Vladimir M. Shalaev
Purdue University

Transforming Light with Metamaterials

(with A.V. Kildishev, W. Cai, V.P. Drachev, S. Xiao, U. Chettiar)

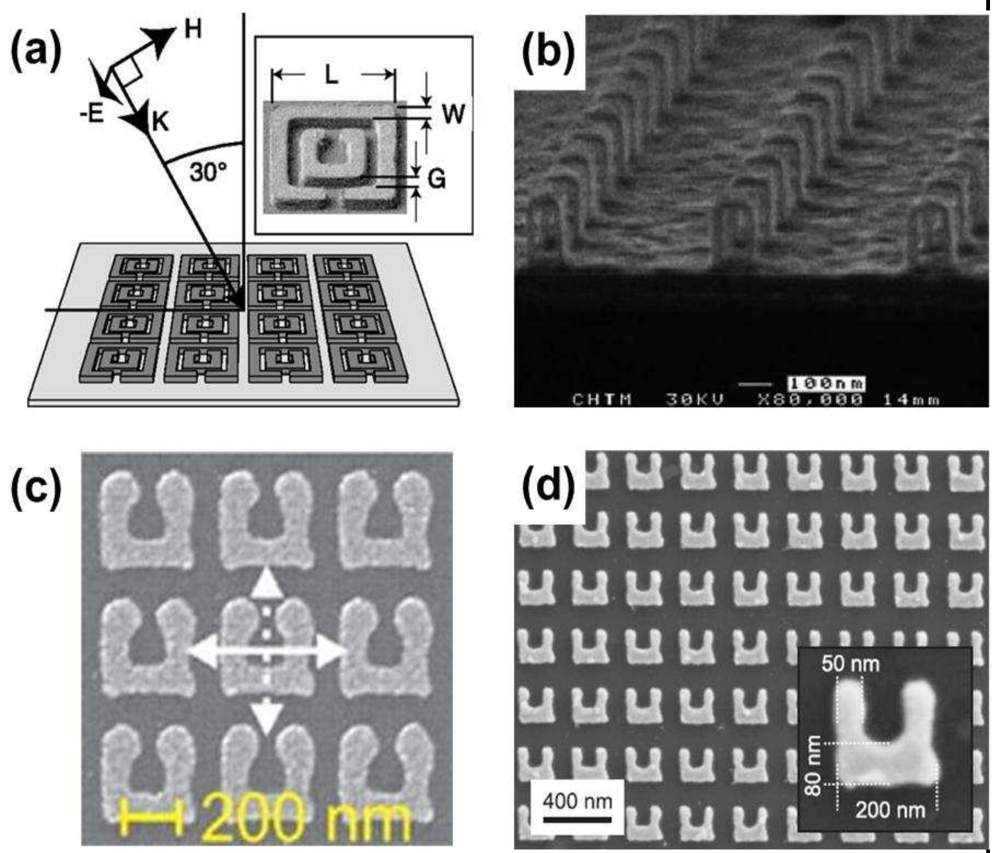
OUTLINE

- Metamagnetics across entire visible (from red to blue)
- Demonstration of "double-negative" MM (with both ε & μ < 0) in the visible: n = -0.8 at 725nm; and "single-negative" n=-0.3 at 580 nm
- Nonlinear Optics with Metamaterials (see also presentation by Natalia Litchinitser)
- Optical Cloaking & Transformation Optics

Meta-Magnetics: from 10GHz to 200THz

Terahertz magnetism

a) Yen, et al. ~ 1THz (2-SRR) – 2004
Katsarakis, et al (SRR – 5 layers) - 2005
b) Zhang et al ~50THz (SRR+mirror) - 2005
c) Linden, et al. 100THz (1-SRR) -2004
d) Enkrich, et al. 200THz (u-shaped)-2005

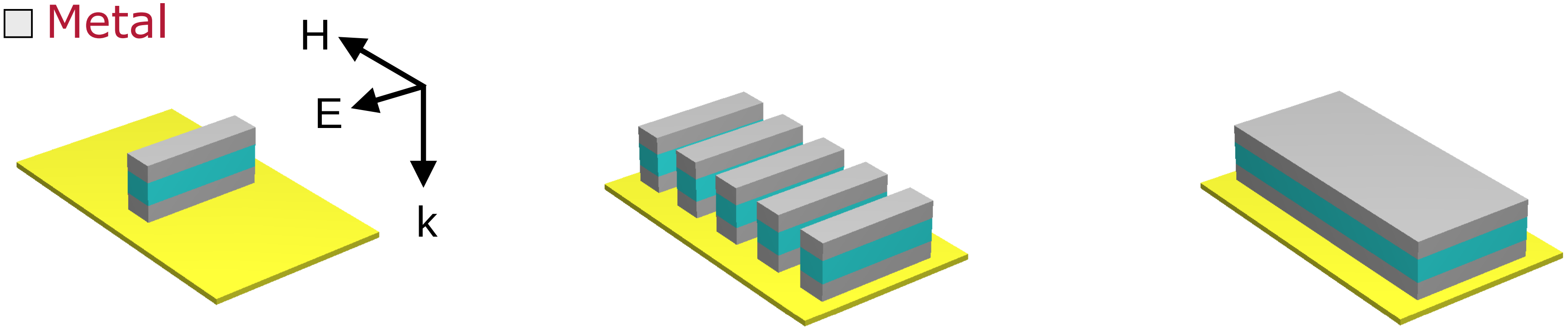


2004-2005 years:
from 10 GHz to 200 THZ

2007: artificial magnetism across entire visible

Artificial Magnetic Metamaterials for Visible

- Dielectric
- Metal

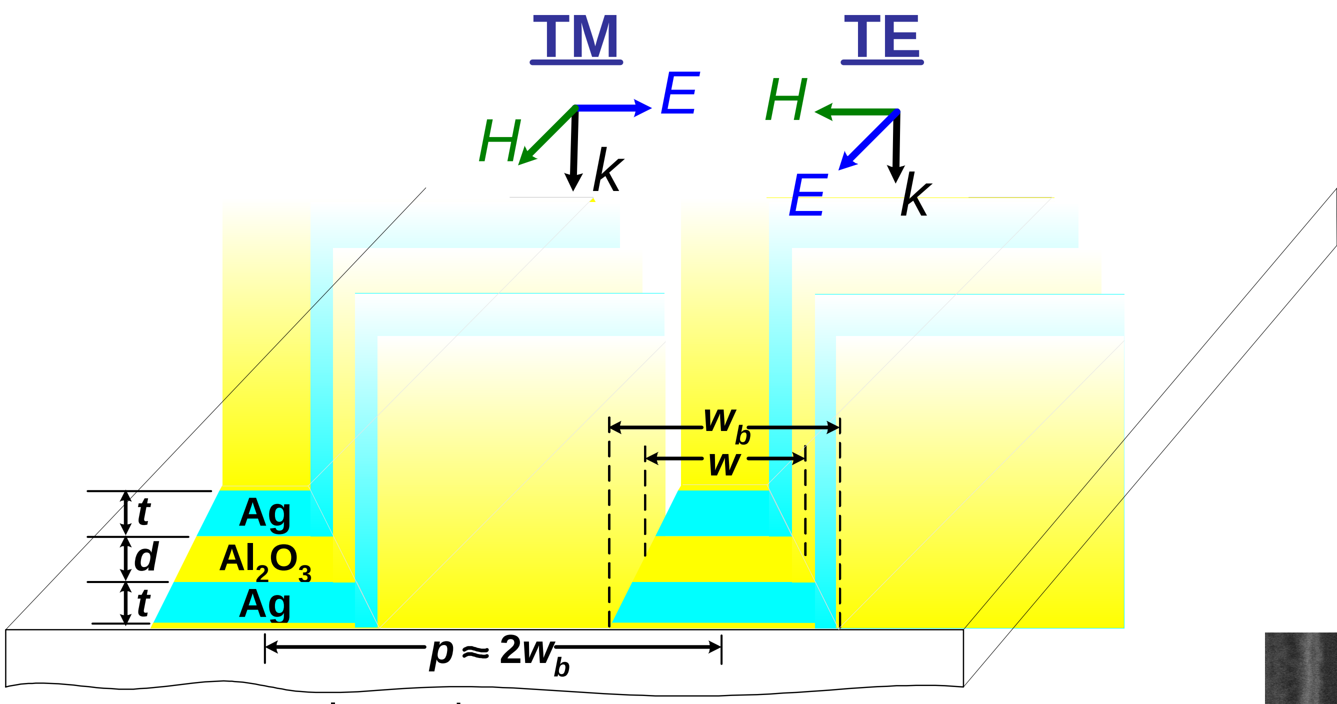


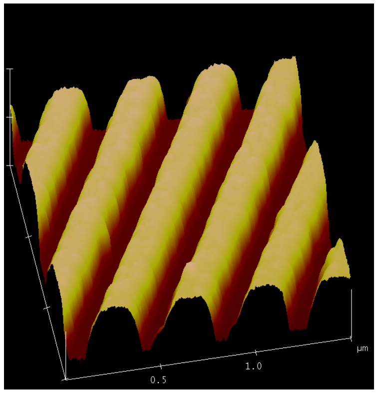
Nanorod pair | Nanorod pair array | Nanostrip pair

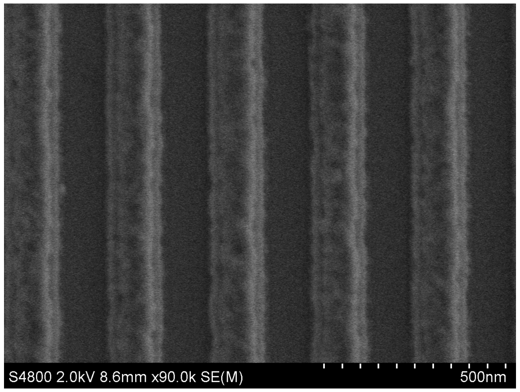
Nanostrip pair has a much stronger magnetic response

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

"Visible" artificial magnetism





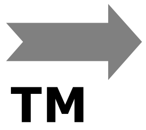


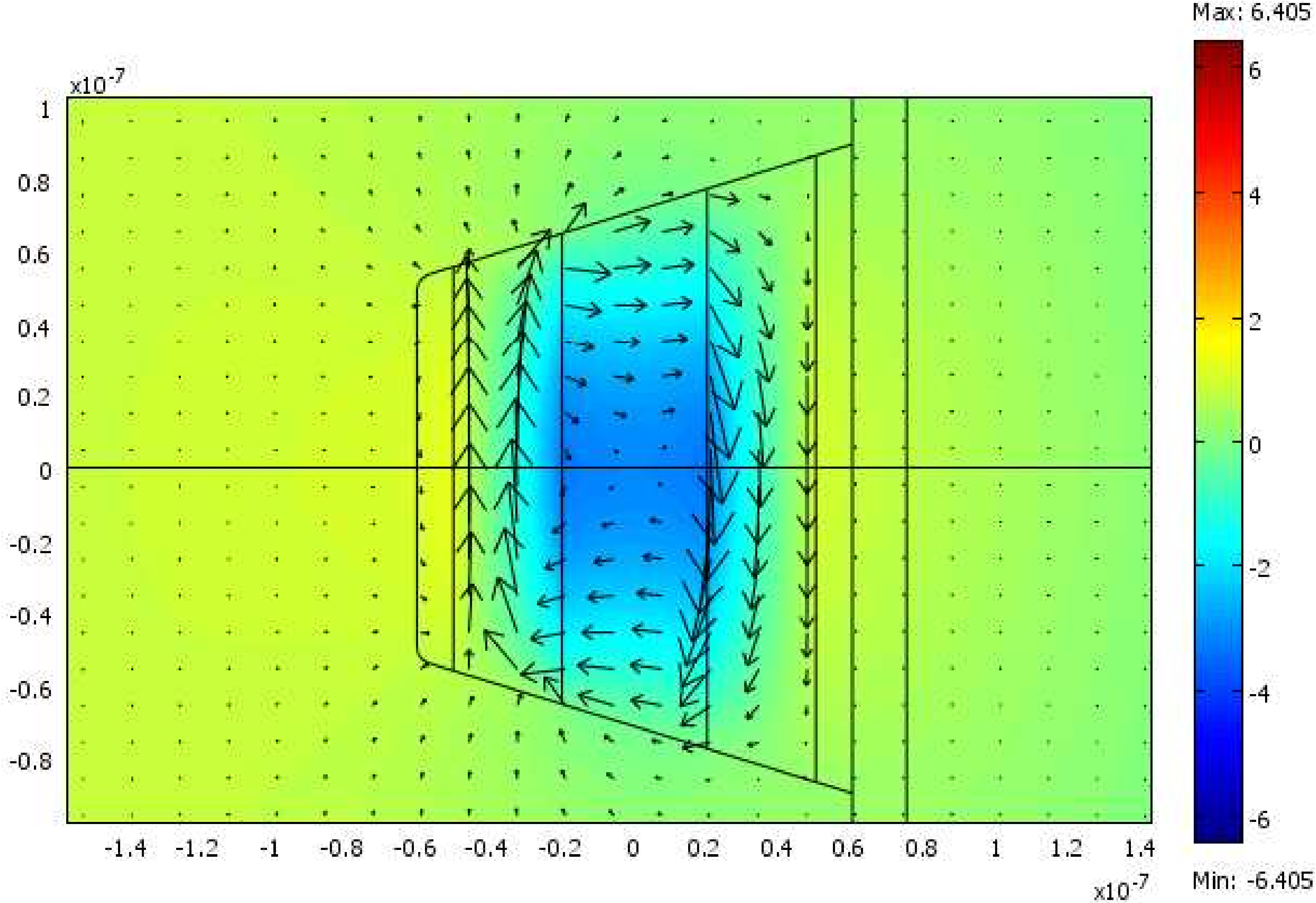
$t = 35\ nm \quad d = 40\ nm \quad p \approx 2w_b$

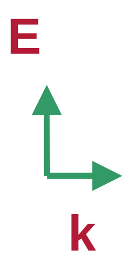
Width varies from 50 nm to 127 nm

Purdue group
Yuan, et al., Opt. Expr., 2007 – red light
Cai, et al., Opt. Expr., 2007 – entire visible

Negative Magnetic Response in Visible

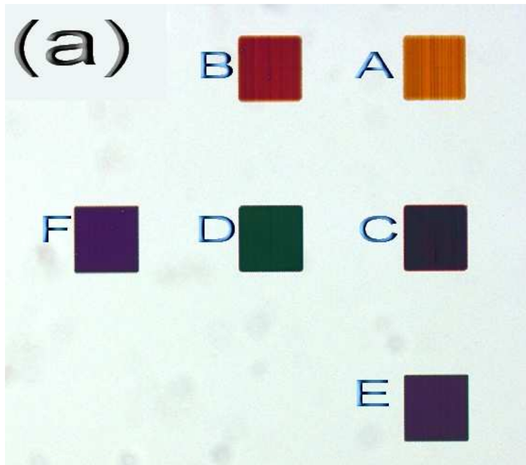


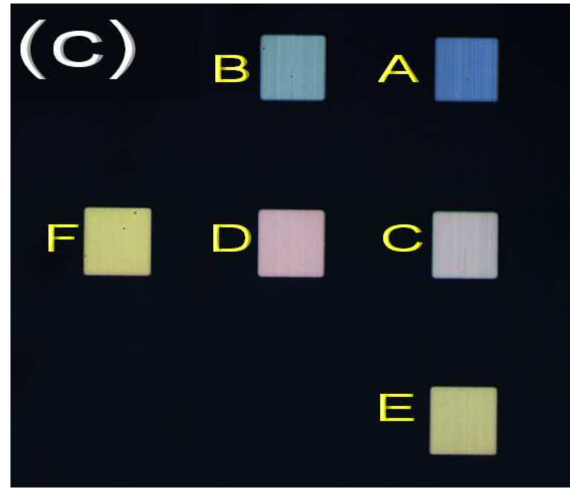




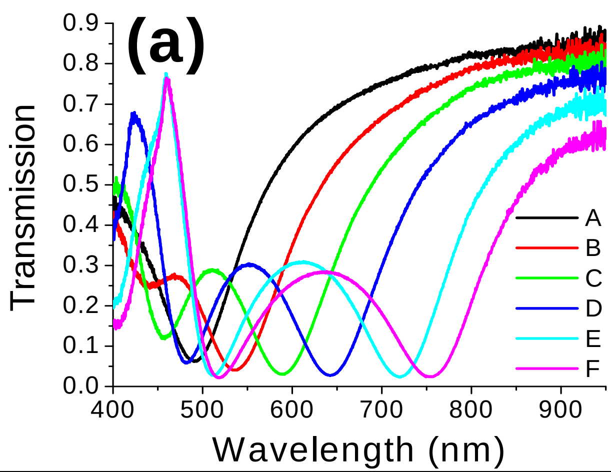
Metamagnetics with Rainbow Colors

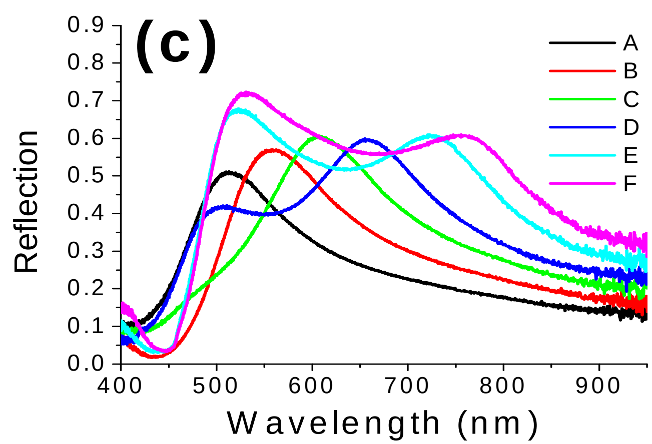
Transmittance





Reflectance

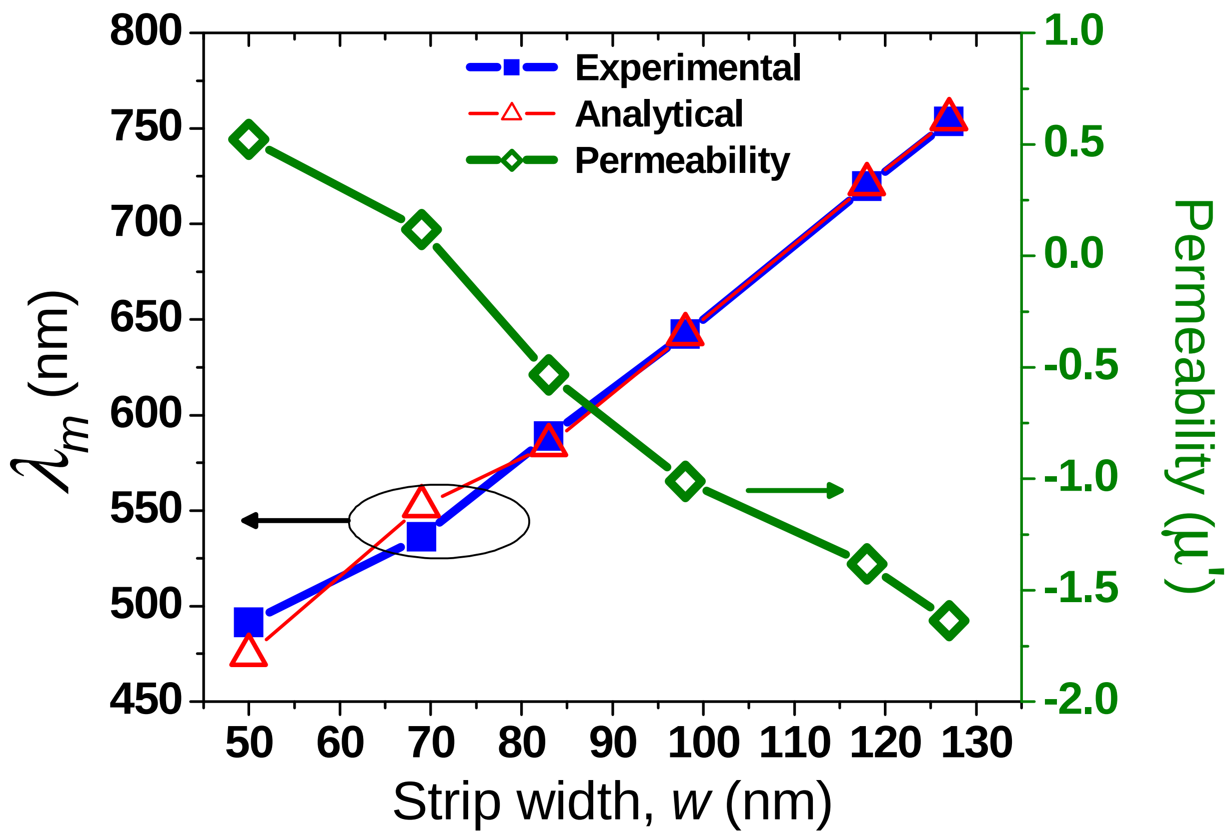




Sample #	***A***	***B***	***C***	***D***	***E***	***F***
Width *w (nm)*	**95**	**118**	**127**	**143**	**164**	**173**

Cai et al.
Opt. Exp., 2007

Visible Meta-Magnetics: from Red to Blue

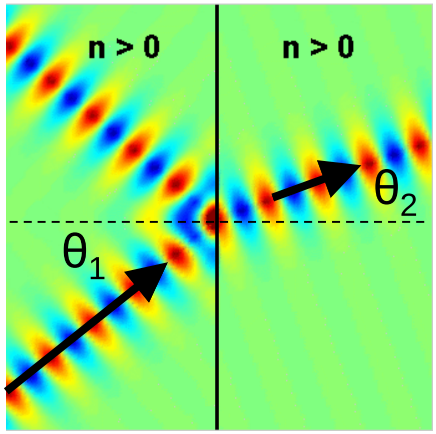


λ_m as a function of strip width "w": experiment vs. theory

Negligible saturation effect on size-scaling

Negative Refractive Index in Optics

Metamaterials with Negative Refraction



Refraction:

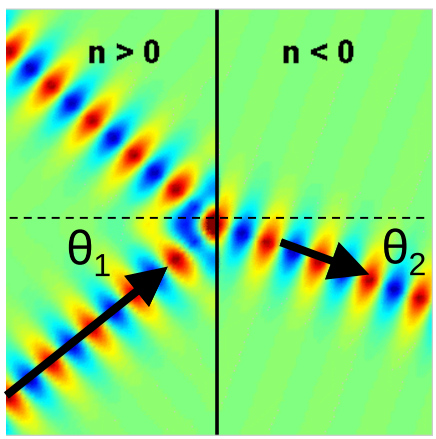
$$n^2 = \varepsilon\mu$$

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

Figure of merit

F = |n′|/n″

n < 0, if **ε′|μ| + μ′|ε| < 0**



<u>Single-negative:</u>

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

<u>Double-negative:</u>

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

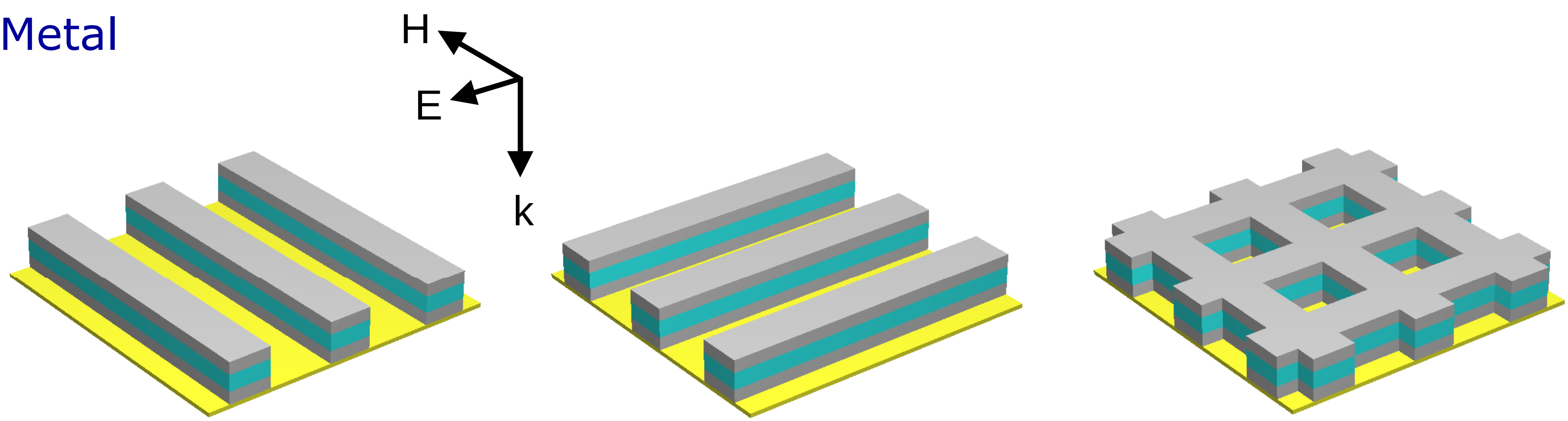
Negative Refractive Index in Optics: State of the Art

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 preparation (2009)	-0.25	580nm	0.3	Nano-fishnet

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

Negative permeability and negative permittivity

- Dielectric
- Metal



Nanostrip pair (TM)

$\mu < 0$ (resonant)

Nanostrip pair (TE)

$\varepsilon < 0$ (non-resonant)

Fishnet

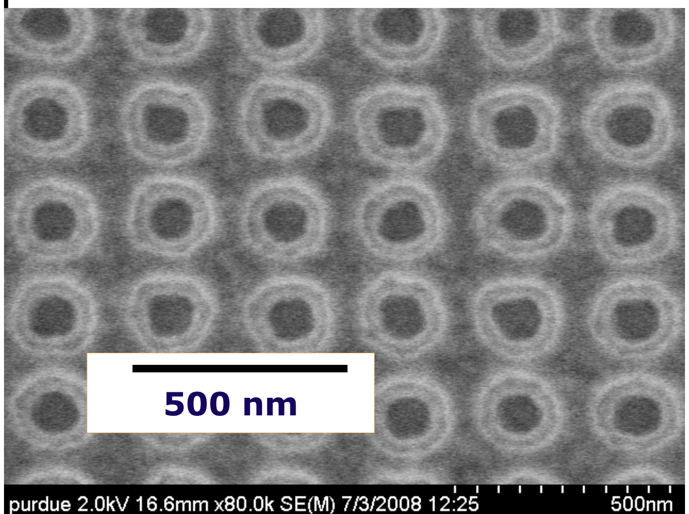
ε and $\mu < 0$

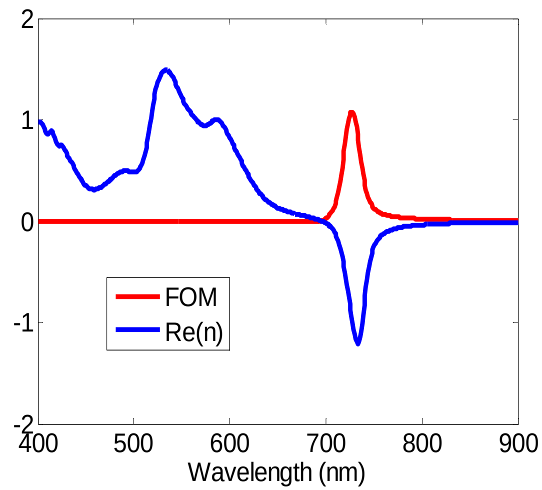
S. Zhang, et al., PRL (2005)

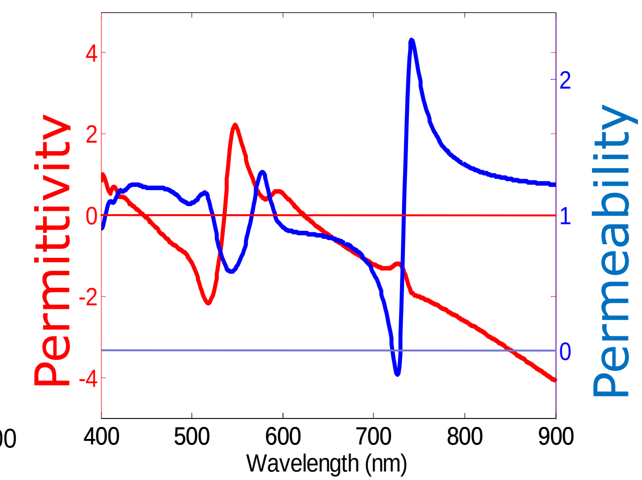
Sample A: Double Negative NIM (n'=-0.8, FOM=1.1, at 725 nm)
Sample B: Single Negative NIM (n'=-0.25, FOM=0.3, at 580 nm)

Sample A. period- E: 250 nm; H: 280 nm

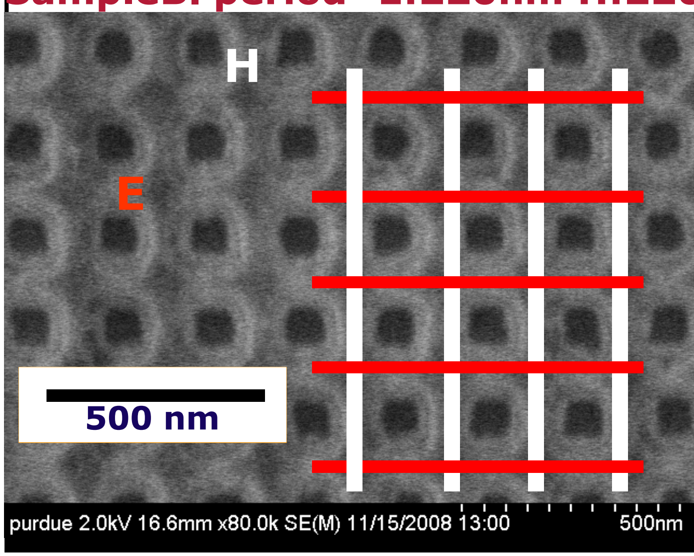
MRS Bulletin (2008)

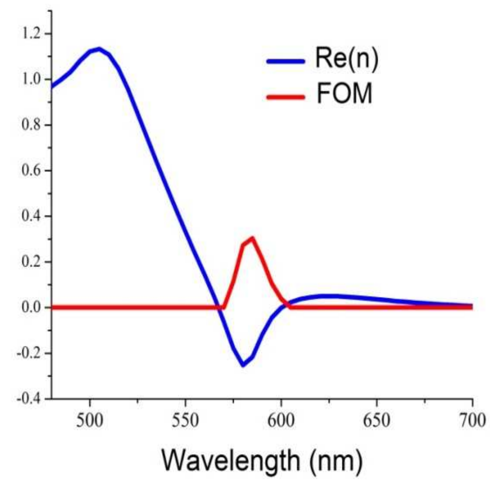


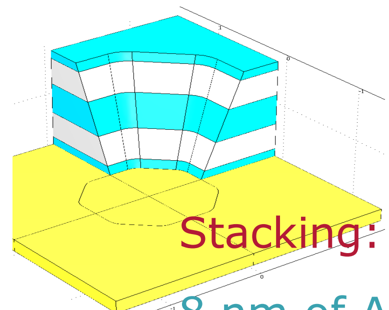




SampleB. period- E:220nm H:220nm







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

with Alex K. Popov

Nonlinear Optics of NIMs:
Optical Parametric Amplification (OPA)

- **OPA: compensating losses with OPA (with $\chi^{(2)}$ – Opt. Lett. 2006; with $\chi^{(3)}$ – OL 2007)**

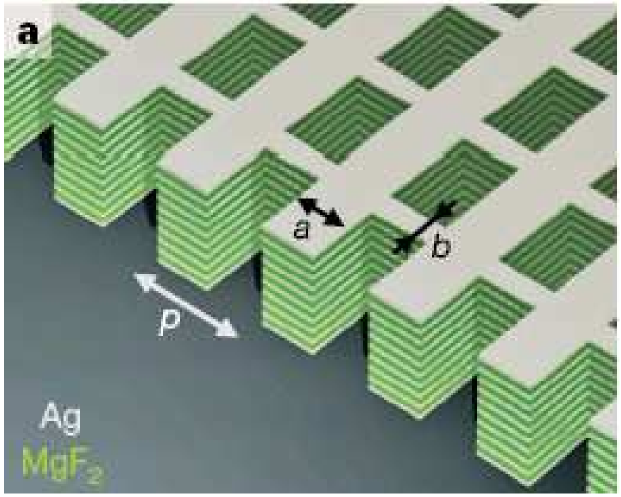
A.K. Popov and V.M. Shalaev - OL 31, 2169 (2006) and OL (2007)

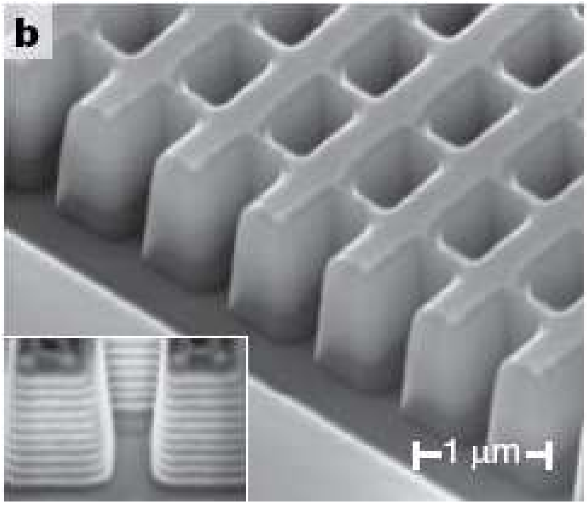
Laser Physics Letts **3**, 293 (2006); APB **84**, 131 (2006);
JOSA B **23**, 535 (2006) (with Gabitov, Litchintser, et al)

early work on SHG: **Kivshar**, et al; Zakhidov et al (2005)
SHG Experiment in SRRs: Klein et al, Science 313, 502 (2006)

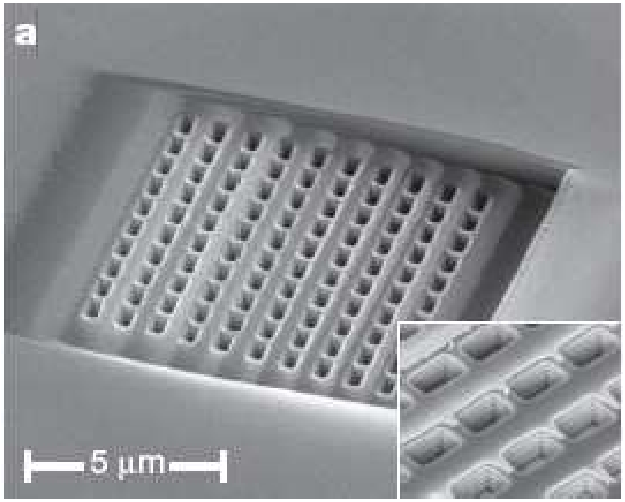
Three-dimensional Optical Metamaterials with a Negative Refractive Index

Schematic and Sem image of 21-layer fishnet, p= 860nm, a= 565,b= 265nm





Sem image of 3D fishnet NIM prism



Stacking: alternating layers
50 nm of MgF2 and 30 nm of Ag

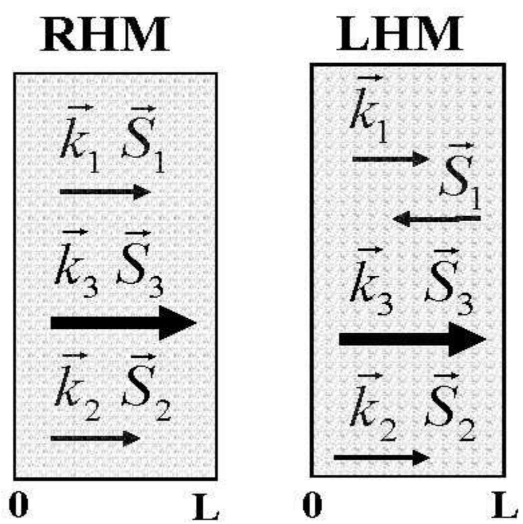
Valentine, et al., Nature (2008)

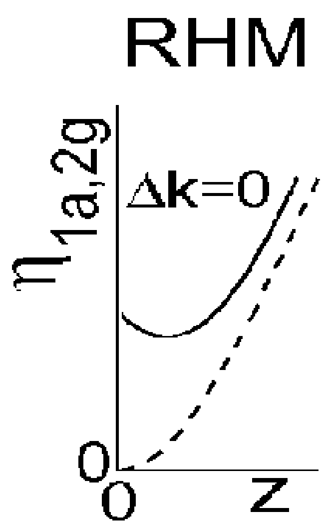
also work by the Wegner & Giessen groups

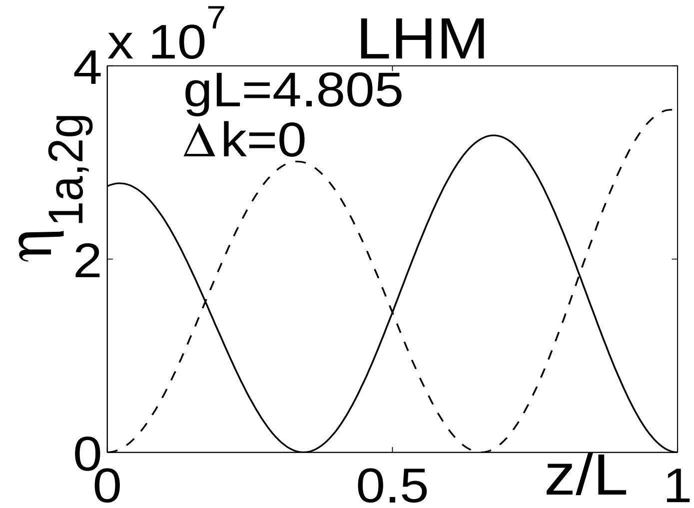
3D NIMs enable new means to compensate for loss – OPA!

Optical Parametric Amplification (OPA) in NIMs

$\omega_3 = \omega_1 + \omega_2$ $(n_1 < 0,\ n_2, n_3 > 0)$ S_3 - Control Field (pump)







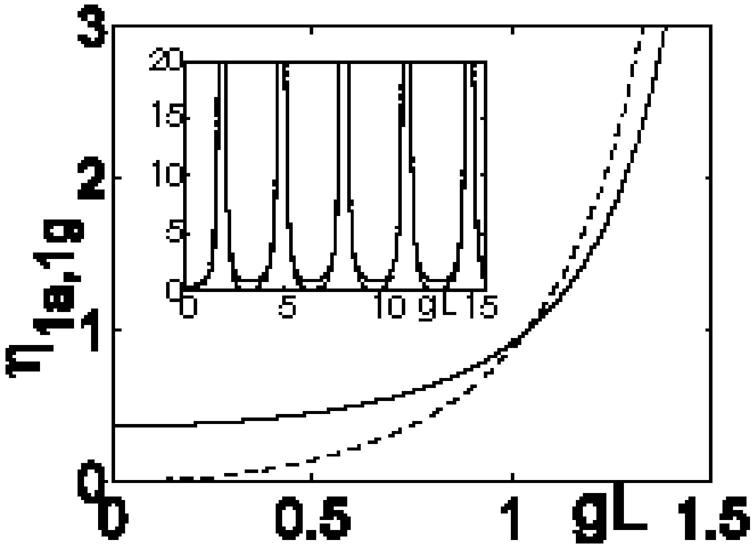
$$\eta_{1a} = \left|a_1(z)/a_{1L}\right|^2, \eta_{1g} = \left|a_1(z)/a_{20}\right|^2, \eta_{2g} = \left|a_2(z)/a_{1L}\right|^2$$

$$g = \left(\sqrt{\omega_1\omega_2}\sqrt[4]{\varepsilon_1\varepsilon_2/\mu_1\mu_2}\right)(8\pi/c)\chi^{(2)}h_3$$

Manley-Rowe Relations:

$$\frac{d}{dz}\left(\frac{S_1}{\hbar\omega_1} - \frac{S_2}{\hbar\omega_2}\right) = 0$$

OPA in NIMs:
Loss-Compensator and Cavity-Free Oscillator



Backward waves in NIMs -> Distributed feedback & cavity-like amplification and generation

$\alpha_1 L = 1,\ \alpha_2 L = 1/2$

$$\Delta k = 0$$

$$g = \left(\sqrt{\omega_1\omega_2}\sqrt[4]{\varepsilon_1\varepsilon_2/\mu_1\mu_2}\right)(8\pi/c)\chi^{(2)}h_3 \qquad \eta_{1a} = |a_1(z)/a_{1L}|^2, \eta_{1g} = |a_1(z)/a_{20}|^2$$

Resonances in output amplification and DFG

- **OPA-Compensated Losses**
- **Cavity-free (no mirrors) Parametric Oscillations**
- **Generation of Entangled Counter-propagating LH and RH photons**

Optical Cloaking
&
Transformation Optics

VMS, Science, Oct. 17, 2008

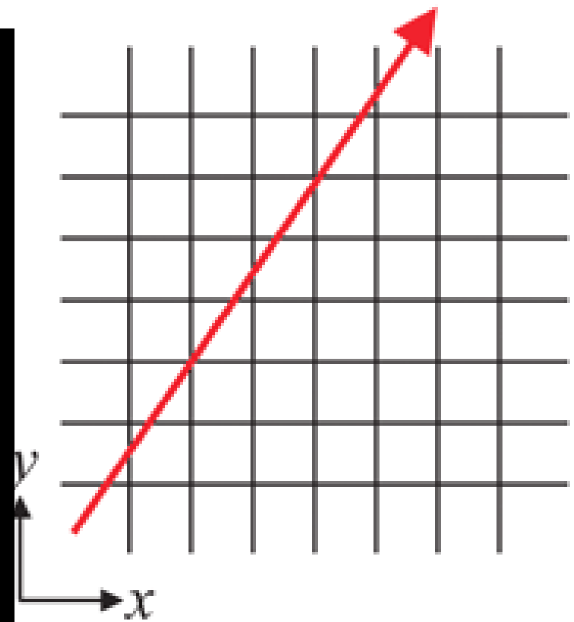
Designing Space for Light with Transformation Optics

Fermat:

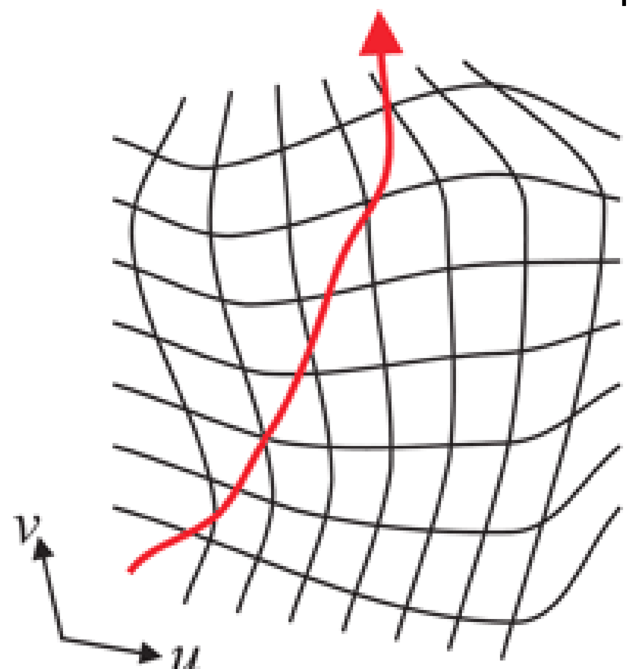
$$\delta \int n\,dl = 0$$

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

"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 coordinate

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

Transformation Optics and Cloaking

ИЗВЕСТИЯ ВЫСШИХ УЧЕБНЫХ ЗАВЕДЕНИЙ

Том IV, № 5 *РАДИОФИЗИКА*

О ВОЗМОЖНОСТИ СОПОСТАВЛЕНИЯ ТРЕХМЕРНЫХ ЭЛЕ МАГНИТНЫХ СИСТЕМ С НЕОДНОРОДНЫМ АНИЗОТРО ЗАПОЛНЕНИЕМ

Л. С. Долин

Показано, что, основываясь на инвариантности уравнений Макс относительно определенного вида преобразований метрики простра проницаемостей среды, можно исследовать трехмерные системы с родным анизотропным заполнением путем их сопоставления с други лее простыми трехмерными системами.

$$\| \varepsilon_{ik} \| = \| \mu_{ik} \| = \begin{vmatrix} \frac{R^2}{r^2(R)} \frac{dr(R)}{dR} & 0 & 0 \\ 0 & \frac{1}{dr(R)/dR} & 0 \\ 0 & 0 & \frac{1}{dr(R)/dR} \end{vmatrix}.$$

Как видно, при условии (4) $\varepsilon_{ik} = \mu_{ik} \xrightarrow[r \to \infty]{} 1$. Плоская волн щая из бесконечности на неоднородность с параметрами (5), через нее без искажений.

ледовательский радиофизический институт при Горьковском университете

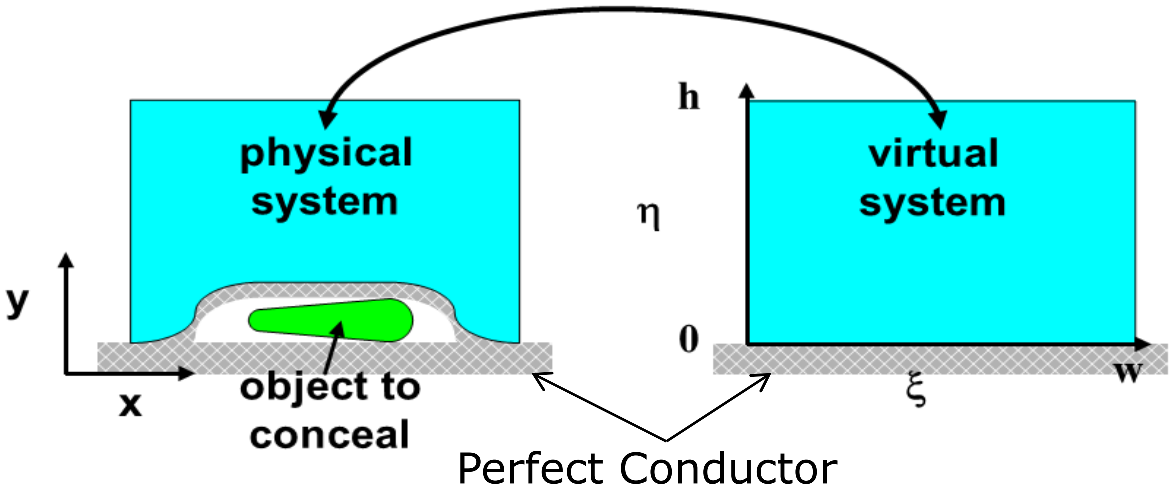
Поступила в редакцию 11 марта 1961 г.

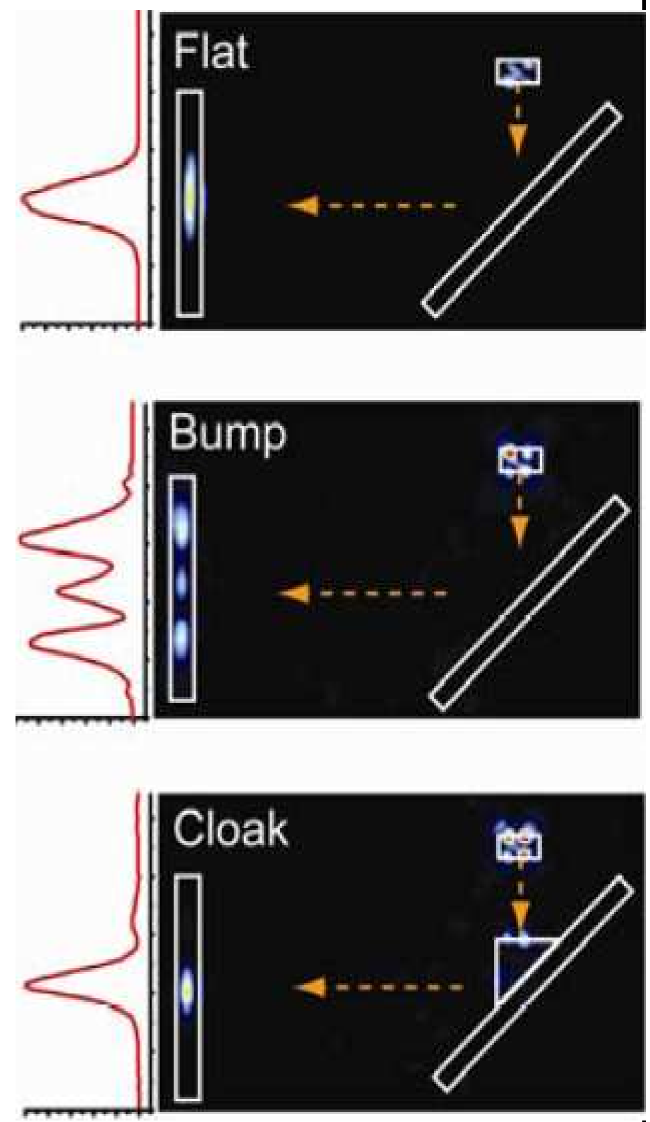
POSSIBILITY OF COMPARISON OF THREE-DIMENSIONAL LECTROMAGNETIC SYSTEMS WITH NONUNIFORM ANISOTROPIC FILLING

L. S. Dolin

s shown that it is possible to investigate three-dimensional systems with anisotropic filling by comparison them with other, more simple three-dimen ems. The examination is made basing on an invariance of Maxwels equations the certain type of transformation of space metric and medium permeability ivity.

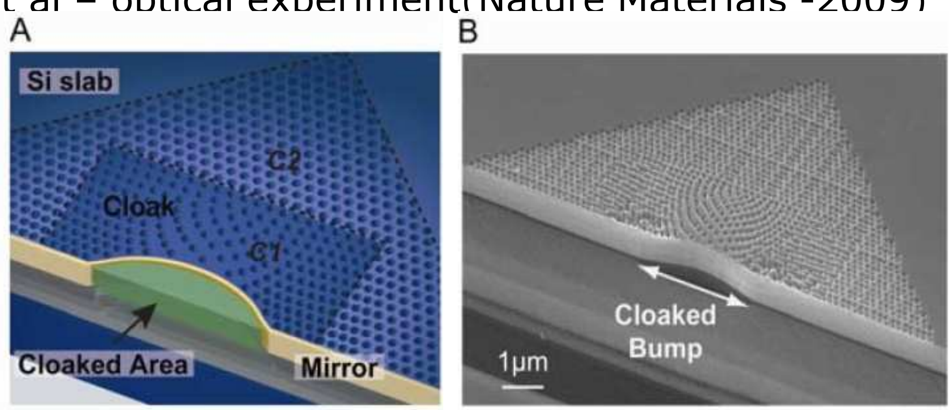
Camouflaging bumps on a metal surface



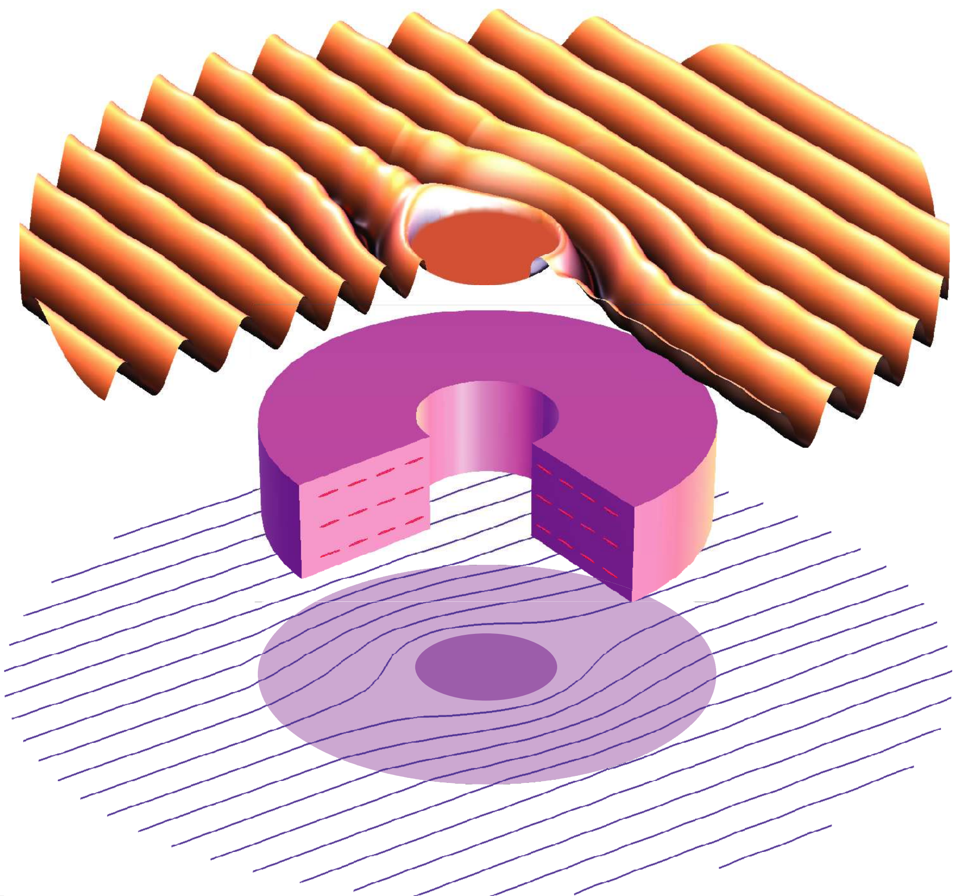


J. Li, J. B. Pendry, “Hiding under the carpet: a new strategy for cloaking”

D. Smith, et al – MW experiment (Science -2009)
Zhang et al – optical experiment(Nature Materials -2009)

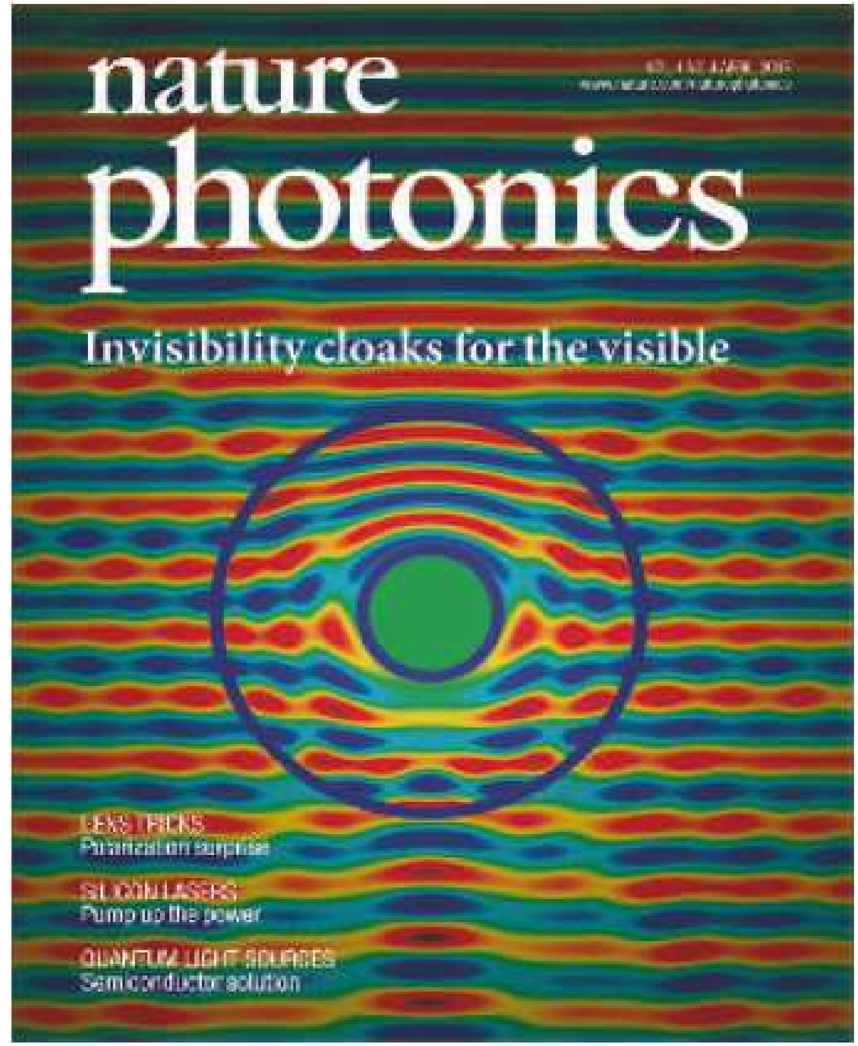


Optical Cloaking with Metamaterials: Can Objects be Invisible in the Visible?



λ = 632 nm

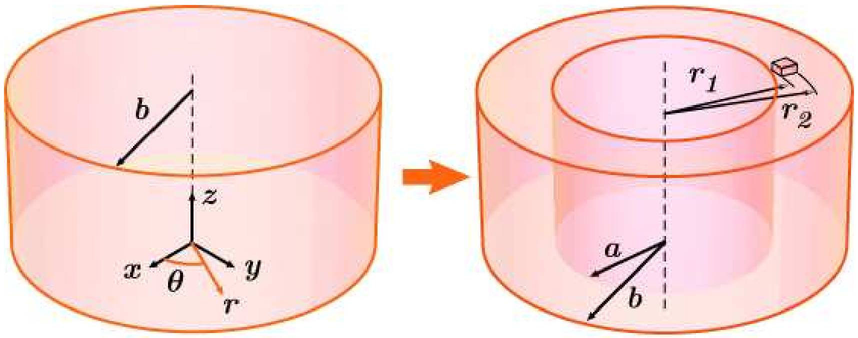
[GHz-cloak: Duke team]

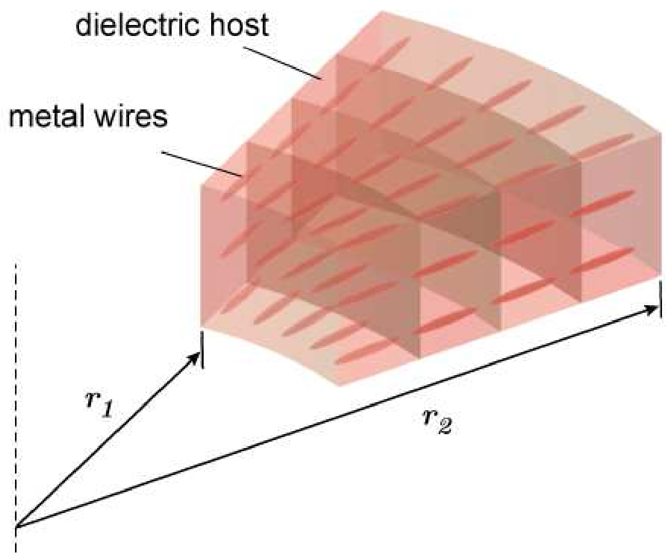


Nature Photonics (April, 2007)

Structure of optical cloak: "Round brush"

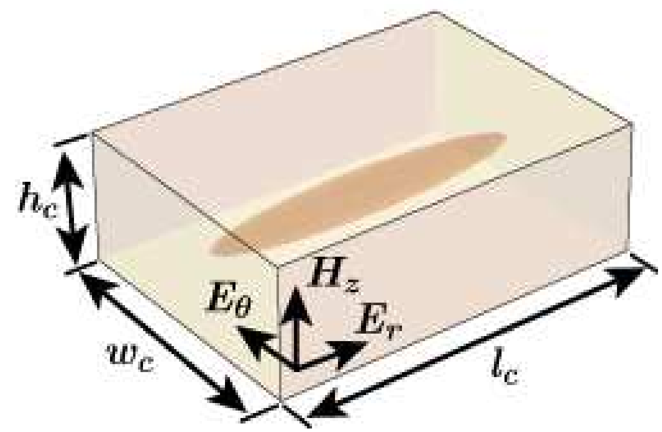
Cai, et al., Nature Photonics, 1, 224 (2007)





metal needles embedded in dielectric host

Unit cell:



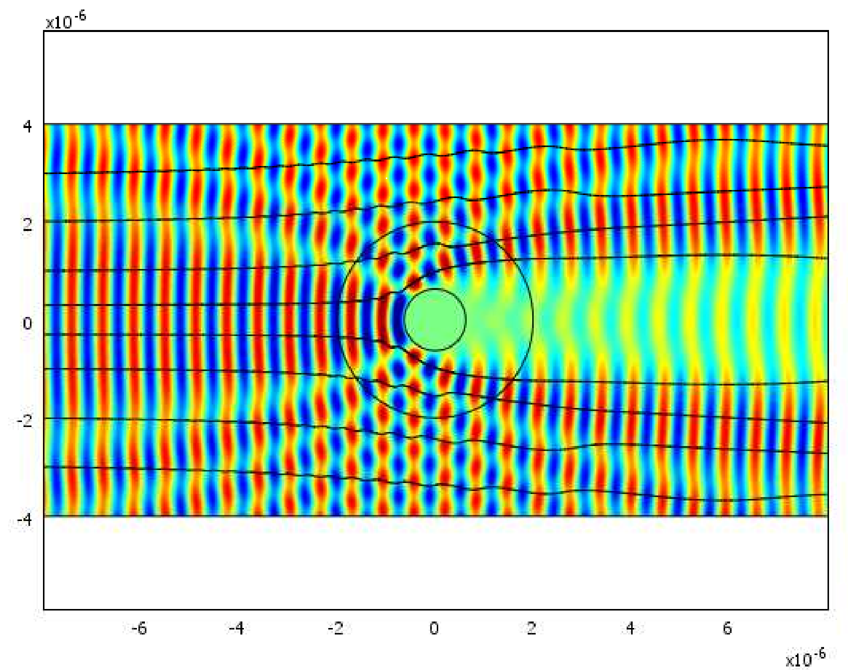
Flexible control of ε_r ;

Negligible perturbation in ε_θ

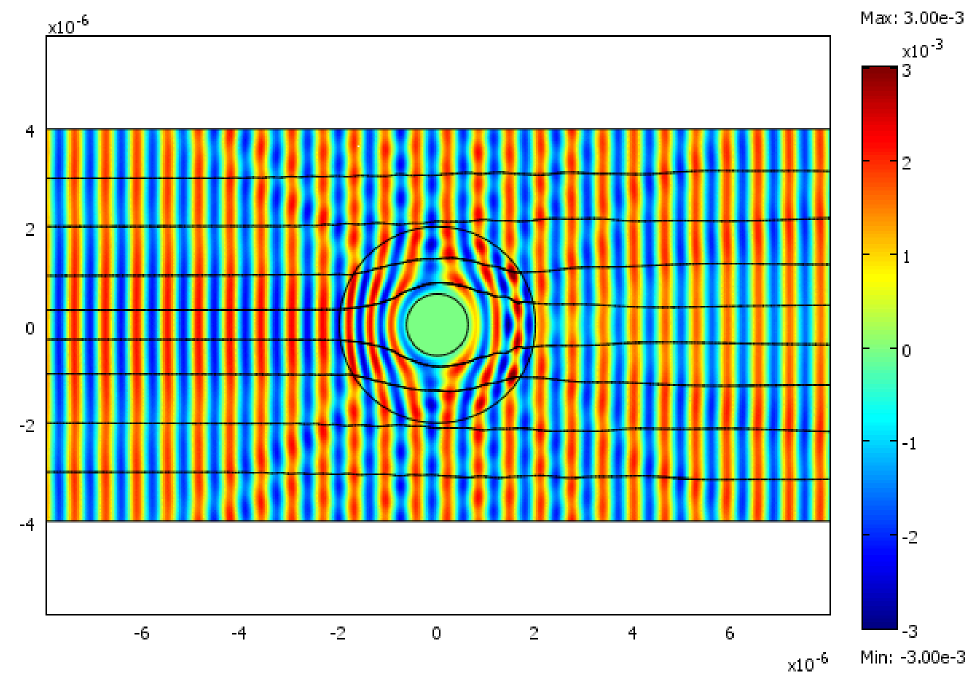
Cloaking performance: Field mapping movies

Example:

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



Cloak OFF



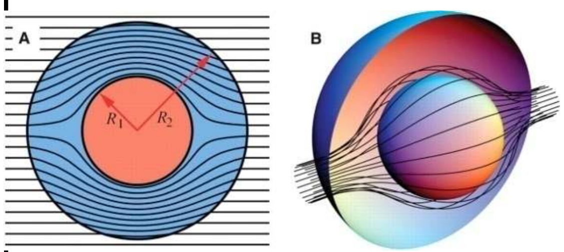
Cloak ON

Bandwidth problem in electromagnetic cloak

Fermat's principle → Curved wave trajectory → Refractive index n<1

$v_p = c/n$ → Phase velocity $v_p > c$

$v_s \leq c$ → $v_p \neq v_s$ Dispersive material



$$\frac{\Delta\omega}{\omega} \leq \frac{\Delta s}{s}$$

ω - operating frequency

$\Delta\omega$ - operating bandwidth

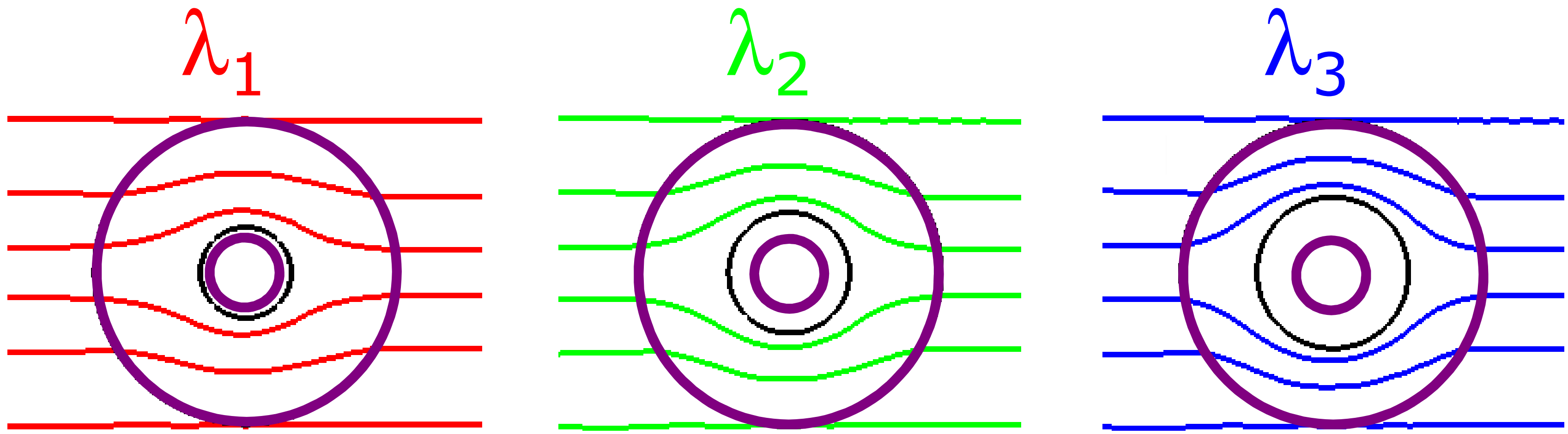
s – geometrical cross-section

Δs - scattering cross-section

For n<0, see also M. I. Stockman PRL 98, 177404 (2007)

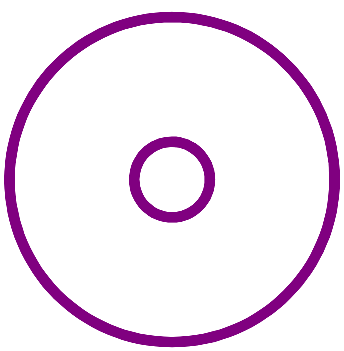
Chen, et al., PRB, 76, 241104 (2007)

Wavelength Multiplexing Cloak

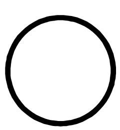


Combination of techniques:

- Virtual inner boundary
- Dispersion control
- Active medium or EIT?



Physical boundaries the cloaking device



Virtual inner boundary for different wavelengths

$$\left(\frac{\partial \varepsilon_z}{\partial \omega}\right)\left(\frac{\partial \mu_r}{\partial \omega}\right) < 0$$

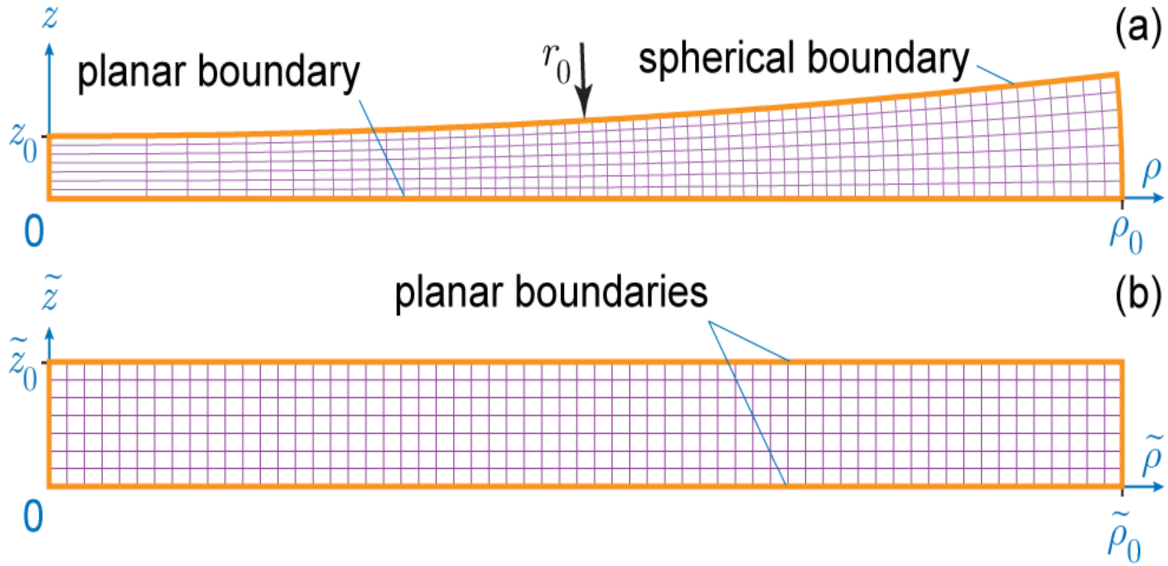
Kildishev, et al (NJP, 2008)

Broadband Optical Cloaking in Tapered Waveguides

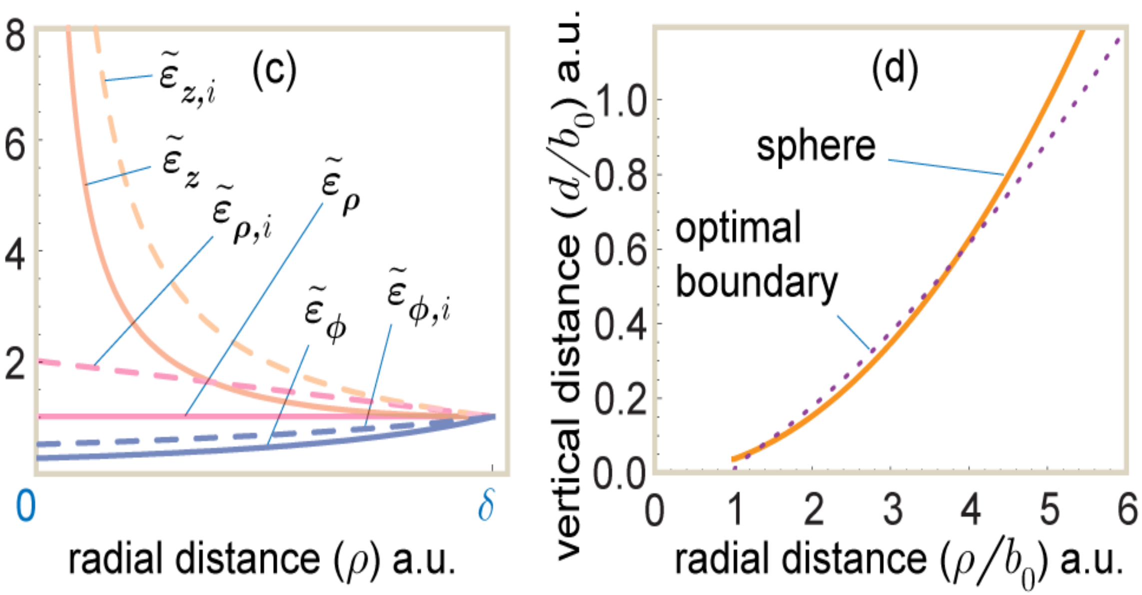
I.I. Smolayninov, V.N. Smolyaninova, A.V. Kildishev and V.M. Shalaev

(PRL , May 29, 2009)

Emulating Anisotropic Metamaterials with Tapered Waveguides



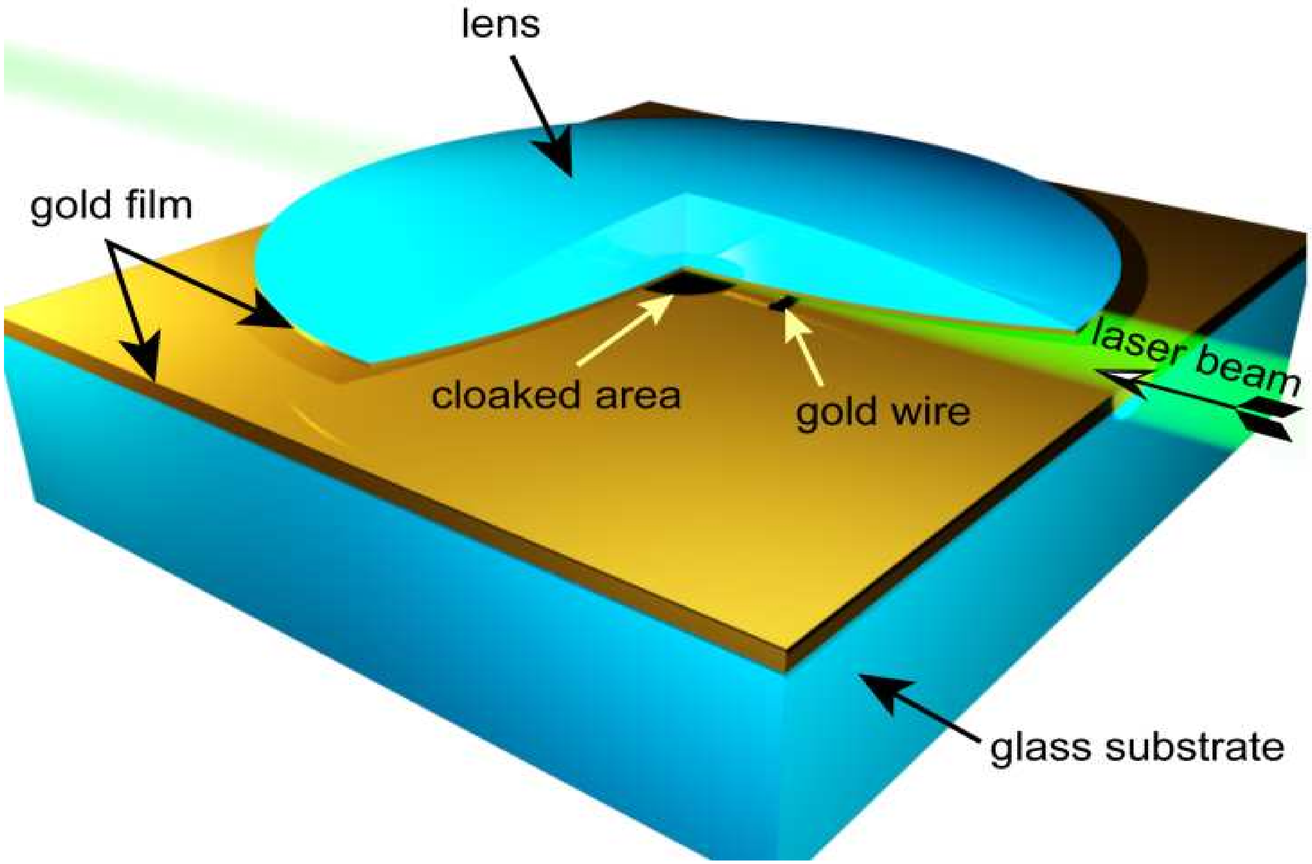
A space between a spherical and a planar surface (a) mapped onto a planar anisotropic MM (b)



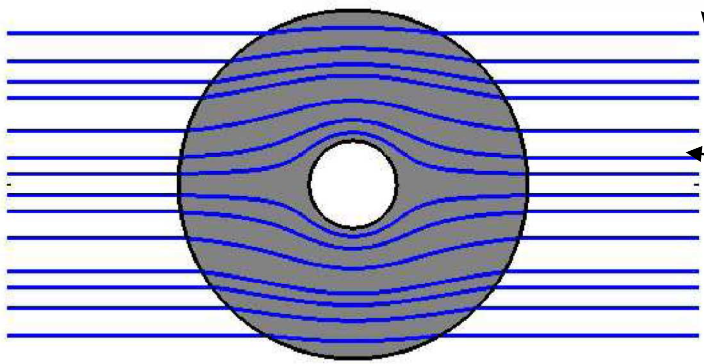
(c) Distribution of radial (top), azimuthal (middle), and axial components of ε = μ in equivalent planar MM. Dashed lines show same components in the ideal cloak.

(d) 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



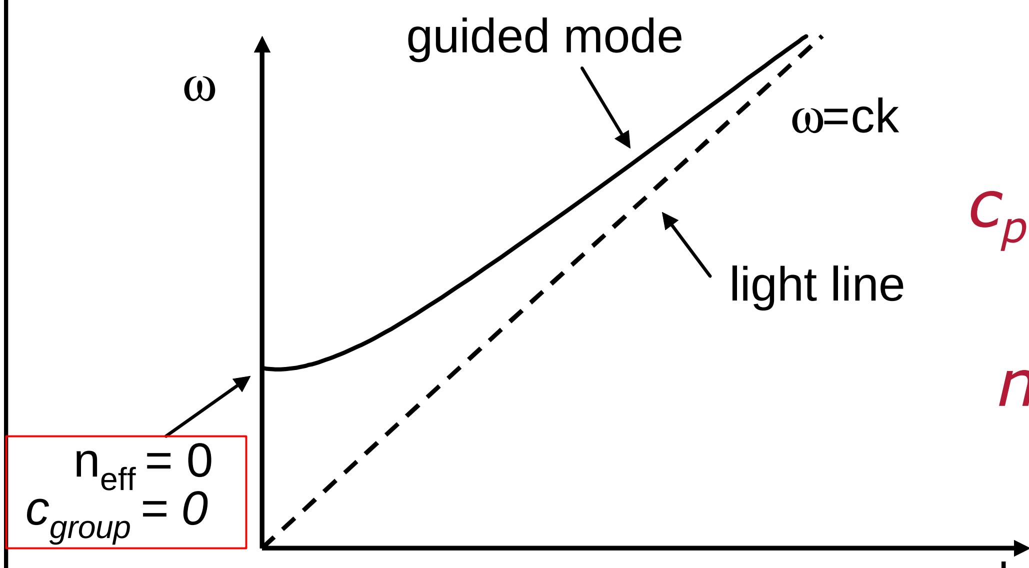
$n_{eff}L$ = const (Fermat)

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:

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

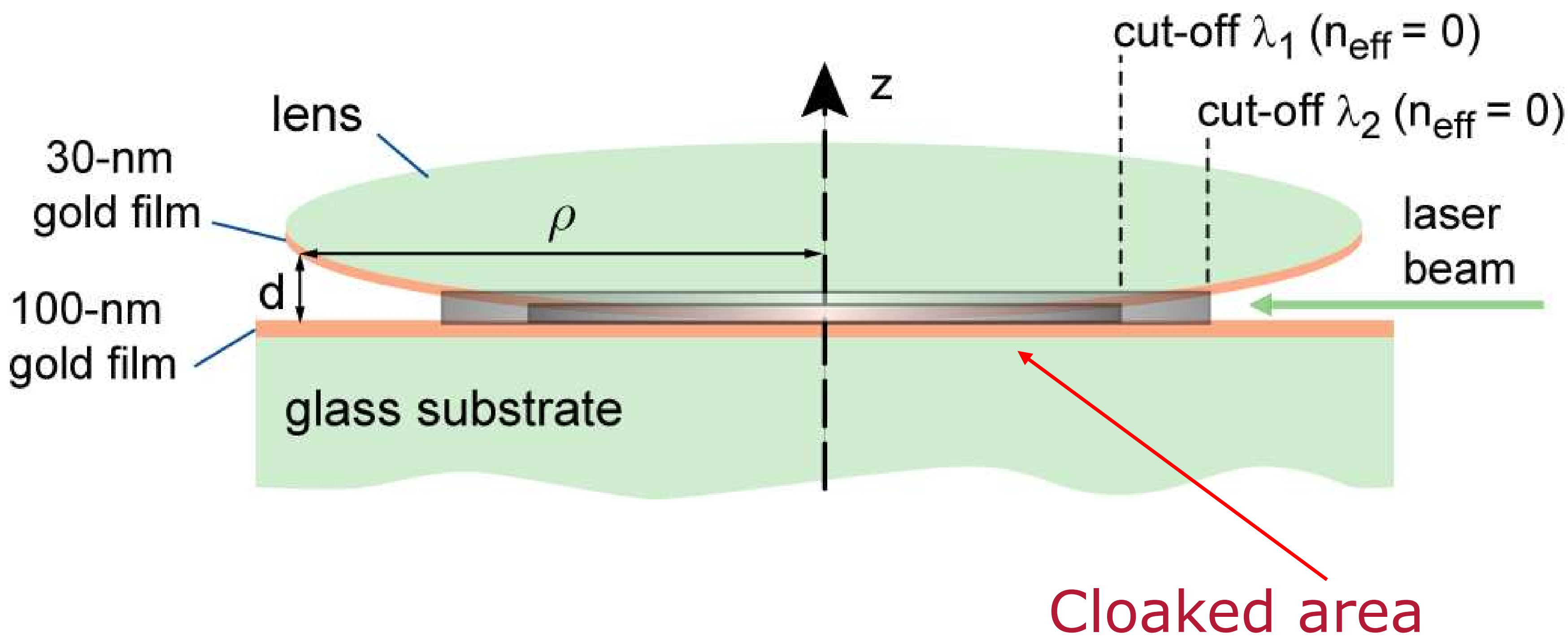


$c_{phase} = \omega/k \quad c_{group} = d\omega/dk$

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

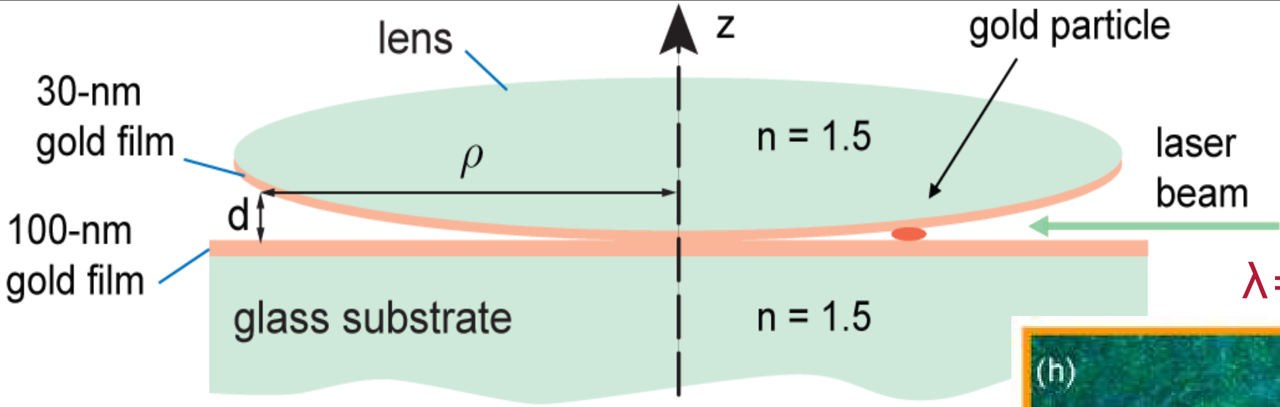
near cutoff

Broadband Cloaking in Tapered Waveguide

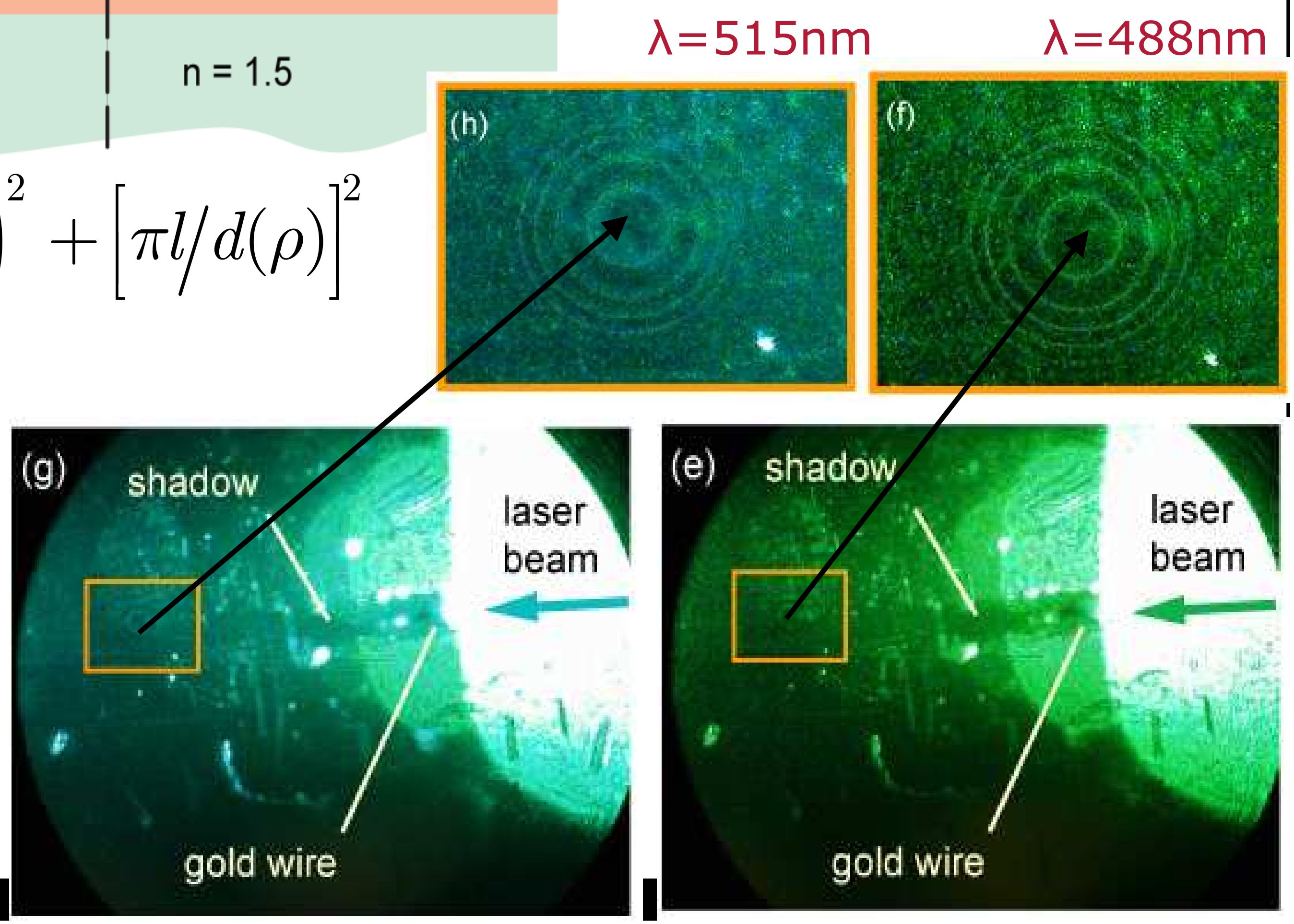


$$\left(\omega/c\right)^2 = k_\rho^2 + \left(m/\rho\right)^2 + \left[\pi l/d(\rho)\right]^2 = k_\rho^2 + k_\phi^2(\rho - b)^{-2}$$

Broadband Optical Cloak



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



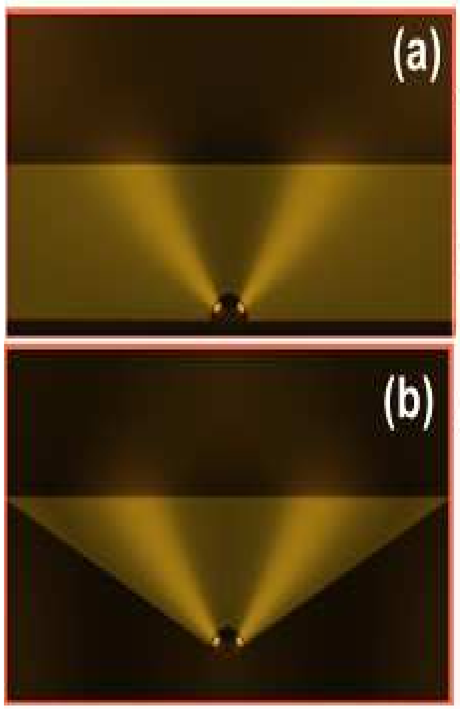
Engineering Meta-Space for Light: via Transformation Optics

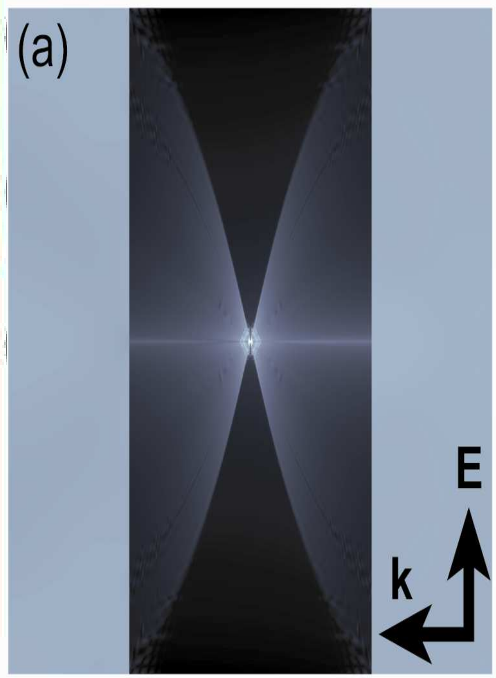
Kildishev, VMS (OL, 2008); VMS, Science 322, 384 (2008)

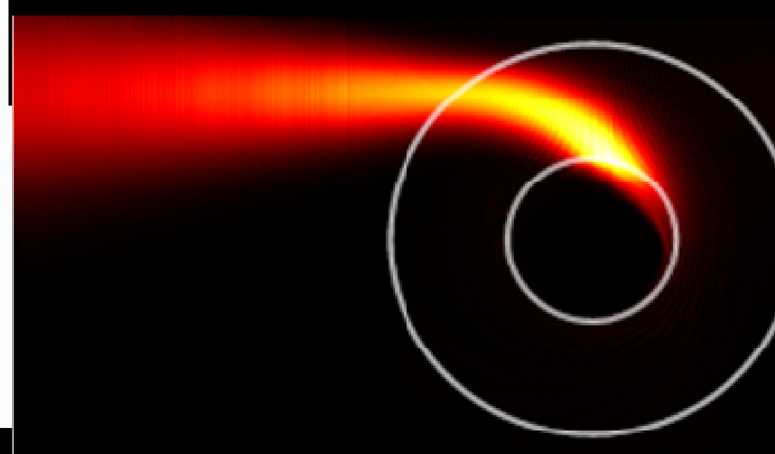
Fermat: $\delta\int n\,dl = 0$

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

curving & nano"crafting" optical space





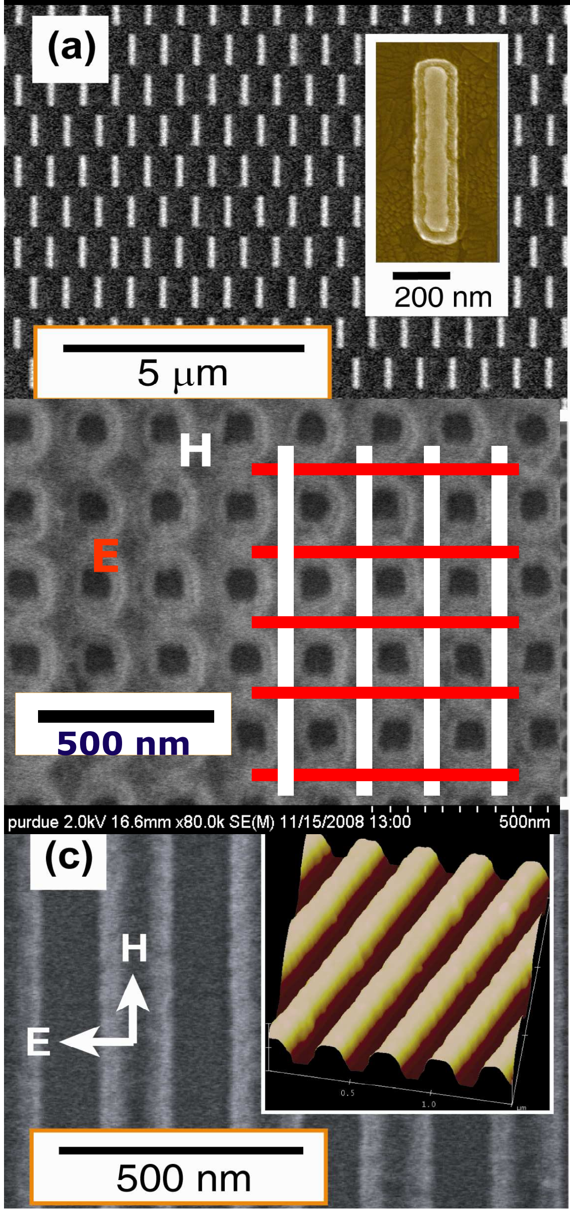


Planar hyperlens
Magnifies; no loss problem

Light concentrator
(also, Schurig et al)

Optical Black Hole
(Narimanov, Kildishev)

Highlights of Purdue "Meta-Research"



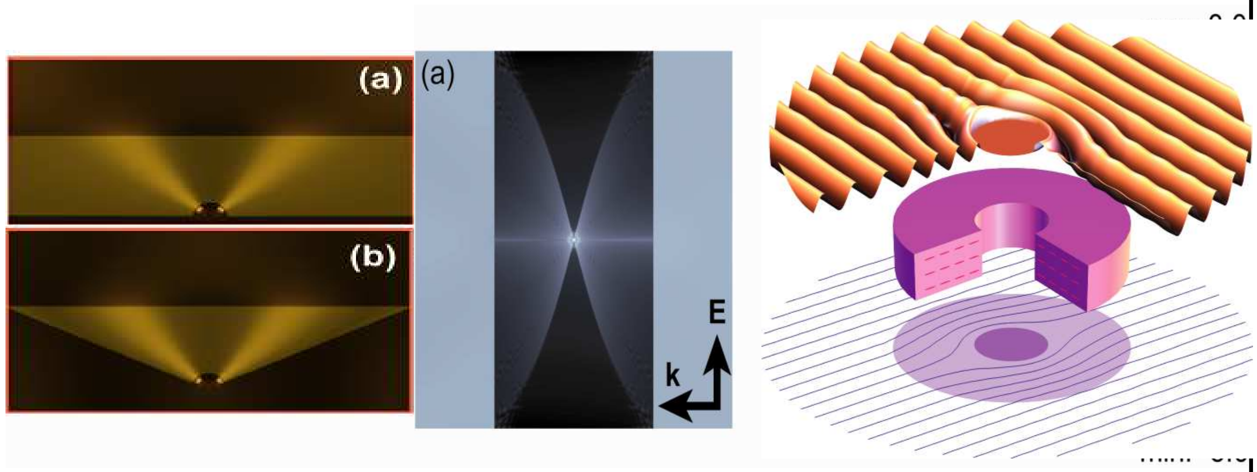
Purdue Photonic Metamaterials

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

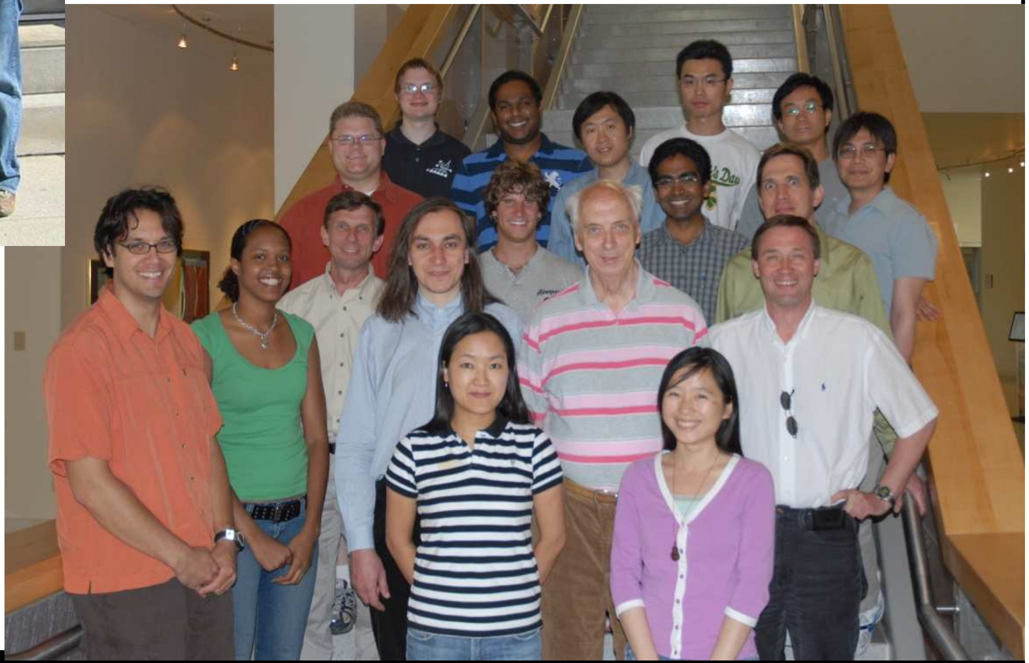
(b) Negative index MM at shortest λ (~580nm; 2009)

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

Transformation Optics with MMs:
Flat hyperlens, concentrator, and cloak

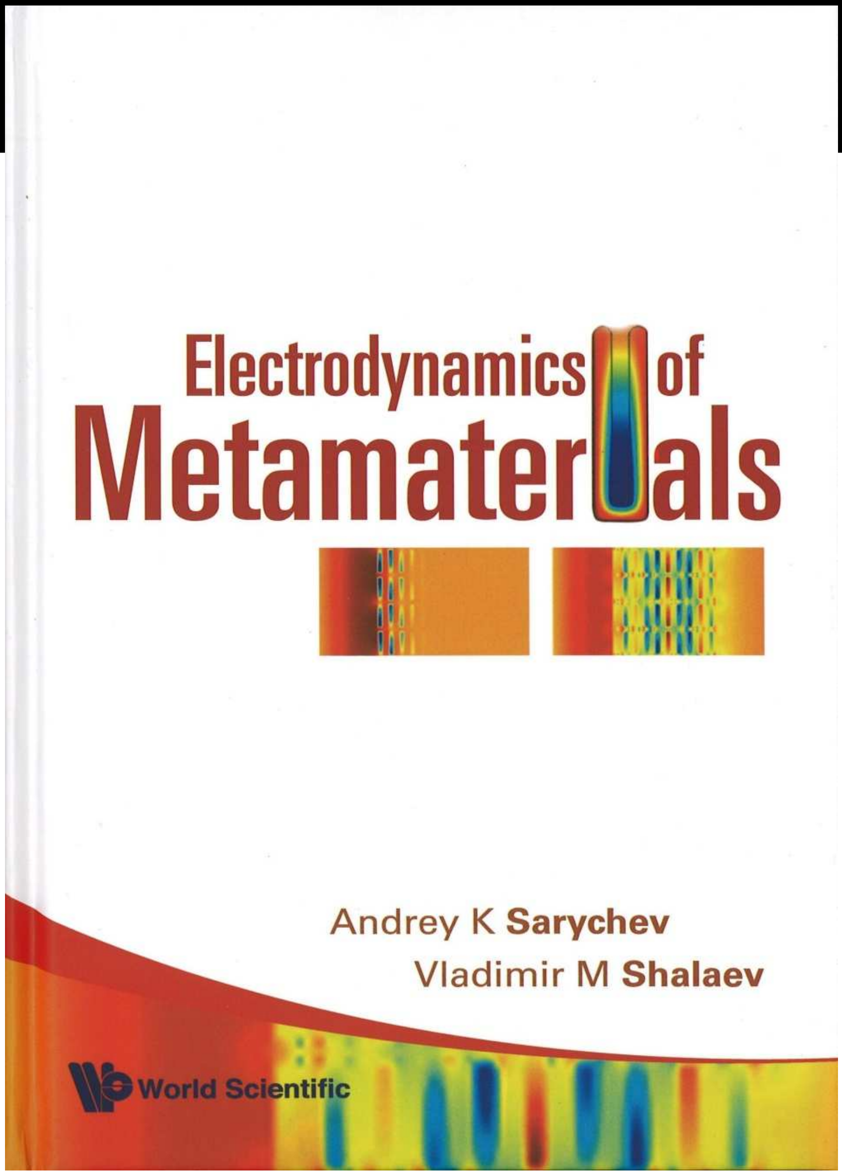


Cast of Characters:



Purdue University College of Engineering

Birck Nanotechnology Center



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