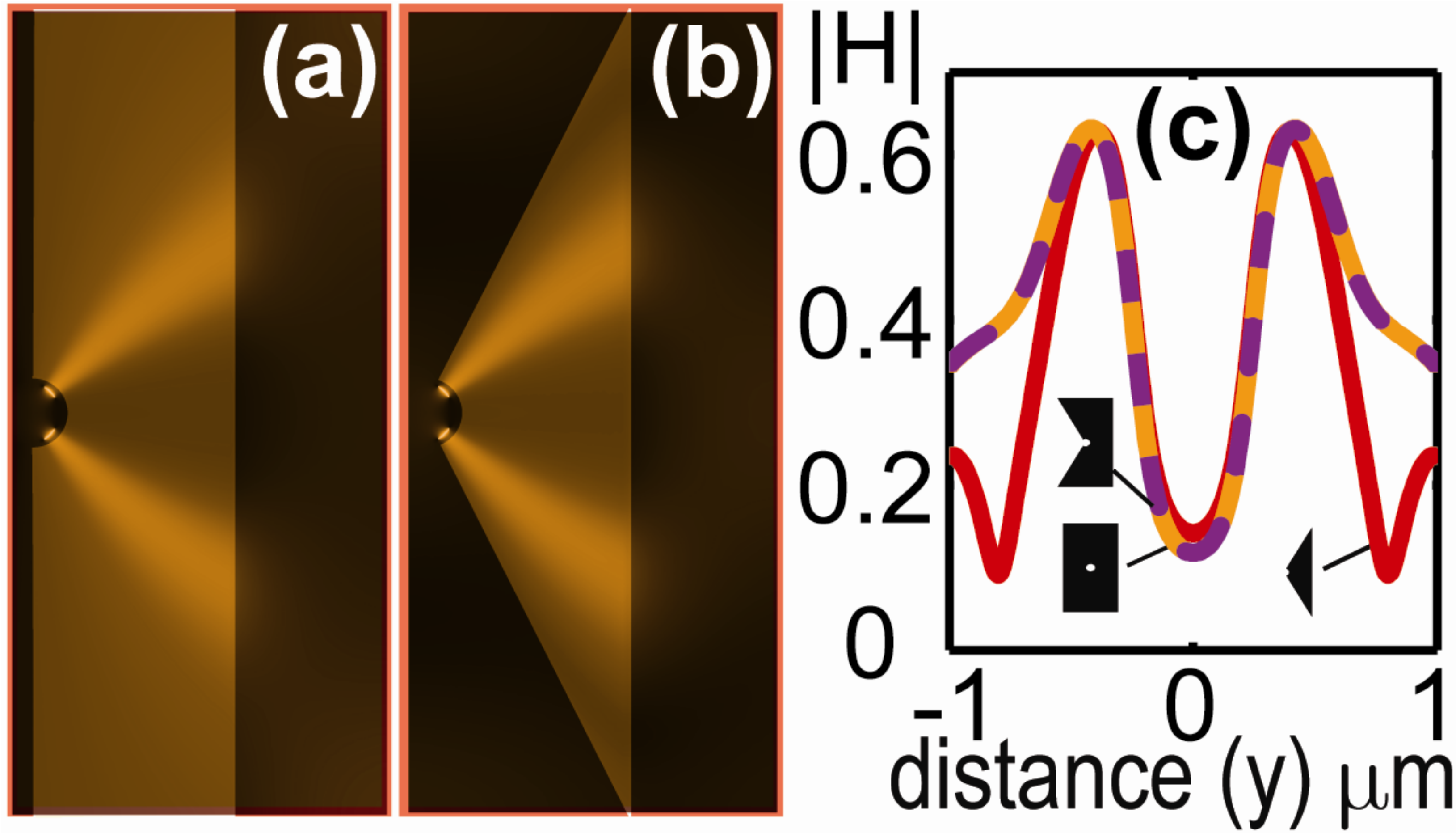
Advanced Optical Hyperlens



Impedance-matched hyperlens

Kildishev, Narimanov, Opt. Lett., 2007

Advanced Optical Hyperlens



Flat hyperlenses: ½ - & ‘¼-body lenses

Kildishev, Shalaev, Opt. Lett., 2008

Optical Cloaking
&
Transformation Optics

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

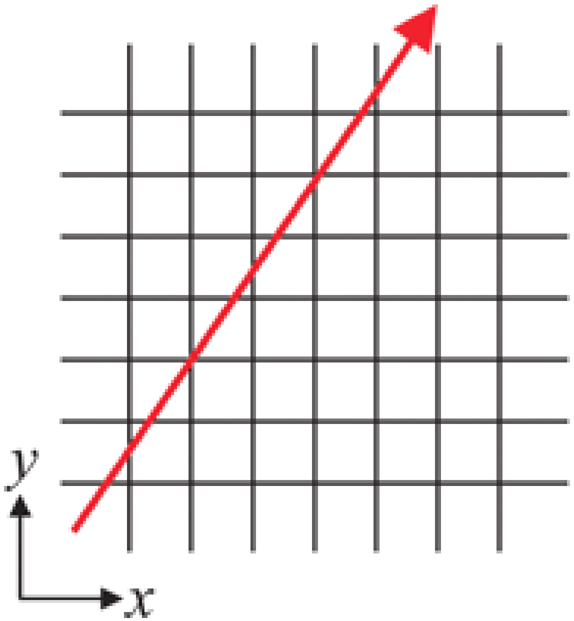
Designing Space for Light with Transformation Optics

Fermat:

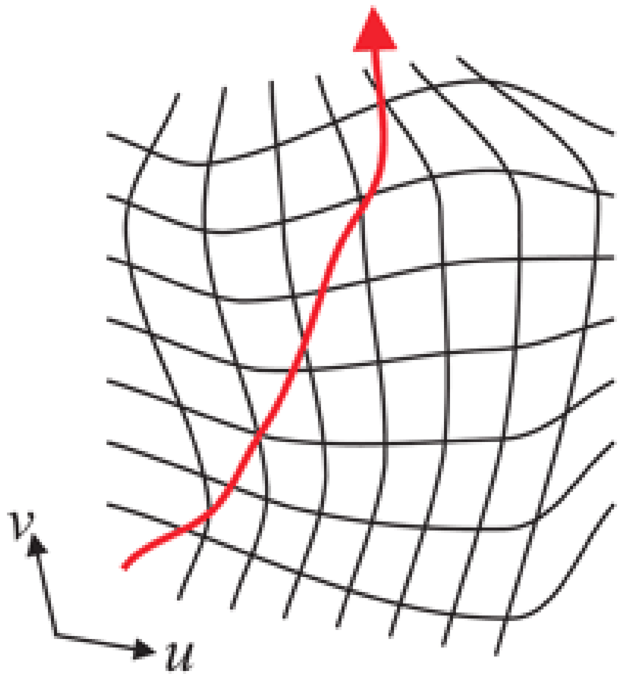
$$\delta \int n\,dl = 0$$

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

"curving" optical space



Straight field line in Cartesian coordinate



Distorted field line in distorted coordinate

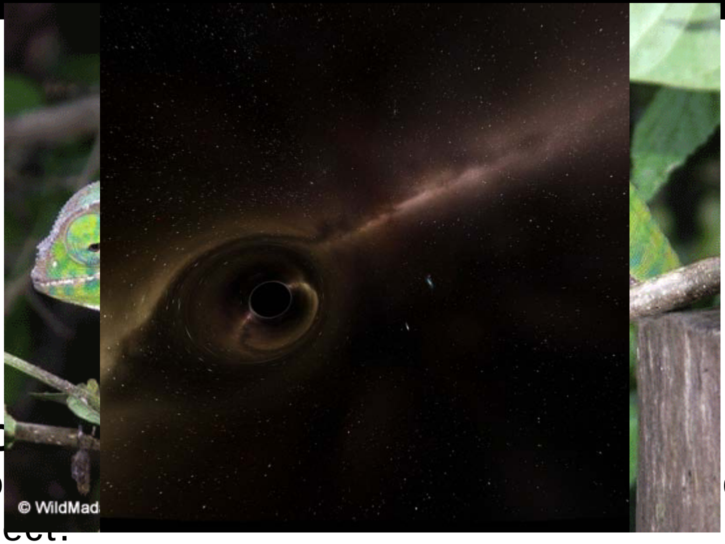
Spatial profile of ε & μ tensors determines the distortion of coordinates

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, 1961

Invisibility in Nature, Physics and Technology

- Natural camouflage
- Black hole
- ...



Current technologies to achieve in

➢ **Stealth technique:**
Radar cross-section reductions by absorbing paint / non-metallic frame / shape effect…

➢ **C**
Pro d
obj

F-117 "Nighthawk" Stealth Fighter

Optical Camouflage, Tachi Lab, U. of Tokyo, Japan

Invisibility: from fiction to fact?

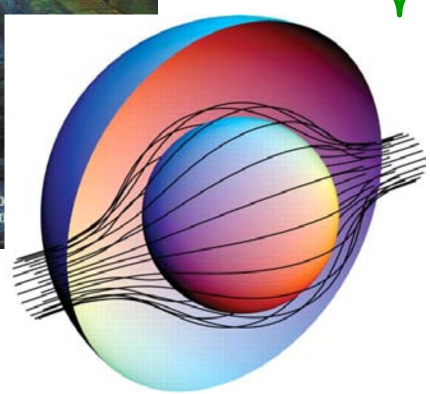
Examples with scientific elements:

- 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

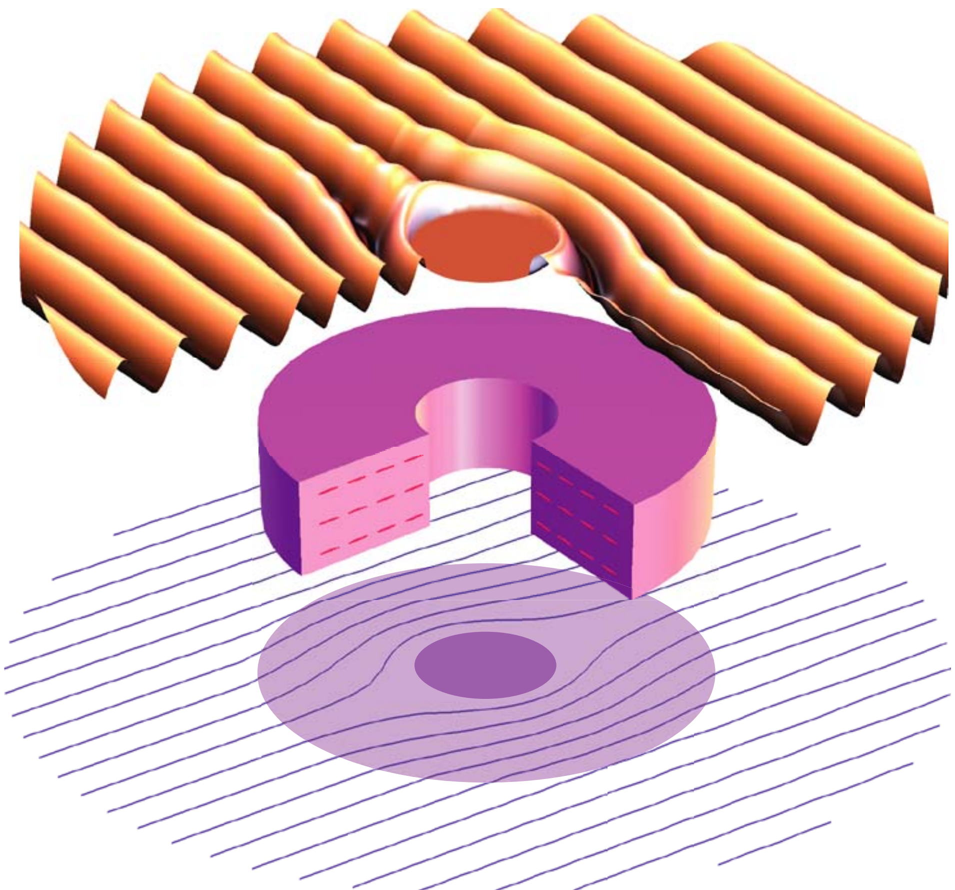


Pendry et al.; Leonhard, Science, 2006
(Earlier related work: Dolin, 1961; Greenleaf et al., 2003)

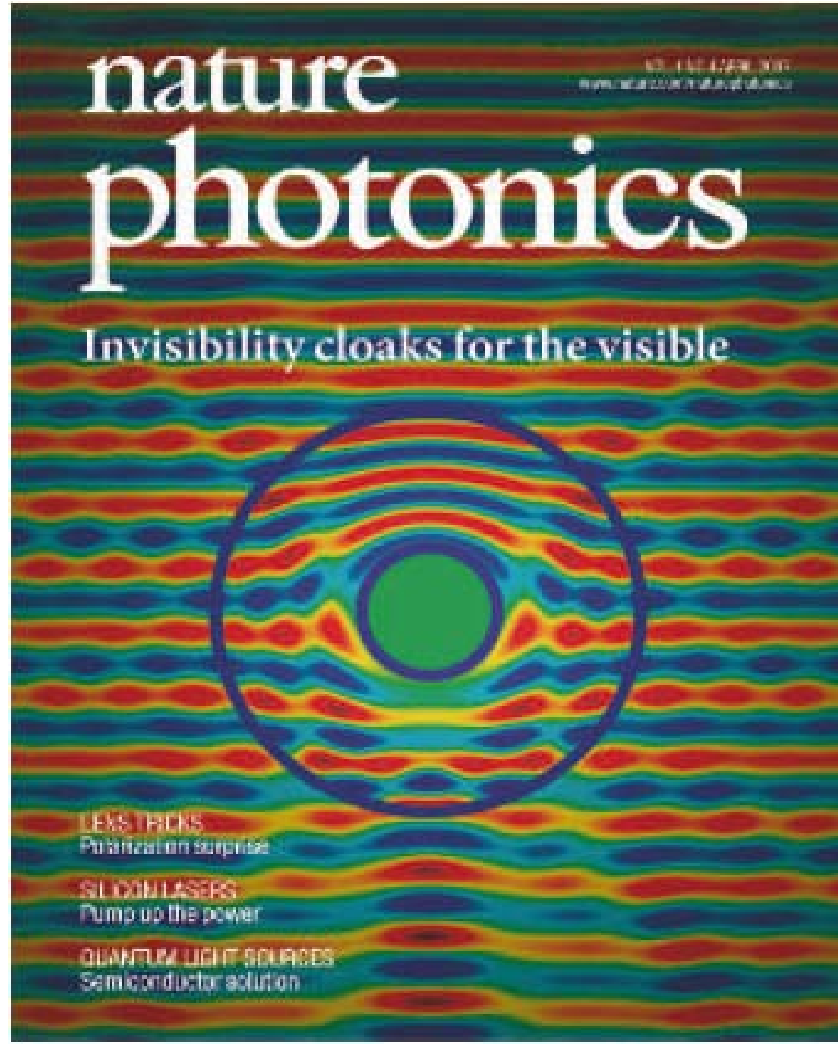
Invisibility?

Ghost djdaileydude87, from the Pop Sci photo pool

Optical Cloaking with Metamaterials: Can Objects be Invisible in the Visible?



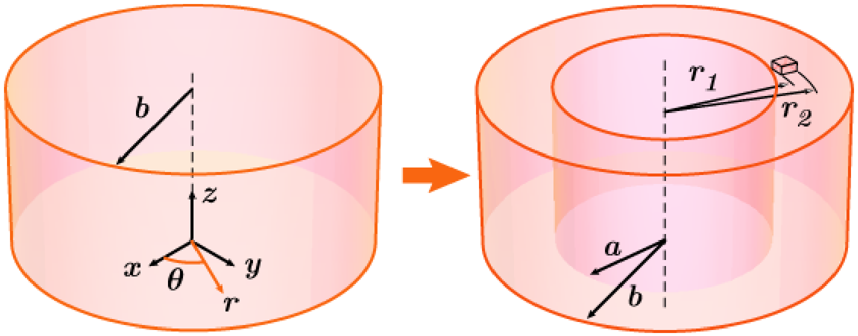
λ = 632 nm

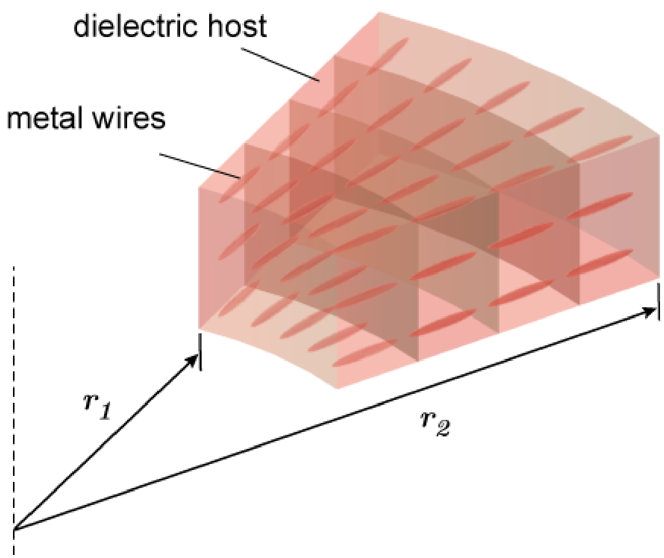


[GHz-cloak: Duke team]

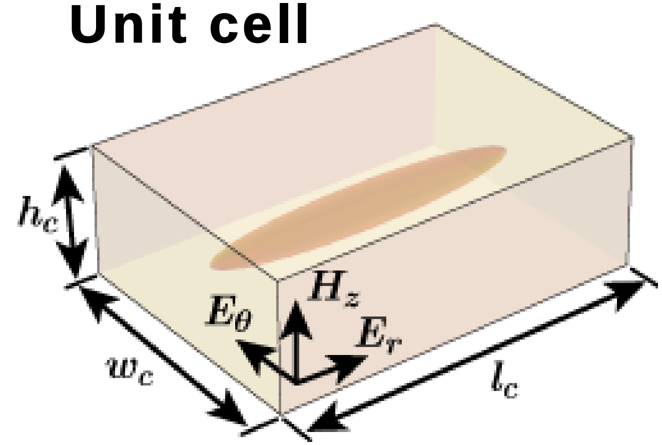
Nature Photonics (April, 2007)

Structure of Optical Cloak: "Round Brush"





metal needles embedded in dielectric host



Flexible control of ε_r ;

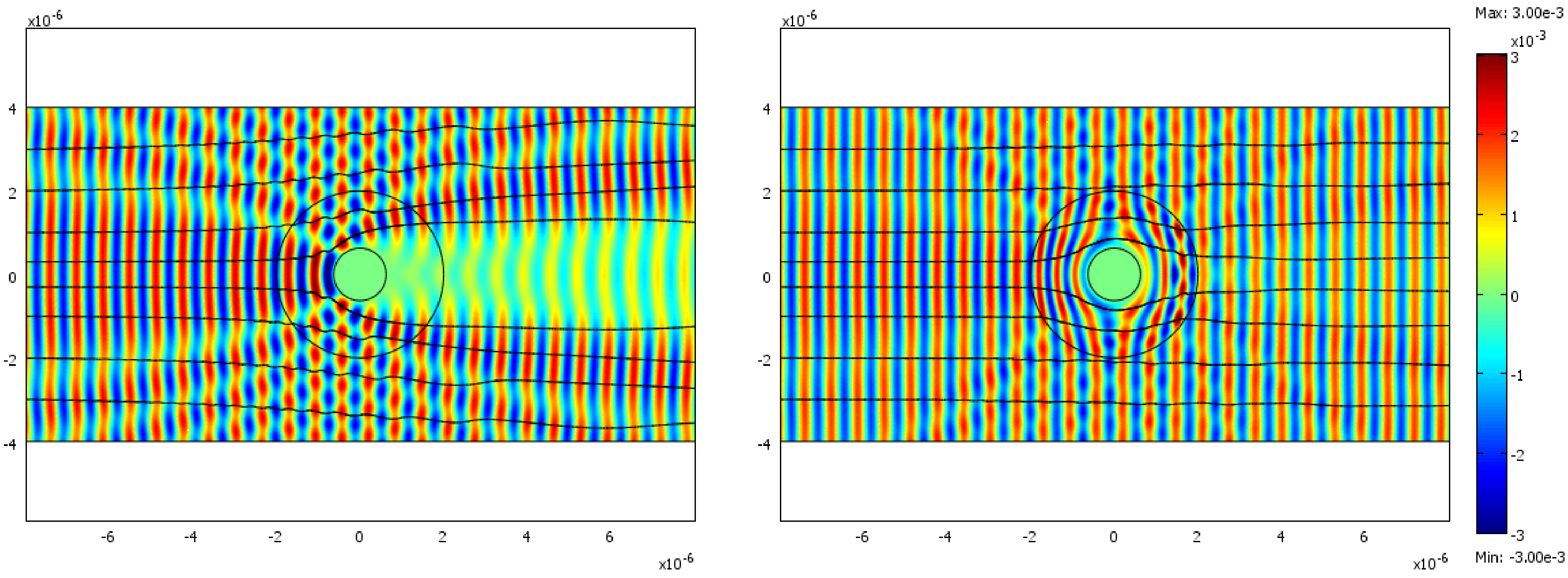
Negligible perturbation in ε_θ

Cai, et al., Nature Photonics, 1, 224 (2007)

Cloaking Performance: Field Mapping Movies

Example:

Non-magnetic cloak @ 632.8nm with silver wires in silica



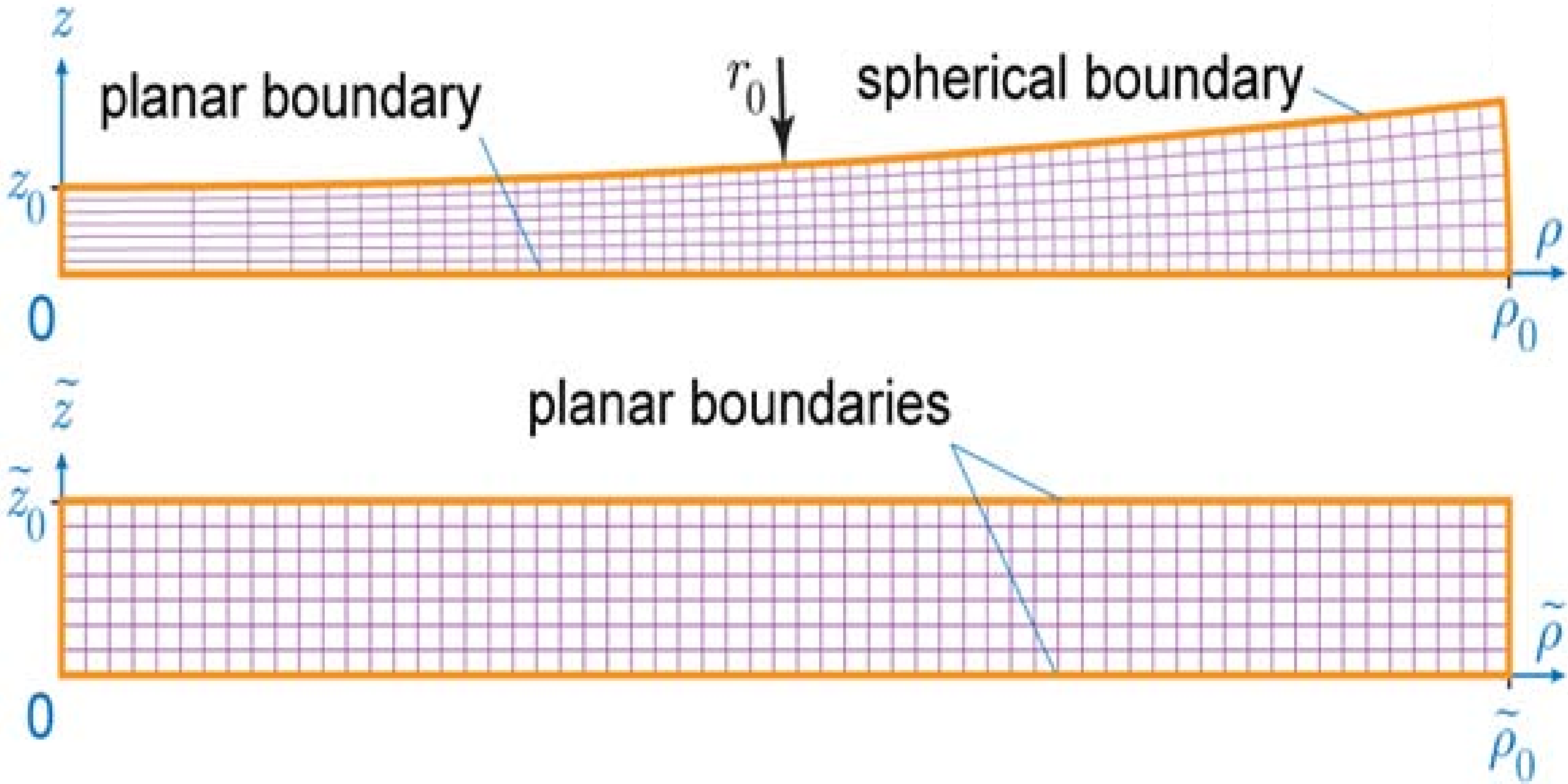
Cloak OFF ***Cloak ON***

Broadband Optical Cloaking in Tapered Waveguides

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

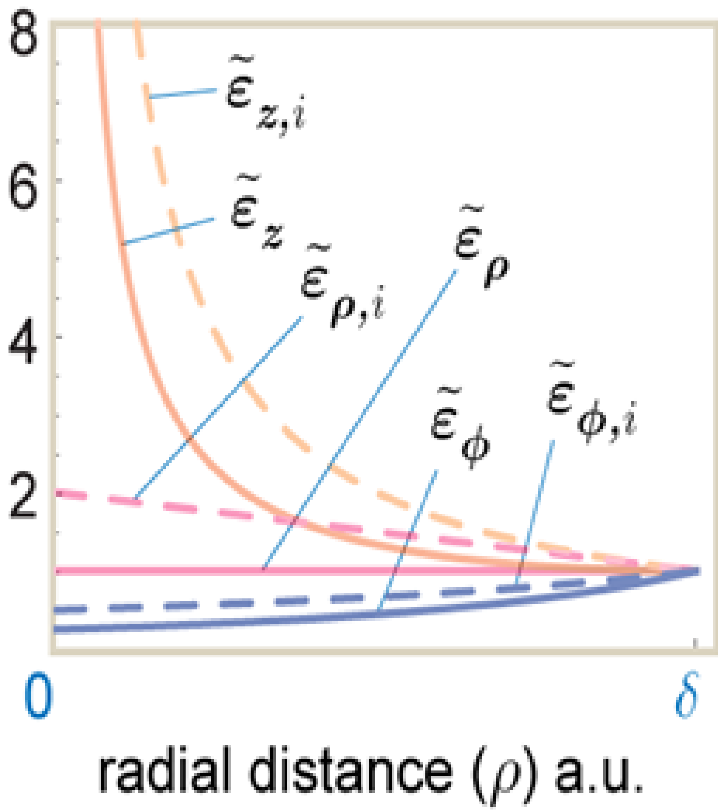
(PRL – 2009)

Emulating Anisotropic Metamaterials with Tapered Waveguides

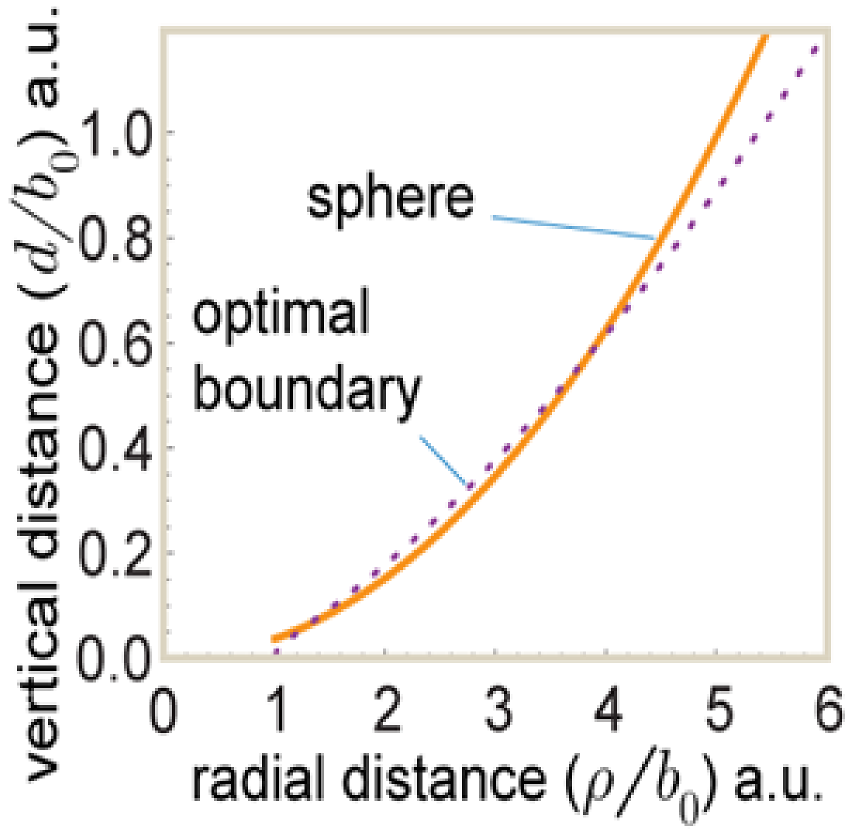


A space between a spherical and a planar surface mapped onto a planar anisotropic metamaterial

Emulating Anisotropic Metamaterials with Tapered Waveguides

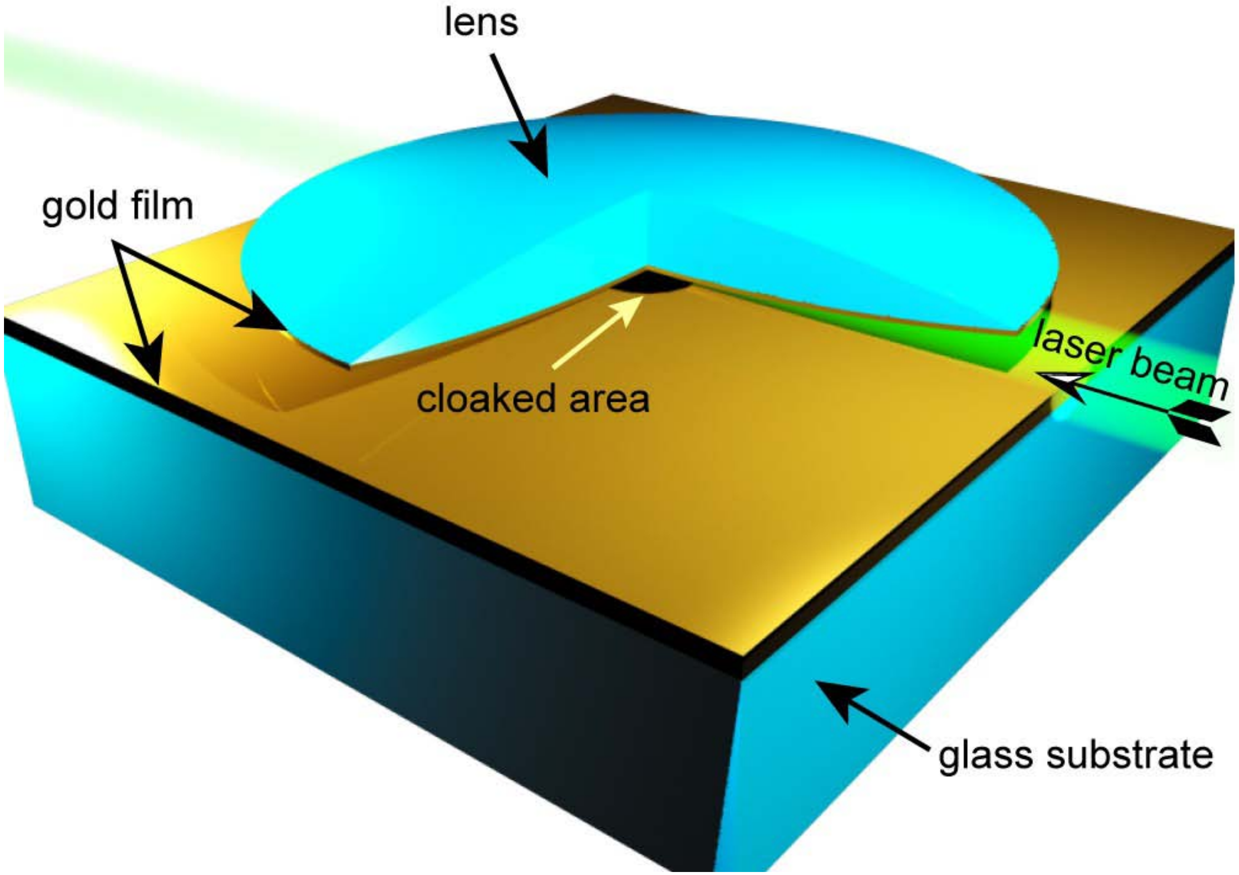


Distribution of radial (top), azimuthal (middle), and axial components of ε = μ in equivalent planar MM. Dashed lines show same components in the ideal cloak.

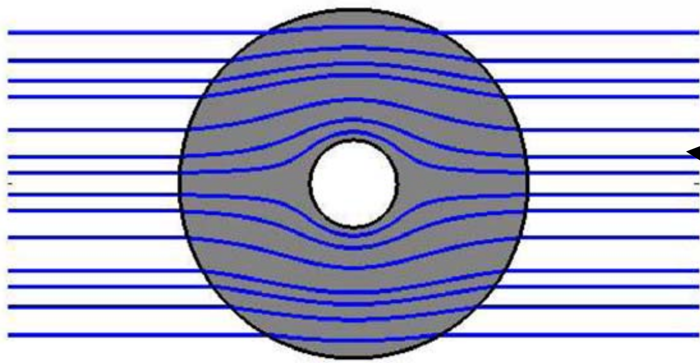


Normalized profile of optimal and "plane-sphere" waveguides for a cloak with radius of b_0 = 172 μm.

Broadband Optical Cloak in Tapered Waveguide



Fermat Principle and Waveguide Cloak



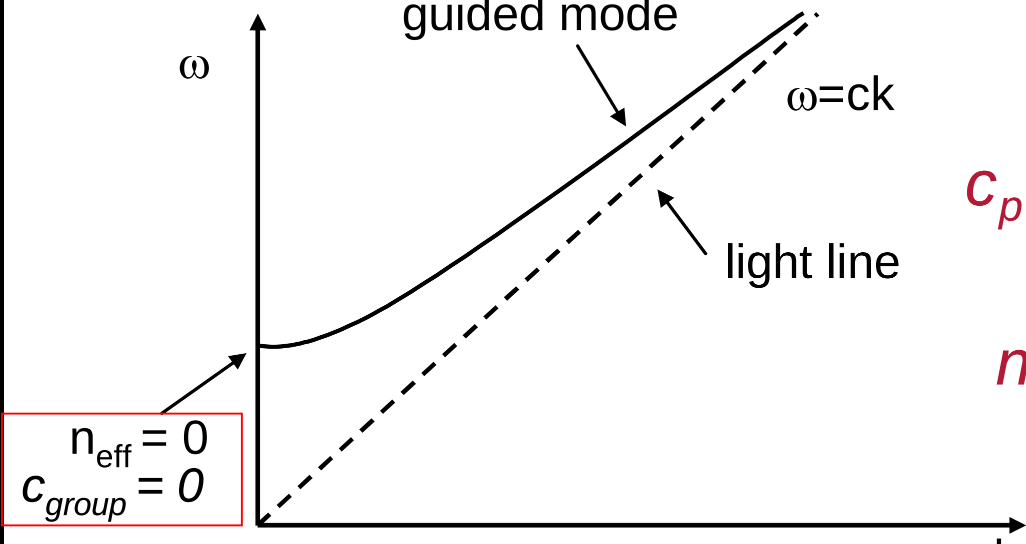
$n_{eff} L$ = const (Fermat)

Cloaking Hamiltonian: (Narimanov, OE, 2008)

$$\left(\omega/c\right)^2 = k_\rho^2 + k_\phi^2\left(\rho - b\right)^{-2}$$

Dispersion law of a guided mode:

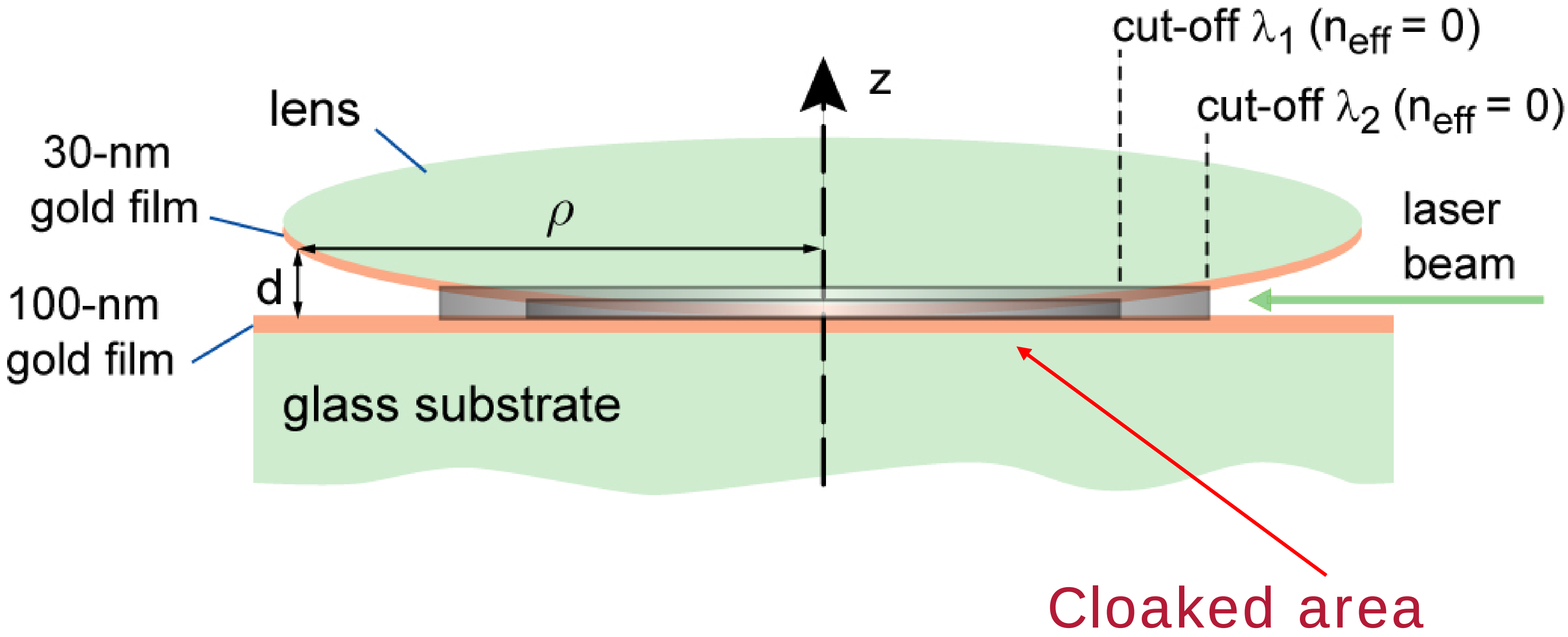
$$\left(\omega/c\right)^2 = k_\rho^2 + \left(k_\phi/\rho\right)^2 + \left[\pi l/d(\rho)\right]^2$$



$c_{phase} = \omega / k \quad c_{group} = d\omega / dk$

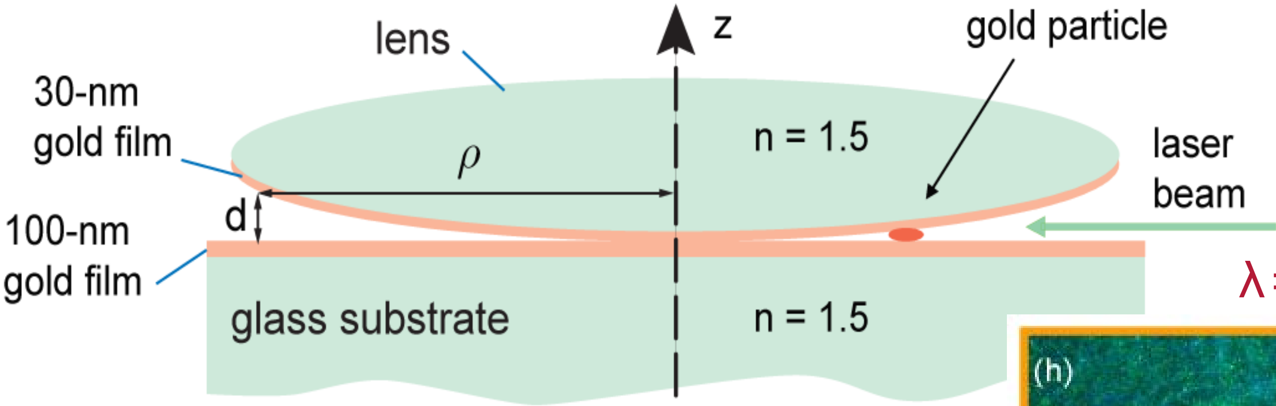
$n_{eff} = c / c_{phase} = ck / \omega \rightarrow 0$ near cutoff

Broadband Cloaking in Tapered Waveguide



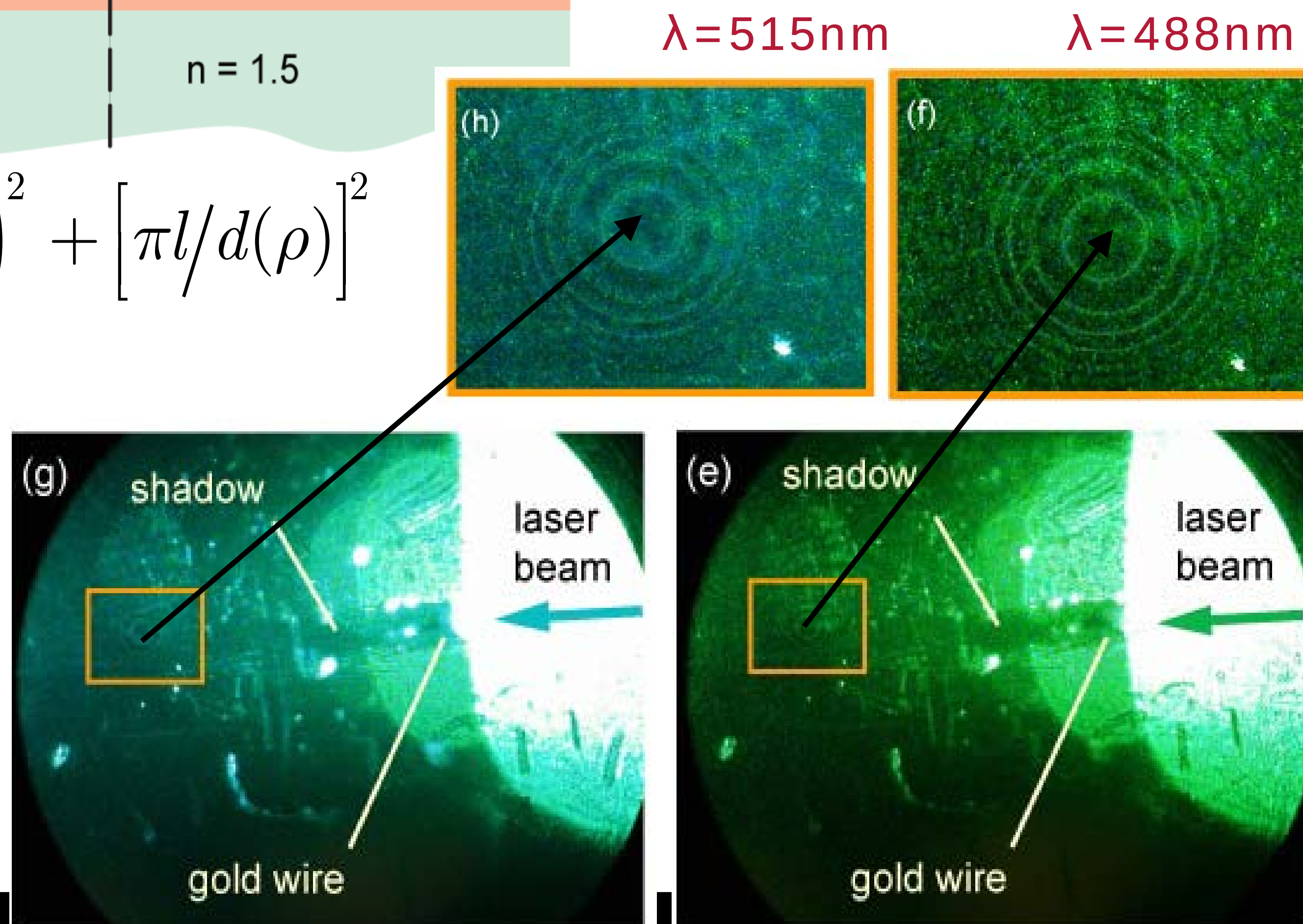
$$\left(\omega/c\right)^2 = k_\rho^2 + \left(m/\rho\right)^2 + \left[\pi l/d(\rho)\right]^2 = k_\rho^2 + k_\phi^2(\rho - b)^{-2}$$

Broadband Optical Cloak

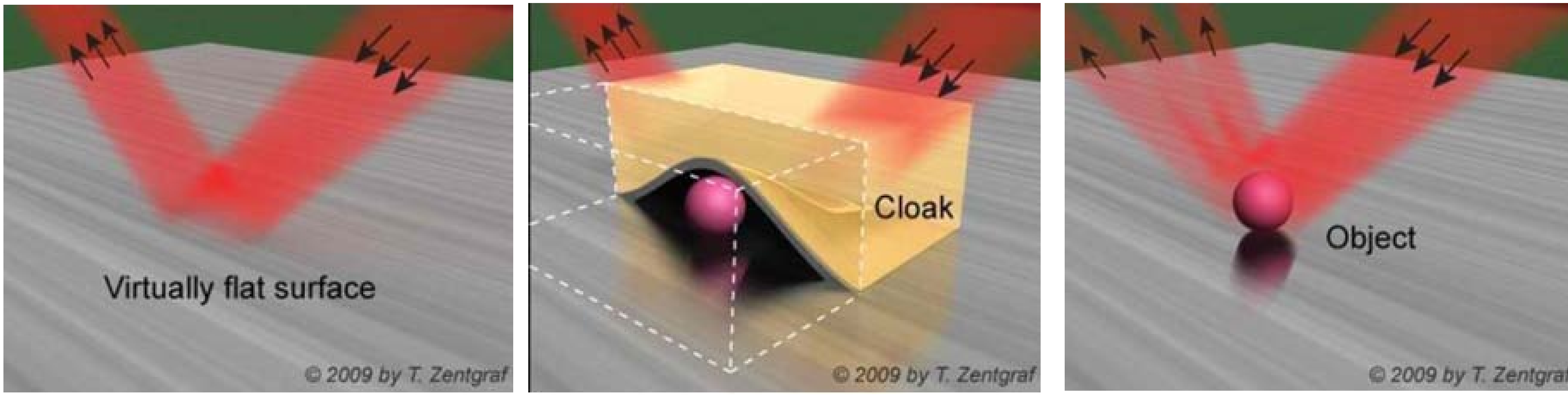


$$\left(\omega/c\right)^2 = k_\rho^2 + \left(m/\rho\right)^2 + \left[\pi l/d(\rho)\right]^2$$

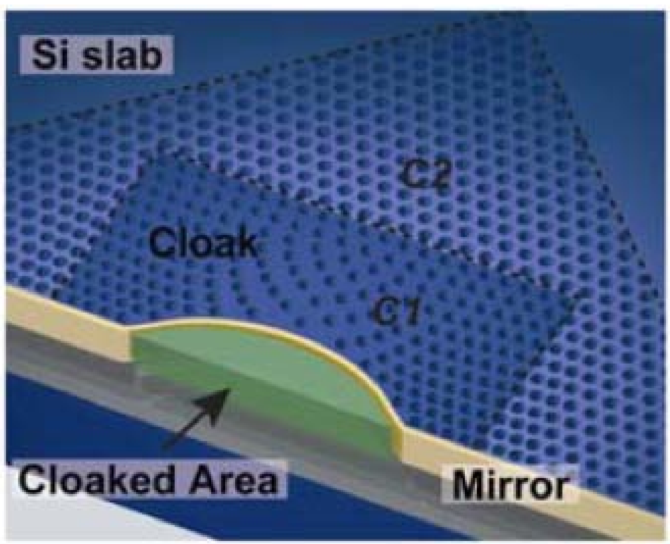
$$= k_\rho^2 + k_\phi^2(\rho - b)^{-2}$$



Optical Mimicry

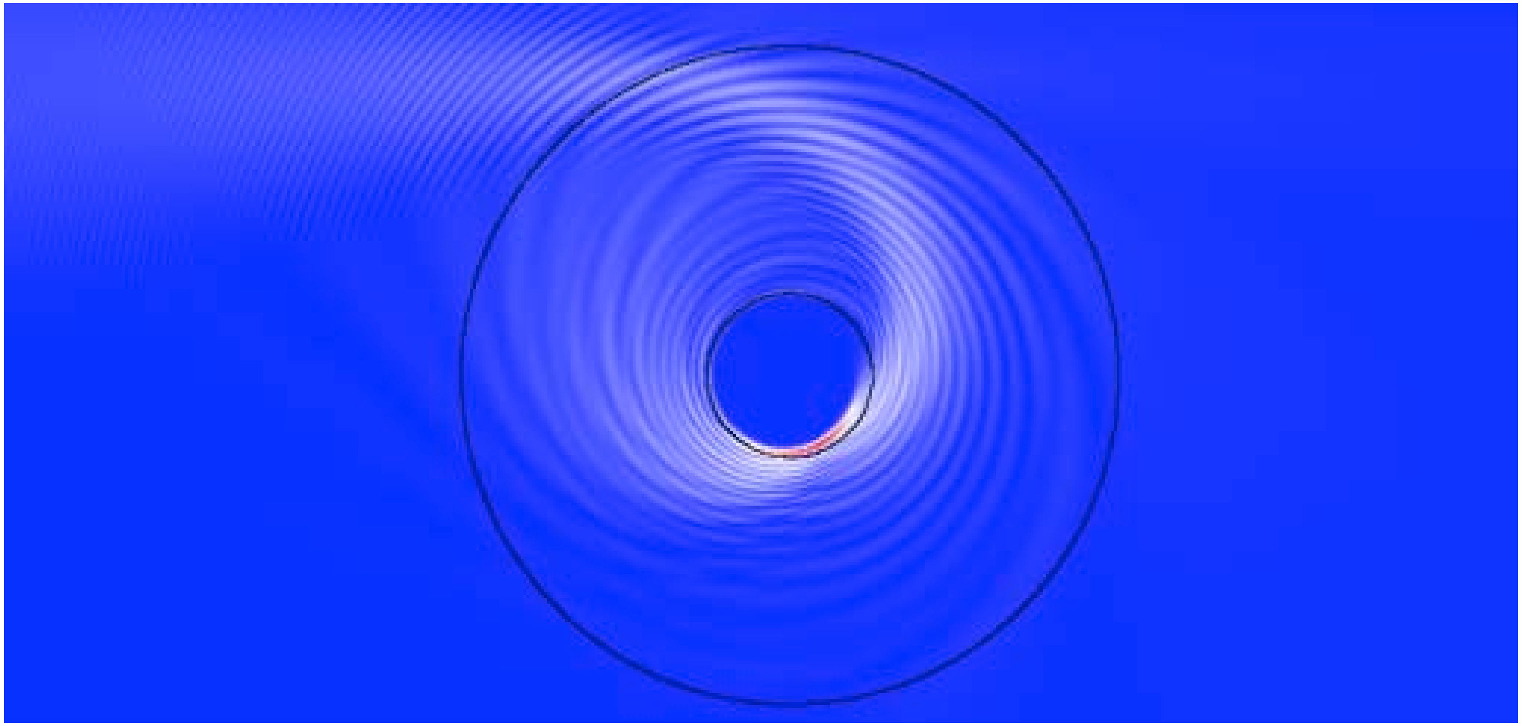


Progress Towards True Invisibility on May.17, 2009, under Science
www.codingfuture.com



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

The Optical Black Hole: Broadband Omnidirectional Light Absorber



All-dielectric

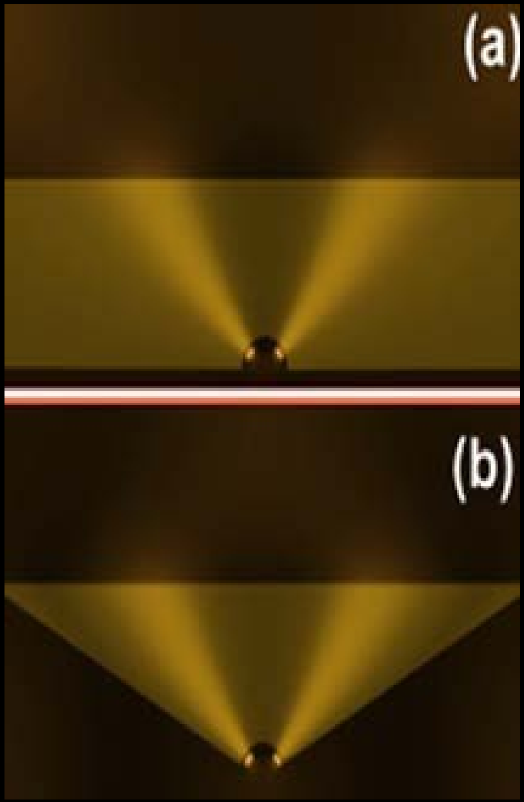
Real materials (e.g. semiconductors)

Narimanov, Kildishev

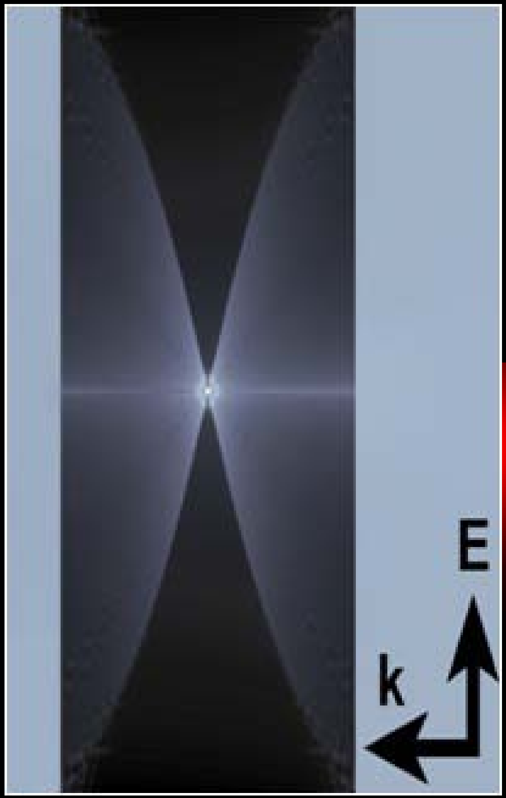
Engineering Meta-Space for Light: via Transformation Optics

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

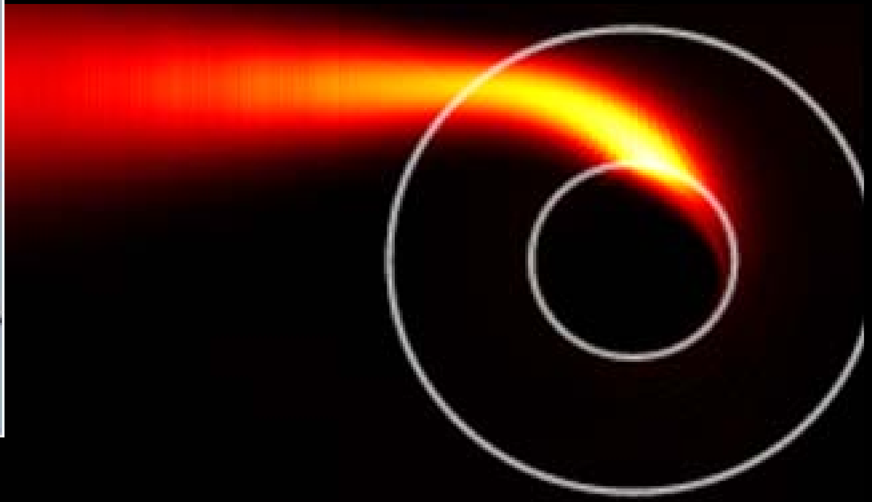
Fermat: $\delta\int n dl = 0$
$n = \sqrt{\varepsilon(r)\mu(r)}$
curving optical space



Planar hyperlens
(Magnifies)

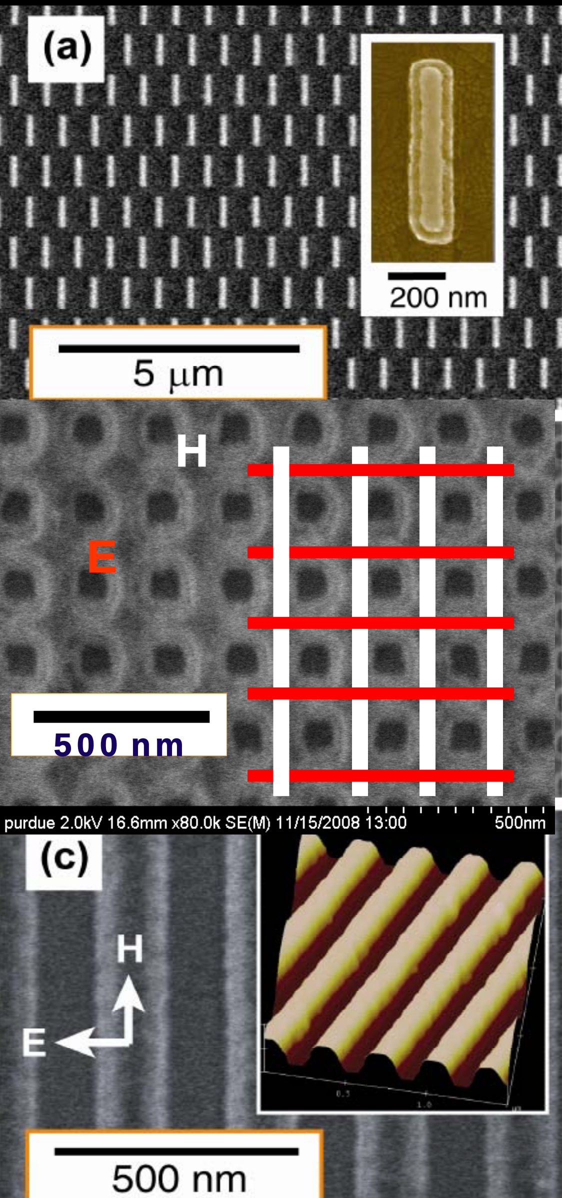


Light concentrator
(also, Schurig et al)



Optical Black Hole
(Narimanov, Kildishev; Zhang et al)

Highlights of Purdue "Meta-Research"



Electrical MMs: **i) Nanoantennae and ii) Nanolaser (with NSU, Cornel)**

Purdue Photonic Metamaterials

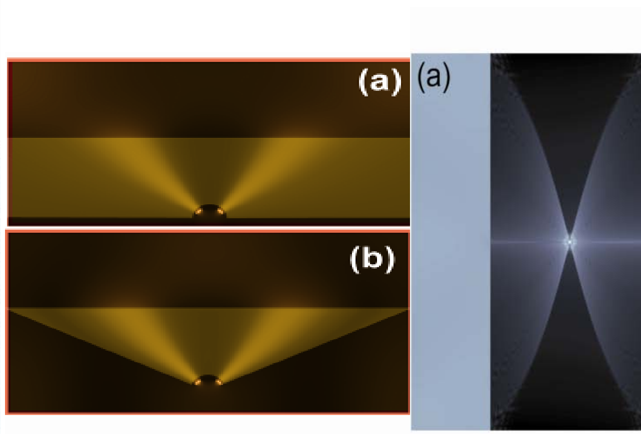
(a) 1-st optical negative-index MM (1.5 µm; 2005)

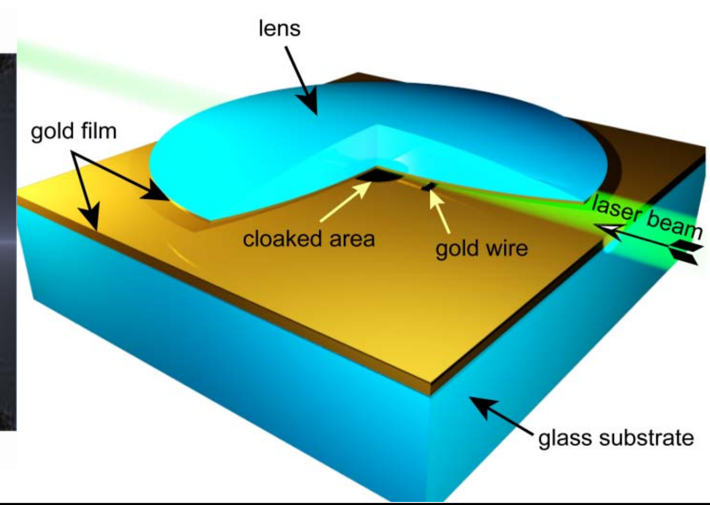
(b) Negative index MM at shortest λ (~580nm; 2009)

(c) 1-st magnetic MM across entire visible (2007)

Transformation Optics with MMs:

Flat hyperlens, concentrator, and cloak





Thanks to Birck Nanotechnology Center

Question & Answer 1

Question & Answer 2

Question & Answer 3