Engineering Space for Light with Metamaterials

Part 1: Electrical and Magnetic Metamaterials

Part 2: Negative-Index Metamaterials, NLO, and super/hyper-lens

<u>Part 3: Cloaking and Transformation Optics</u>

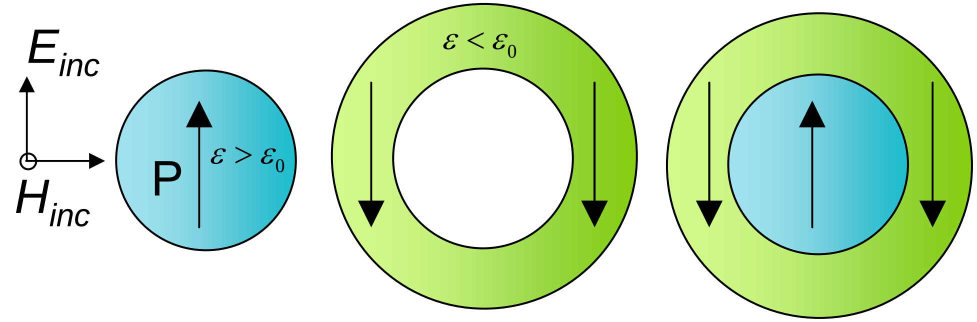
Outline

- What are metamaterials?
- Early electrical metamaterials
- Magnetic metamaterials
- Negative-index metamaterials
- Chiral metamaterials
- Nonlinear optics with metamaterials
- Super-resolution
- Optical cloaking and Transformation Optics

Other versions of cloak/invisibility/transparency

Plasmonic scattering ancellation

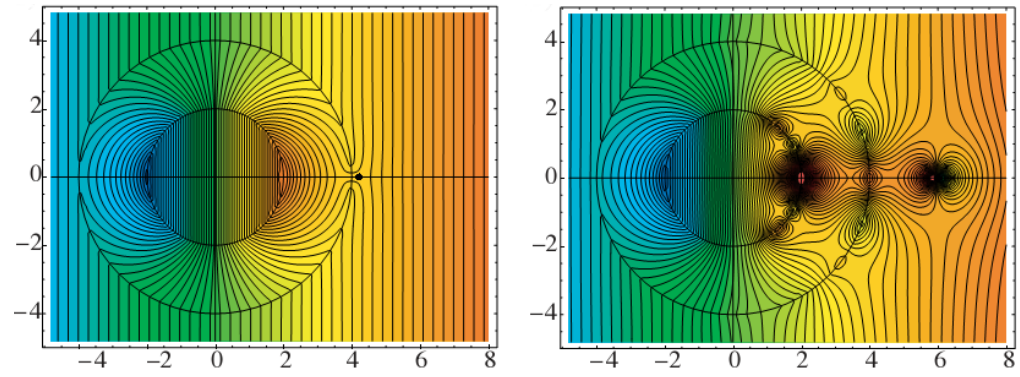
Alu and Engheta, PRE, 72, 016623, 2005



$P_{DPS} = (\varepsilon_{DPS} - \varepsilon_0) E_{inc}$ $\quad$ $P_{ENG} = (\varepsilon_{ENG} - \varepsilon_0) E_{inc}$ $\quad$ $c_1^{TM} = 0$

Anomalous localized resonance

Nicorovici, McPhedran and Milton, PRB, 1994
Milton & Nicorovici, Proc. R. Soc. A, 2006



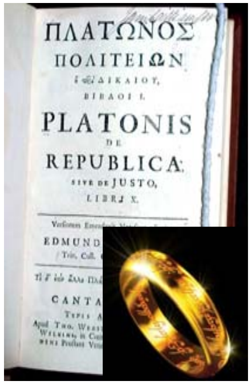
Other schemes include tunneling light transmissions (de Abajo) , active sources (Miller),invisible fish-scale structure (Zheludev et al)

Invisibility: An Ancient Dream

Perseus' helmet
(Greek mythology)

Tarnhelm of invisibility
(Norse mythology)

Cloaking devices
(Star Trek, USA)



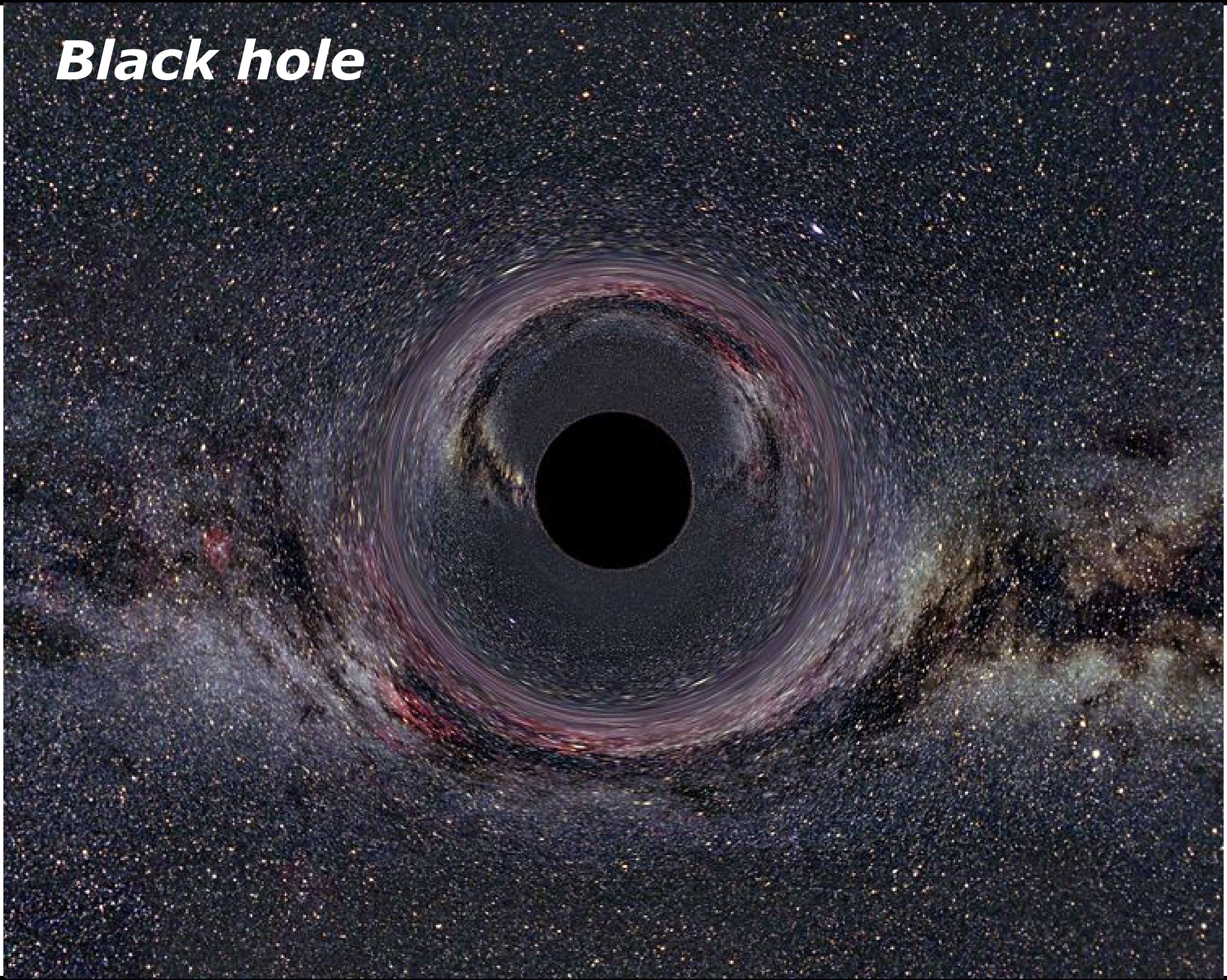
Ring of Gyges
("The Republic", Plato)

The 12 Dancing Princesses
(Brothers Grimm, Germany)

Harry Potter's cloak
(J. K. Rowling, UK)

Invisibility in Nature: Chameleon Camouflage

Invisibility by Transformation of Time-Space



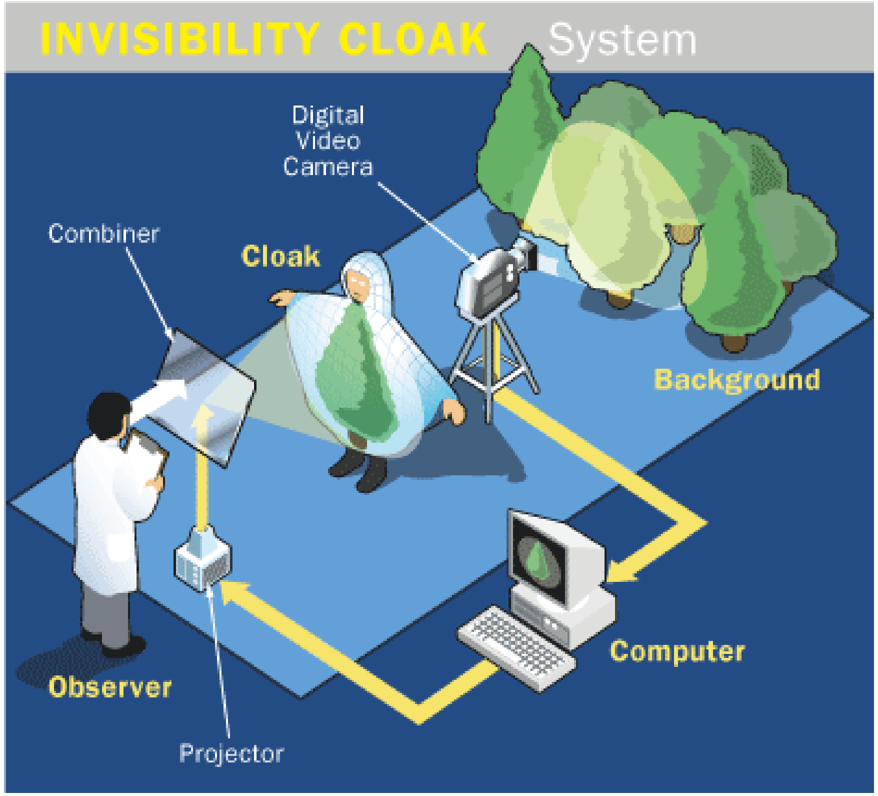
Invisibility to Radar: Stealth Technology

Stealth technique:

Radar cross-section reductions by absorbing paint / non-metallic frame / shape effect…

Optical camouflage (Tachi lab, U. Tokyo)

The camera + projector approach



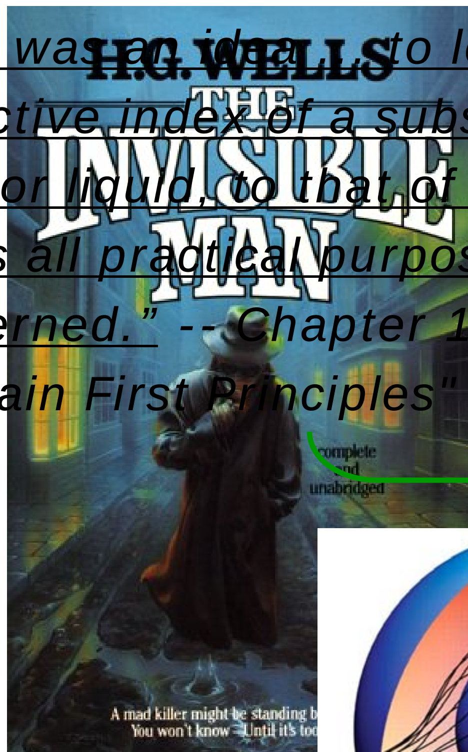
From: http://www.star.t.u-tokyo.ac.jp

Invisibility: from fiction to fact?

Examples with scientific elements:

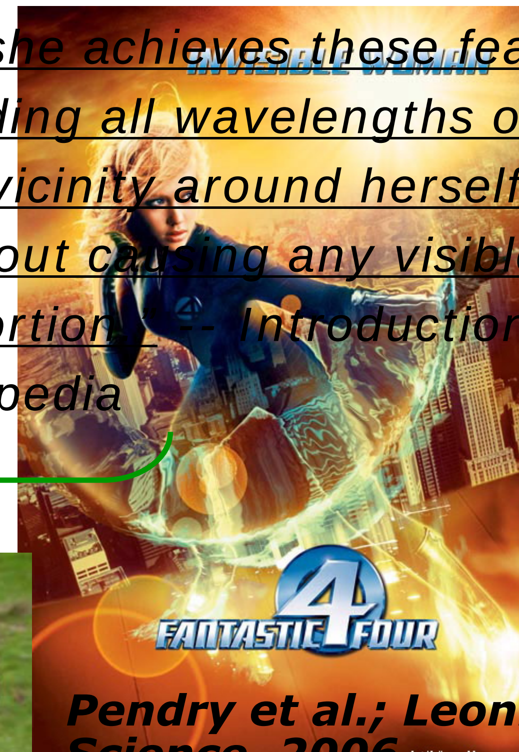
- ***The Invisible Man*** by H. G. Wells (1897)

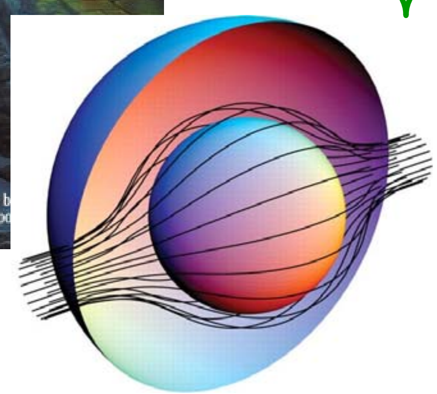
"… it was an idea … to lower the refractive index of a substance, solid or liquid, to that of air — so far as all practical purposes are concerned." -- Chapter 19 "Certain First Principles"



- **"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 work: cloak of thermal conductivity by Greenleaf et al., 2003)

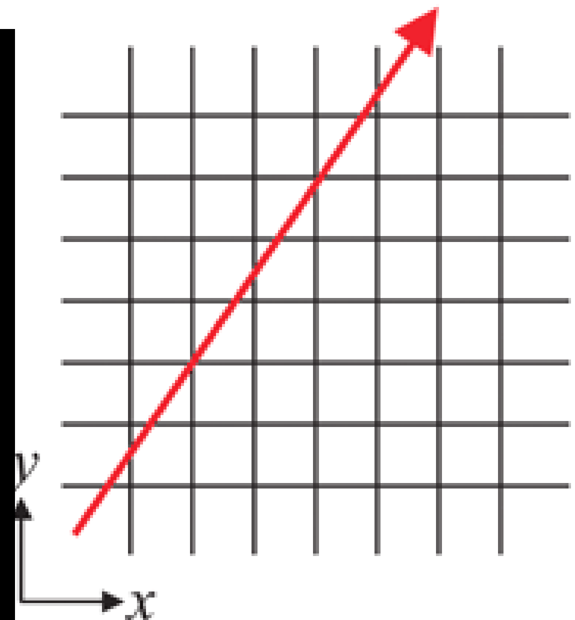
Designing Space for Light with Transformation Optics

Fermat:

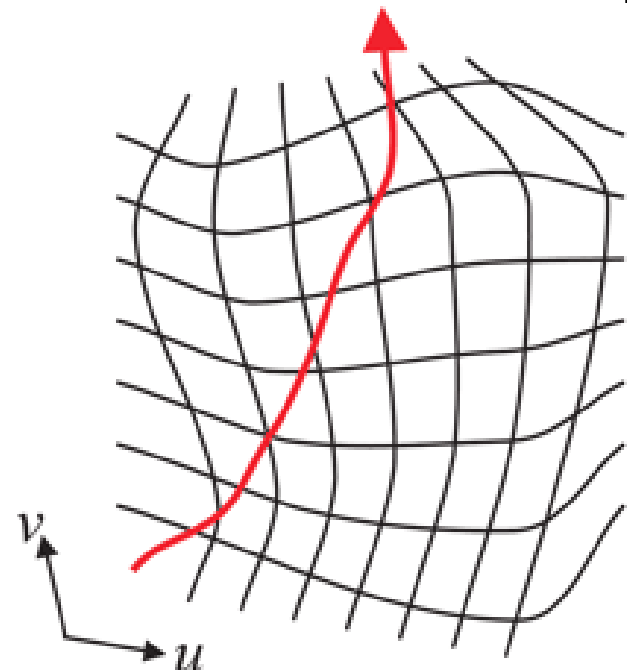
$$\delta \int n\, dl = 0$$

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

"curving" optical space



Straight field line in Cartesian coordinate



Distorted field line in distorted coordinate

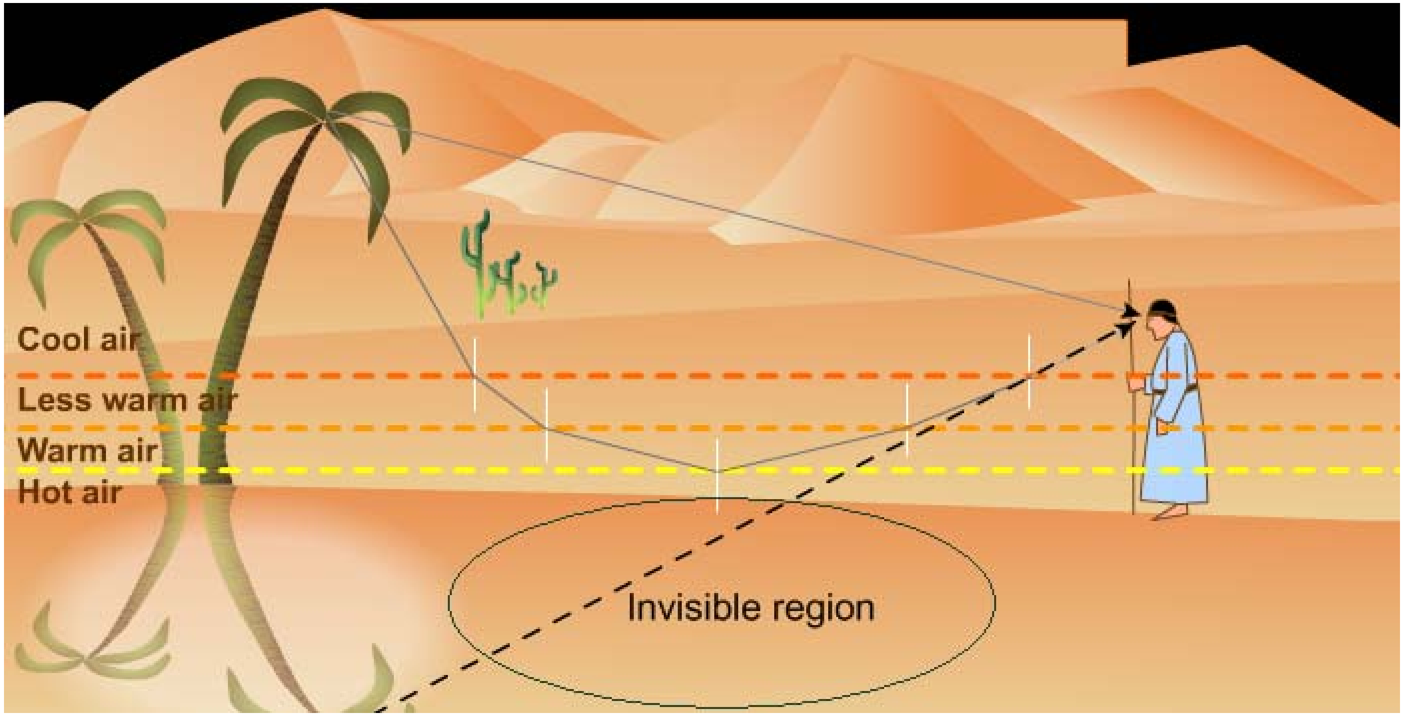
Spatial profile of ε & μ tensors determines the distortion of coordinate

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

Pendry et al., Science, 2006

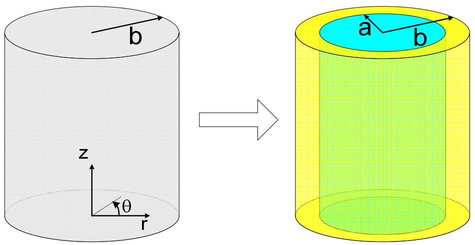
A similarity in Mother Nature

The bending of light due to the gradient in refractive index in a desert mirage



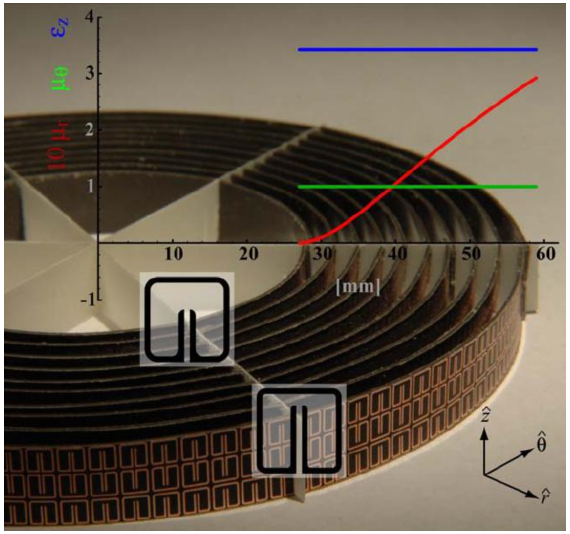
Cloaking based on coordinate transformation

General math. requirements and microwave demonstrations

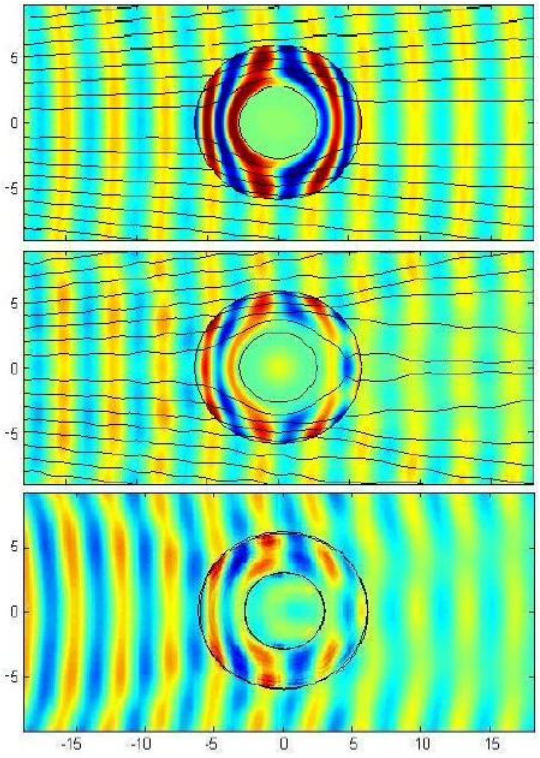


$$r \Rightarrow \frac{b-a}{b} r' + a$$

$$\begin{cases} \varepsilon_r = \mu_r = \dfrac{r-a}{r} \\ \varepsilon_\theta = \mu_\theta = \dfrac{r}{r-a} \\ \varepsilon_z = \mu_z = \left(\dfrac{b}{b-a}\right)^2 \dfrac{r-a}{r} \end{cases}$$



Structure of the cloak



Ideal case
Reduced parameter
Experimental data

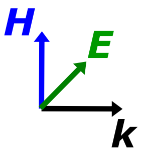
Schurig et al., Science, 2006

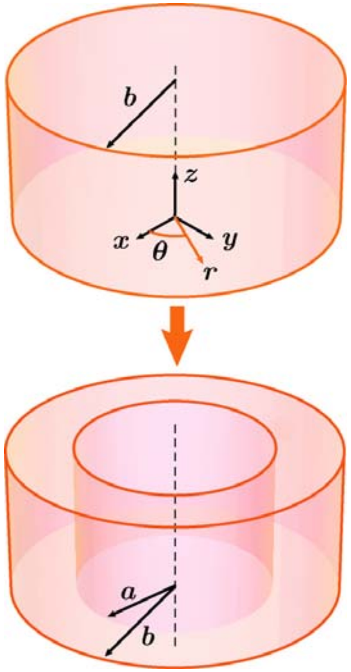
How about optical frequencies?

Scaling the microwave cloak design?

☹ ***Intrinsic limits to the scaling of SRR size***

☹ ***High loss in resonant structures***





$$\varepsilon_r = \mu_r = \frac{r-a}{r}, \quad \varepsilon_\theta = \mu_\theta = \frac{r}{r-a}, \quad \varepsilon_z = \mu_z = \left(\frac{b}{b-a}\right)^2 \frac{r-a}{r}$$

TM incidence

$$\begin{cases} \mu_z = \left(\dfrac{b}{b-a}\right)^2 \dfrac{r-a}{r} \\ \varepsilon_\theta = \dfrac{r}{r-a} \\ \varepsilon_r = \dfrac{r-a}{r} \end{cases}$$

To maintain the dispersion relation

$$\begin{cases} \mu_z \varepsilon_\theta = constant \\ \mu_z \varepsilon_r = constant \end{cases}$$

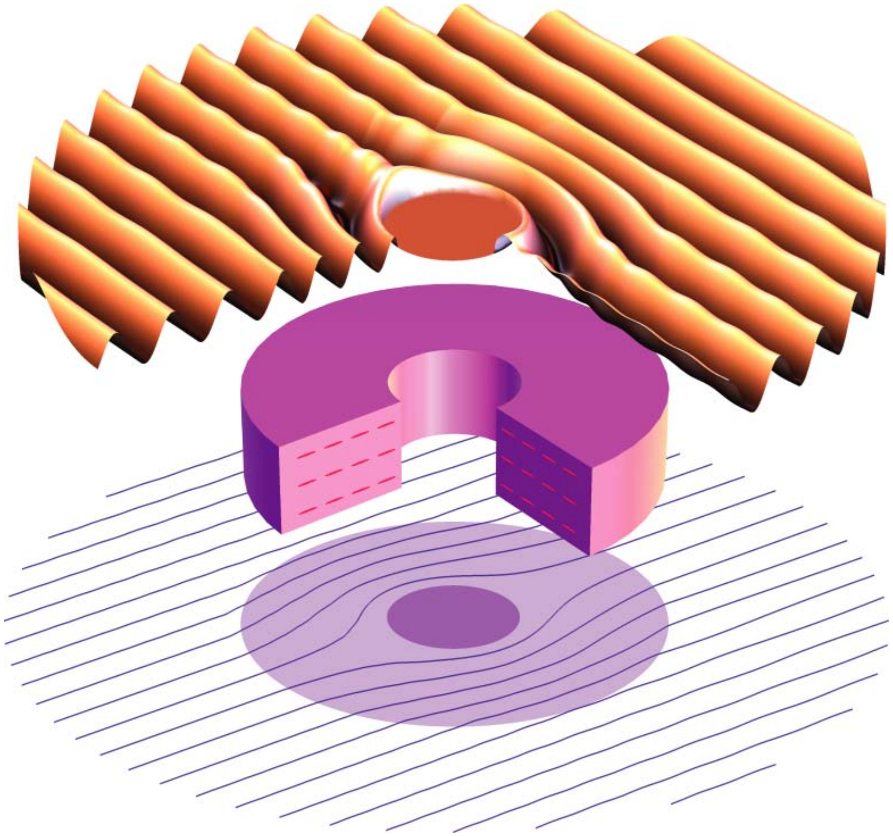
(for in-plane k)

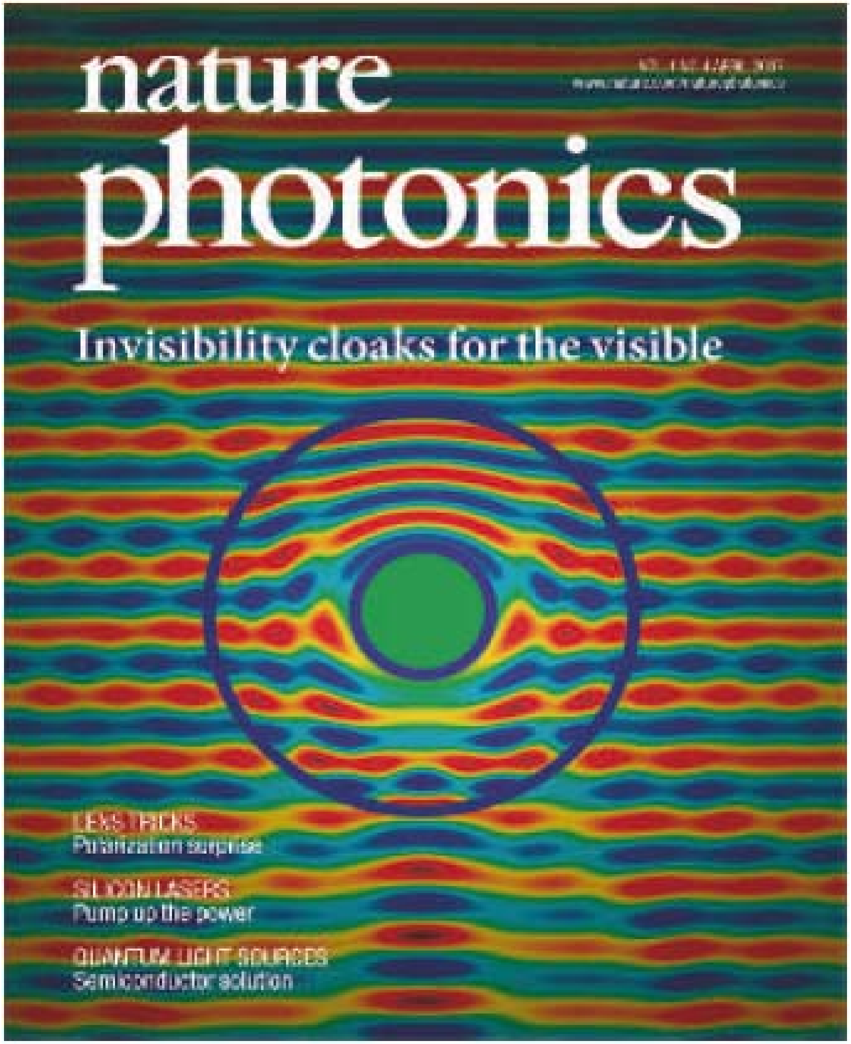
$$\begin{cases} \mu_z = 1 \\ \varepsilon_\theta = \left(\dfrac{b}{b-a}\right)^2 \\ \varepsilon_r = \left(\dfrac{b}{b-a}\right)^2 \left(\dfrac{r-a}{r}\right)^2 \end{cases}$$

- $\mu_z = 1$ → **No magnetism required!**
- ε_θ → **A constant permittivity of a dielectric; $\varepsilon_\theta > 1$**
- ε_r → **Gradient in r direction only; ε_r changing from 0 to 1.**

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

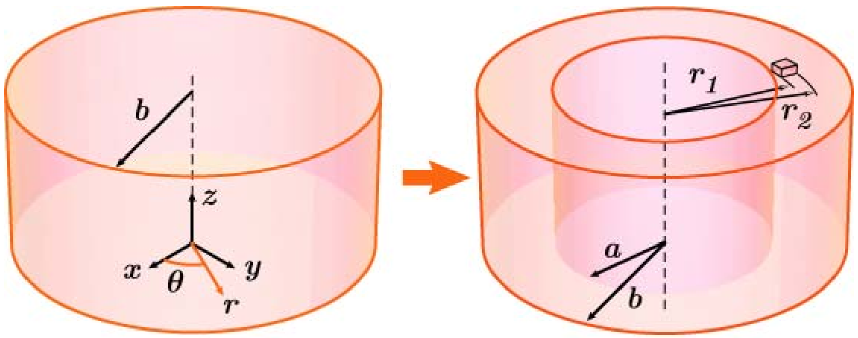
Optical Cloaking with Metamaterials: Can Objects be Invisible in the Visible?

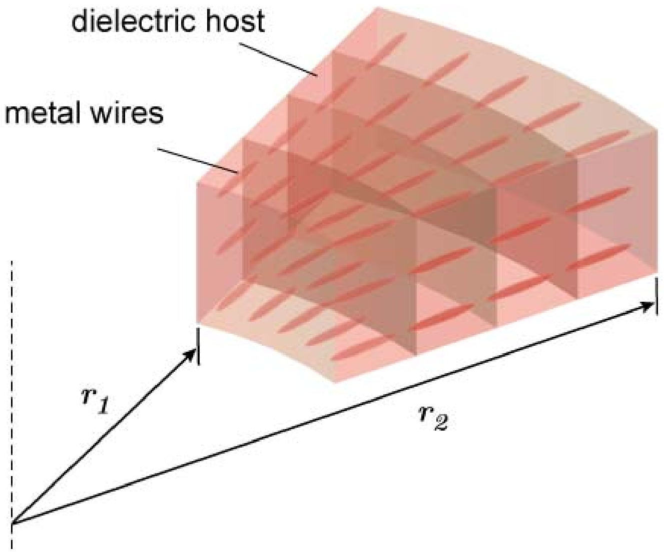




Cover article of Nature Photonics (April, 2007)

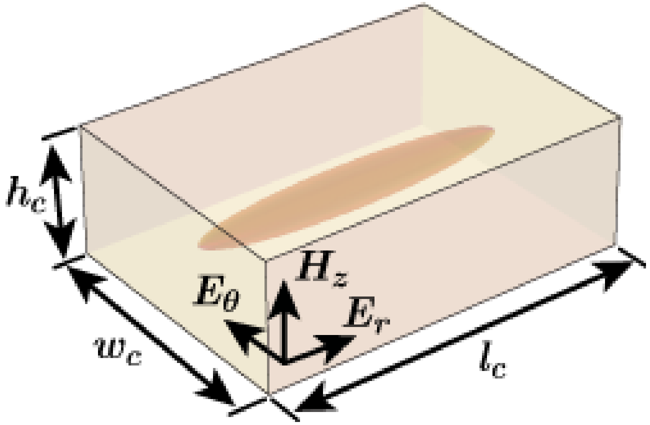
Structure of the cloak: "Round brush"





metal needles embedded in dielectric host

Unit cell:



Flexible control of ε_r ;

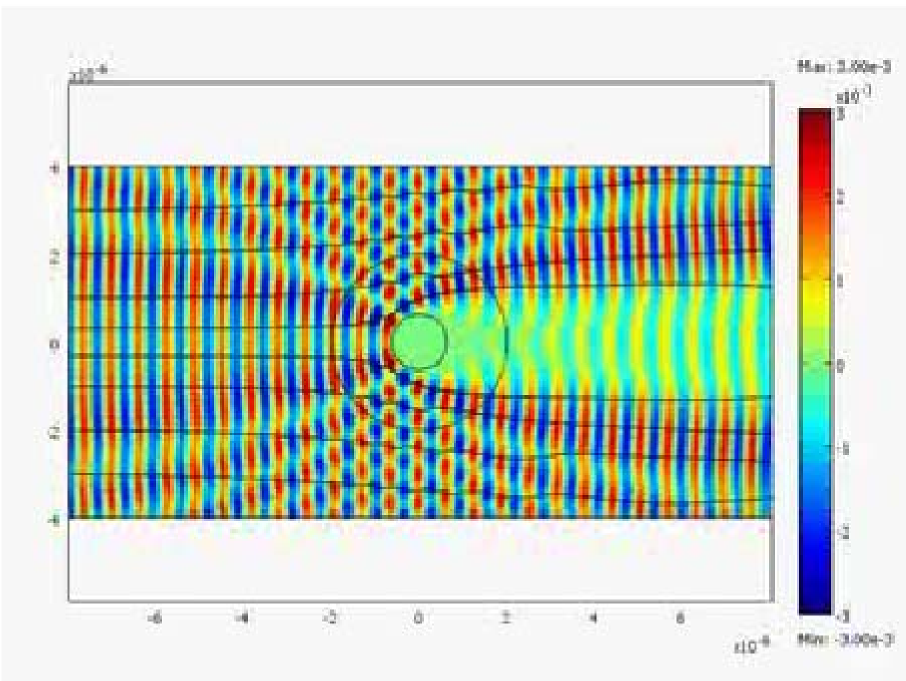
Negligible perturbation in ε_θ

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

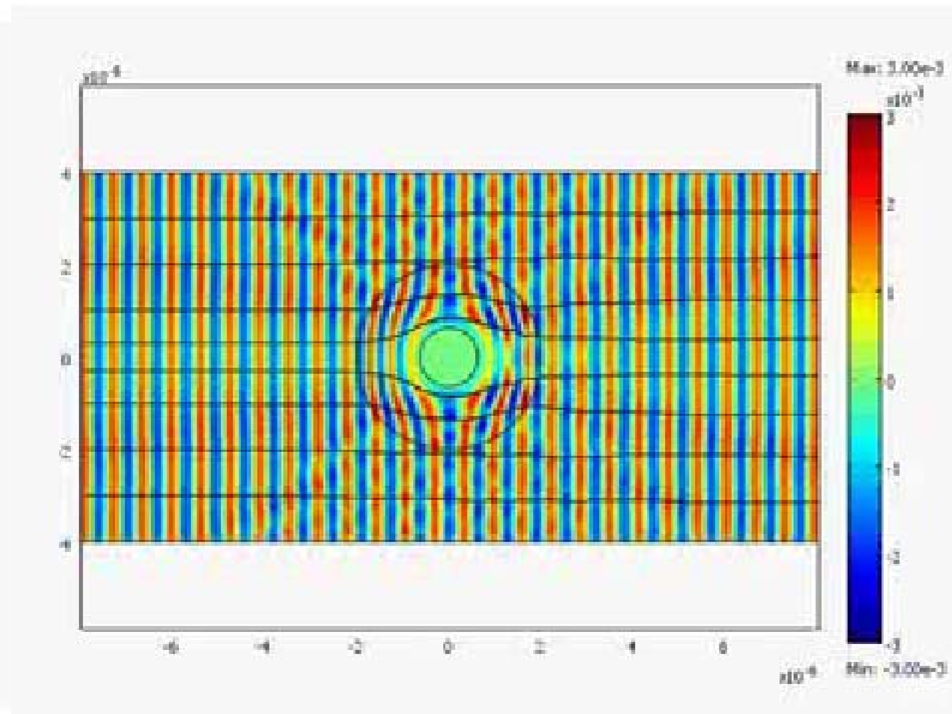
Cloaking performance: Field mapping movies

Example:

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

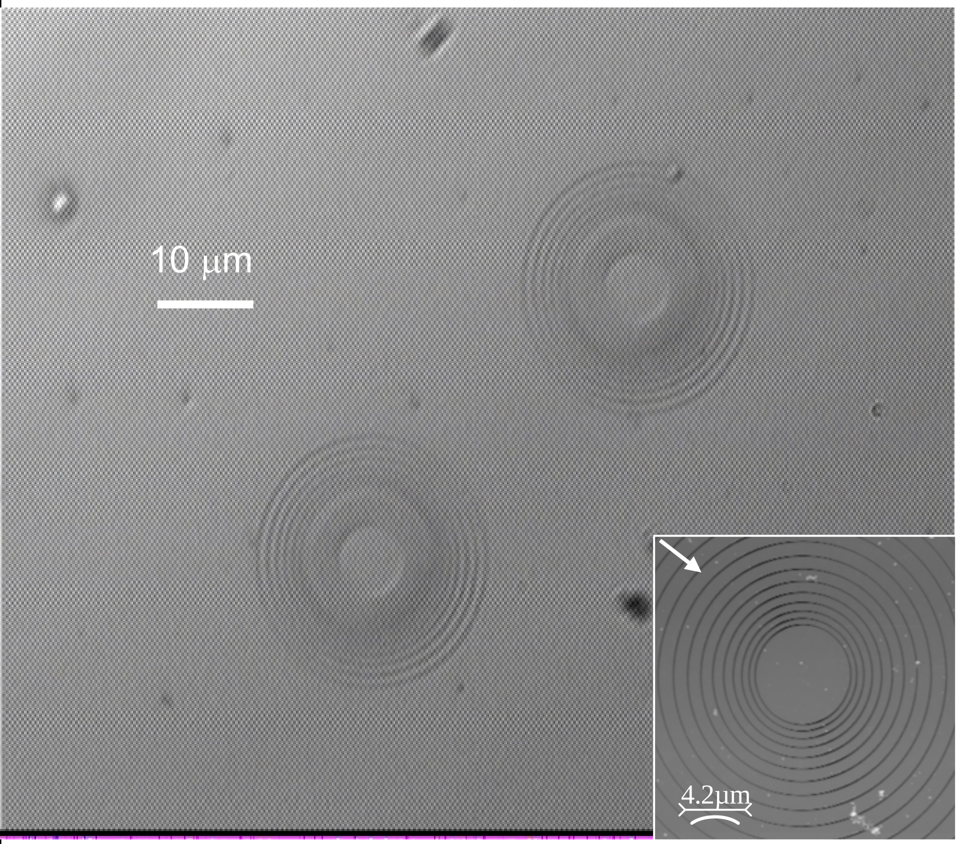


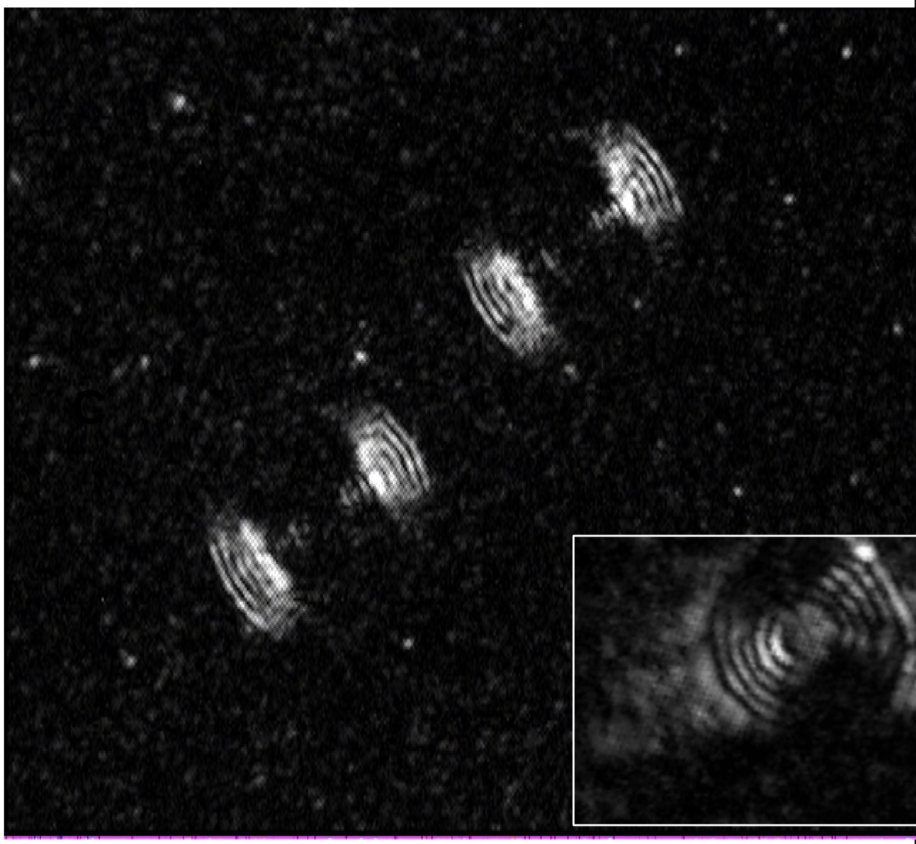
Cloak OFF



Cloak ON

Plasmonic cloaking (Smolyaninov et al - collaboration)

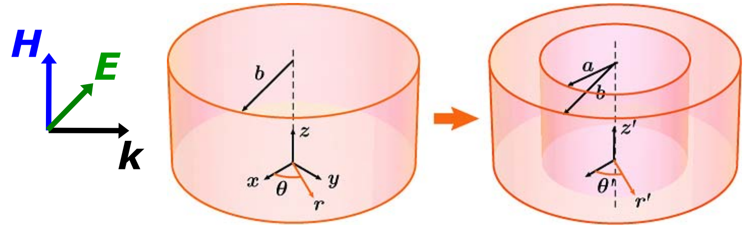


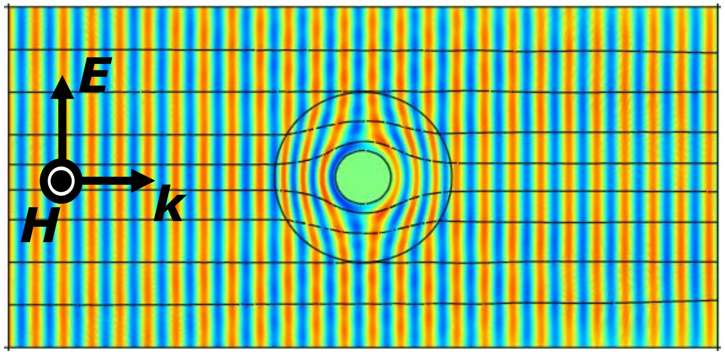


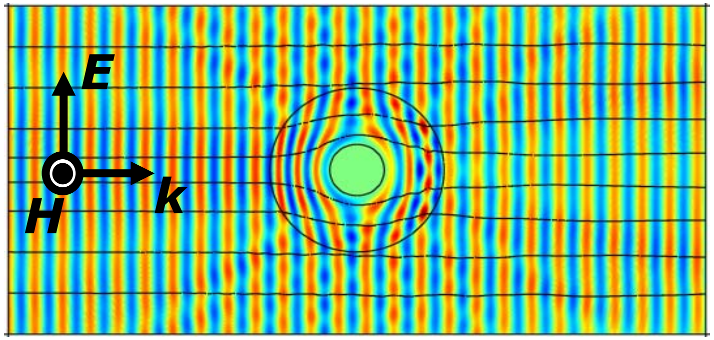
Scattering issue in a linear non-magnetic cloak

Linear transformation

$$r = \frac{b-a}{b} r' + a$$







Ideal cloak:

$$Z\big|_{r=b} = \sqrt{\mu_z / \varepsilon_\theta}\,\Big|_{r=b} = 1$$

Perfectly matched impedance results in zero scattering

Linear non-magnetic cloak:

$$Z\big|_{r=b} = \sqrt{\mu_z / \varepsilon_\theta}\,\Big|_{r=b} = 1 - a/b$$

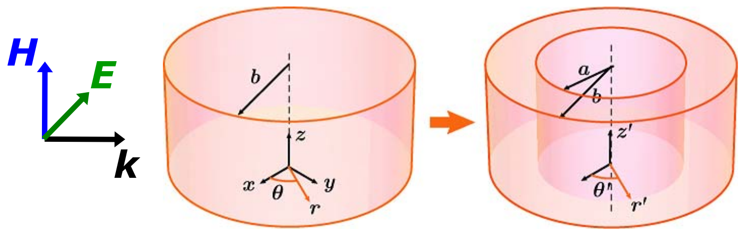
Detrimental scattering due to impedance mismatch

Nonlinear transformation –> no scattering

High-order transformations to minimize scattering

Linear transformation

$$r = \frac{b-a}{b} r' + a$$



Nonlinear transformation

$r = g(r')$ → $g(0) = a;\ \ g(b) = b;\ \ \partial g(r')/\partial r' > 0$

↓

Jacobian Matrix

↓

ε And μ tensors for ideal cloak →

$$\begin{cases} \varepsilon_r = \mu_r = \left(r'/r\right) \partial g(r')/\partial r' \\ \varepsilon_\theta = \mu_\theta = \left(r/r'\right)\left[\partial g(r')/\partial r'\right]^{-1} \\ \varepsilon_z = \mu_z = \left(r'/r\right)\left[\partial g(r')/\partial r'\right]^{-1} \end{cases}$$

↓

Corresponding non-magnetic parameters →

$$\varepsilon_r = \left(r'/r\right)^2;\ \ \varepsilon_\theta = \left[\partial g(r')/\partial r'\right]^{-2};\ \ \mu_z = 1$$

↓

Set Z=1 at r=b to fix g(r′) →

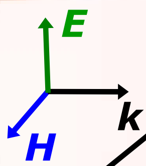
$$Z\big|_{r=b} = \sqrt{\mu_z/\varepsilon_\theta}\Big|_{r=b} = \partial g(r')/\partial r'\Big|_{r=b} = 1$$

Cai, et al., App. Phys. Lett, 91, 111105 (2007)

Designs of optical cloak with **high-order** transformations

Examples in cylindrical system

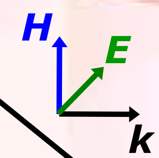
$$\varepsilon_r = \mu_r = \left(r'/r\right)\partial g(r')/\partial r' ;\ \varepsilon_\theta = \mu_\theta = 1/\varepsilon_r ;\ \varepsilon_z = \mu_z = \left(r'/r\right)\left[\partial g(r')/\partial r'\right]^{-1}$$



TE Simplification

$$n_\theta = \sqrt{\varepsilon_z \mu_r}$$
$$n_r = \sqrt{\varepsilon_z \mu_\theta}$$

$$\mu_r = \left(r'/r\right)^2 \left[\partial g(r')/\partial r'\right]^2$$
$$\mu_\theta = 1$$
$$\varepsilon_z = \left[\partial g(r')/\partial r'\right]^{-2}$$



TM Simplification

$$n_\theta = \sqrt{\mu_z \varepsilon_r}$$
$$n_r = \sqrt{\mu_z \varepsilon_\theta}$$

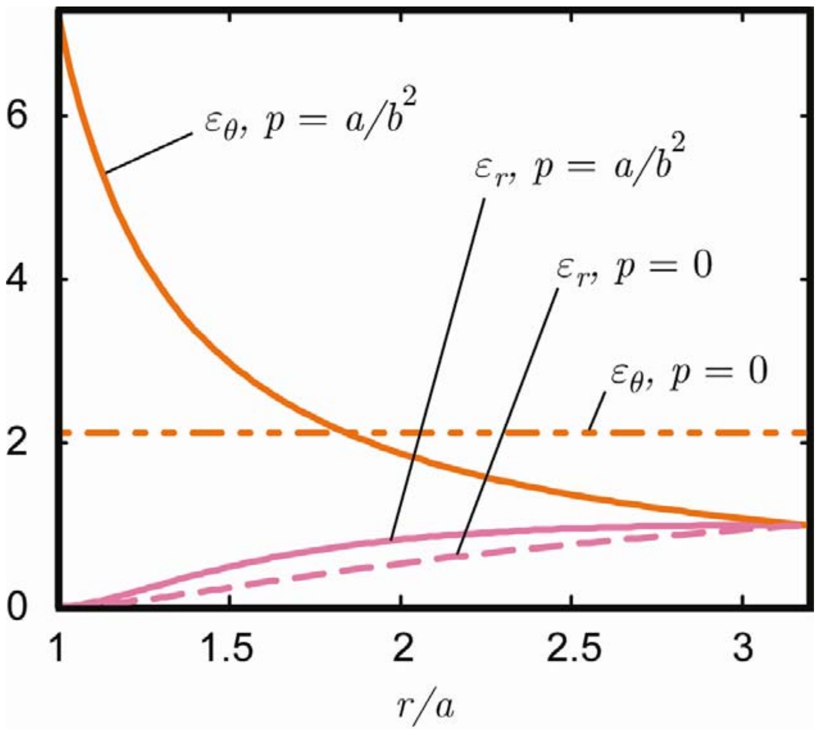
$$\varepsilon_r = \left(r'/r\right)^2$$
$$\varepsilon_\theta = \left[\partial g(r')/\partial r'\right]^{-2}$$
$$\mu_z = 1$$

Cai, et al APL (2008)

Example: Optimized quadratic transformation

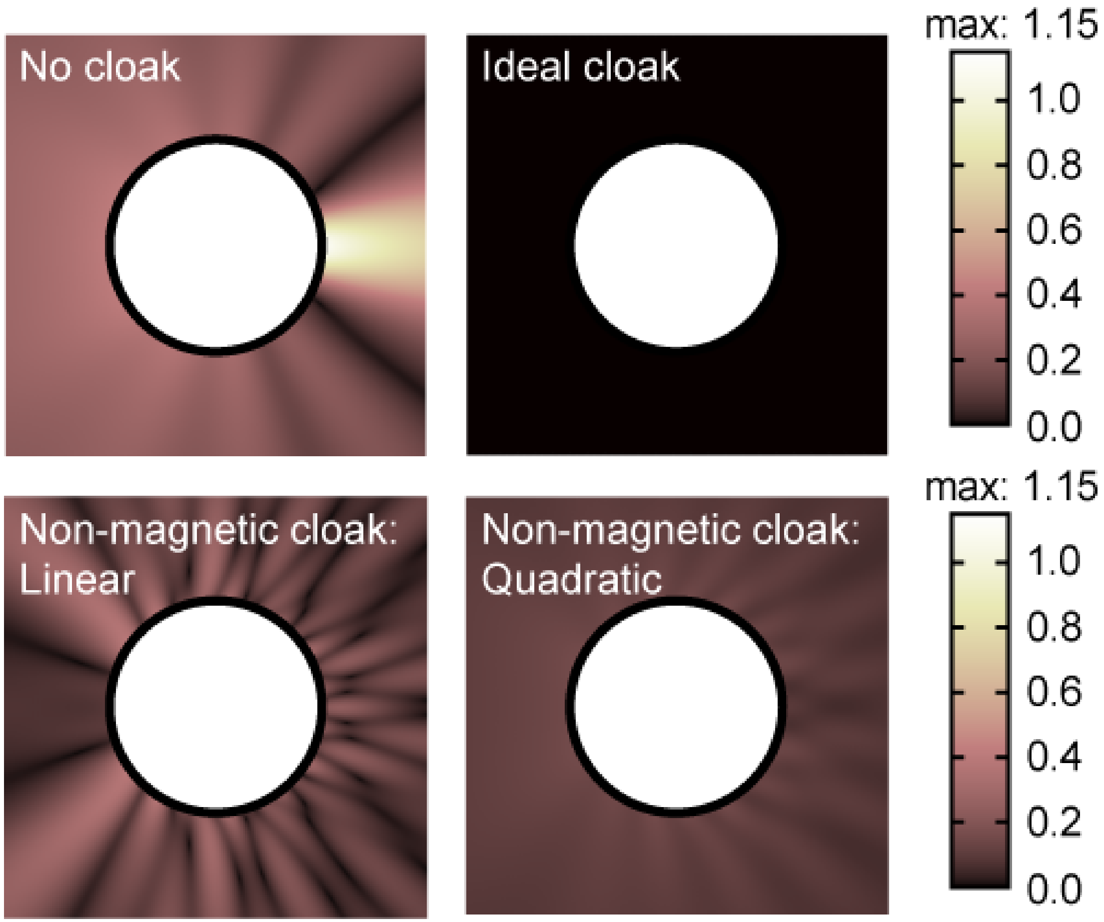
A second-order transformation for non-magnetic cloak with minimized scattering

$$r = g(r') = \left[1 - a/b + p\left(r' - b\right)\right] r' + a \qquad \textit{with} \qquad p = a/b^2$$



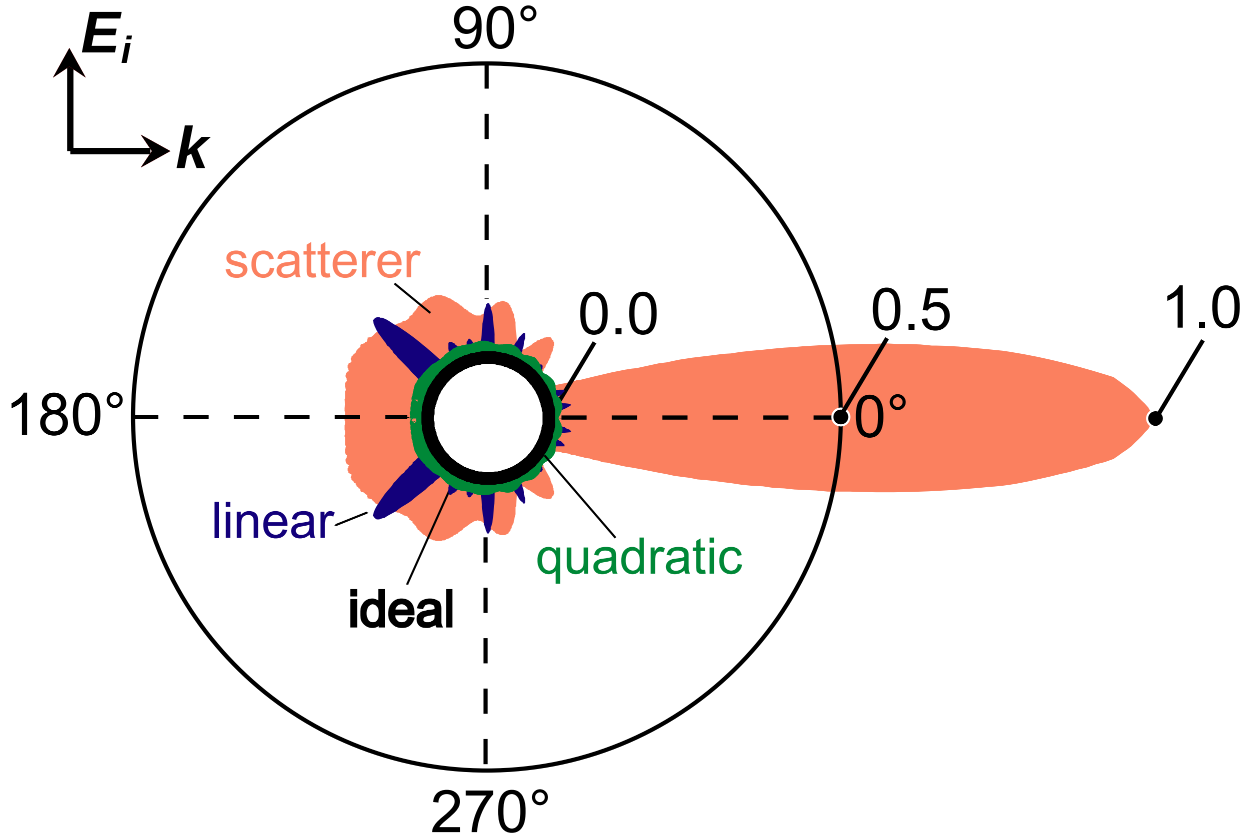
Reduced scattering from nonlinear cloak

Normalized scattered field



Suppression in both magnitude and directivity

Scattering radiation pattern

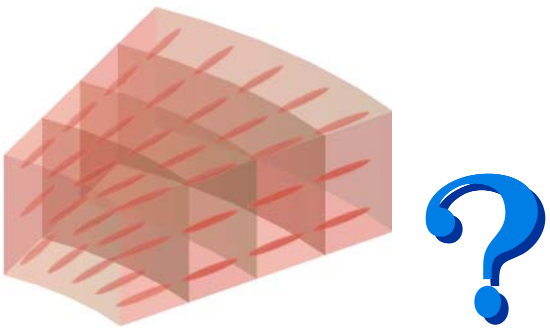


Towards experimental realization

We need a design that is …

- ***Less complicated in fabrication***

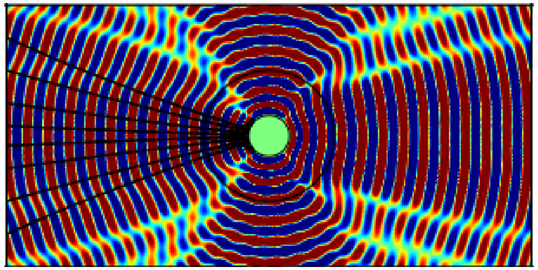
Compatibility with mature fabrication techniques like direct deposition and direct etching

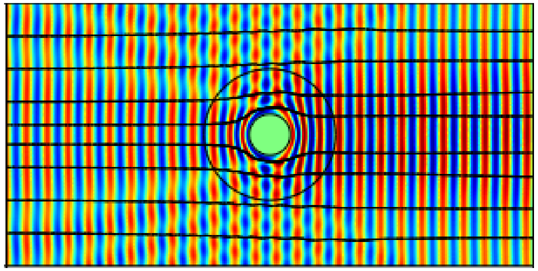


- ***Better loss features***

Loss might be ultimate limiting issue for cloaking

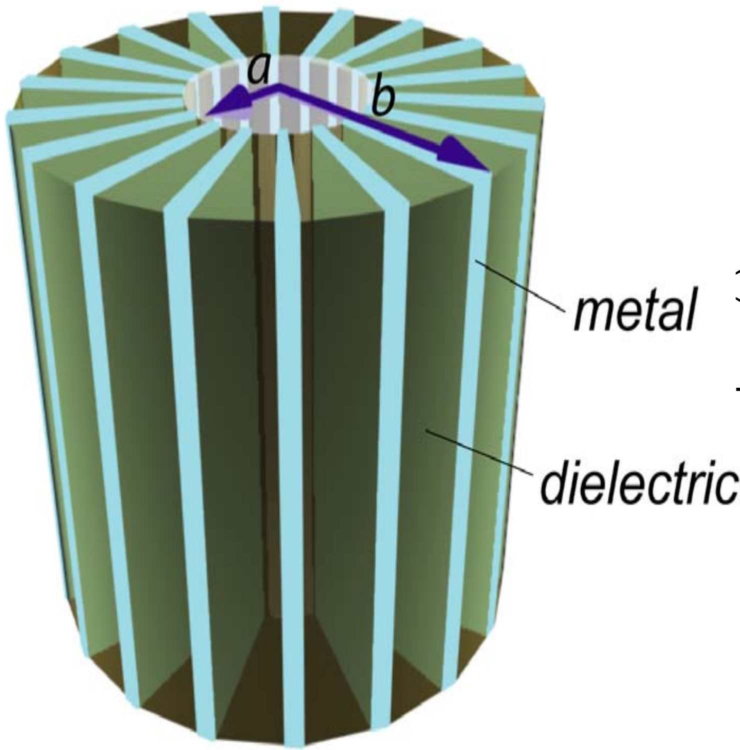
$\varepsilon_r'' = 0.1$

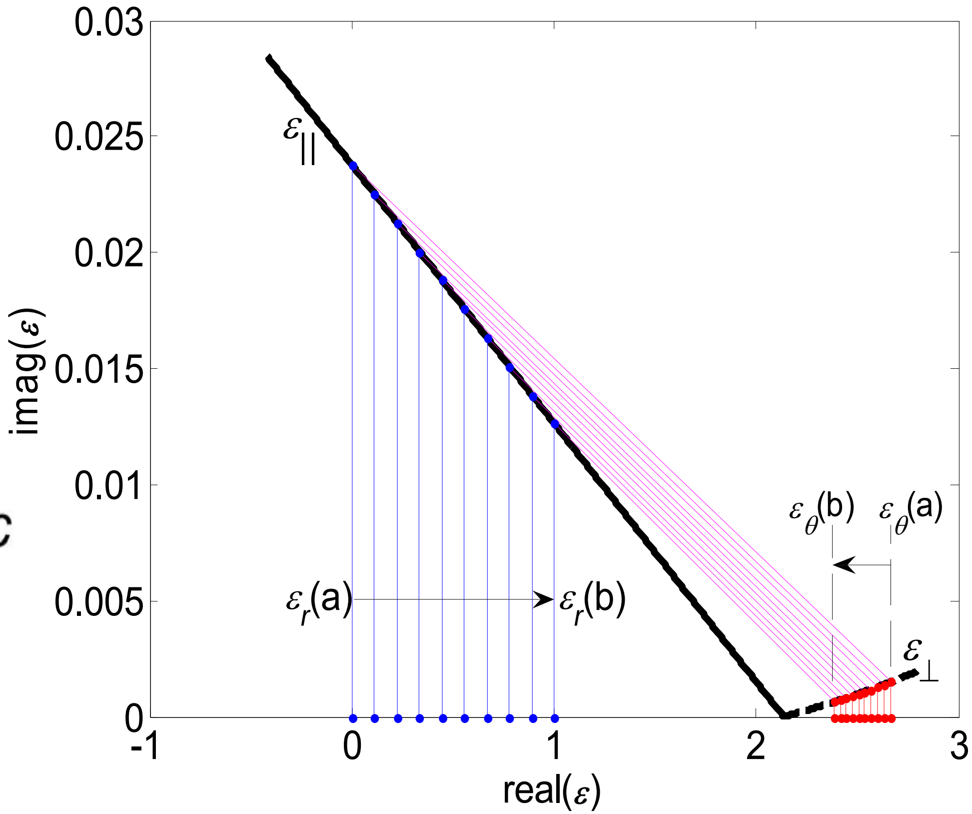




$\varepsilon_r'' = 0.03$

Structures of realistic “nonlinear” TO cloaks



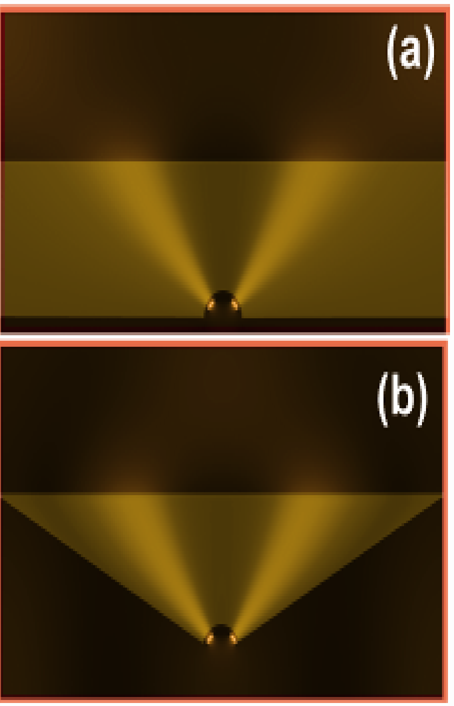


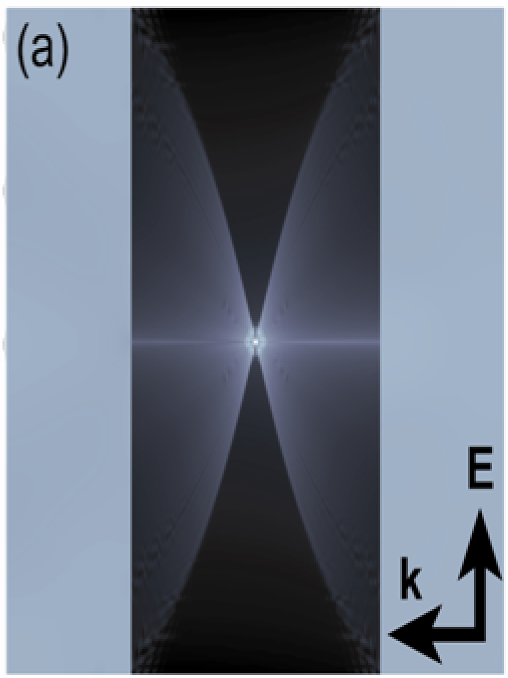
ε found from Wiener’s bounds

cloak @ 532 nm with alternating silver- silica slices based on nonlinear transformations

Engineering Meta-Space for Light: via Transformation Optics

Kildishev, VMS (OL, January 2008)





Flat hyperlens:
½- & '¼-body lenses

Light concentrator

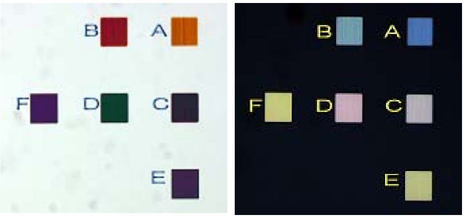
Fermat:

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

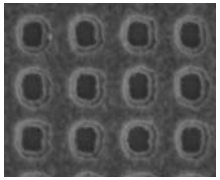
$$n = \sqrt{\varepsilon(r)\mu(r)}$$

"curving" optical space

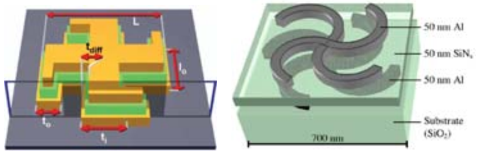
Take Home Messages:



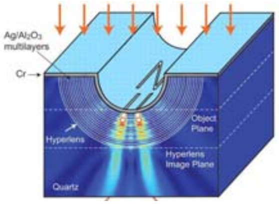
- Metamagnetics with rainbow colors



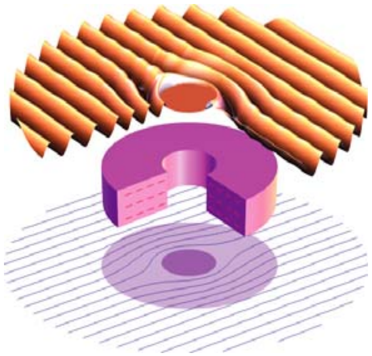
- (single-negative) MM with n = -0.9 at 770nm (double-negative) MM with n = -1 at 810 nm

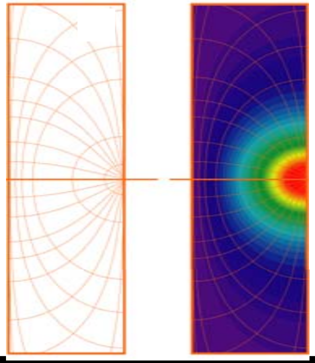


- Chiral metamaterials



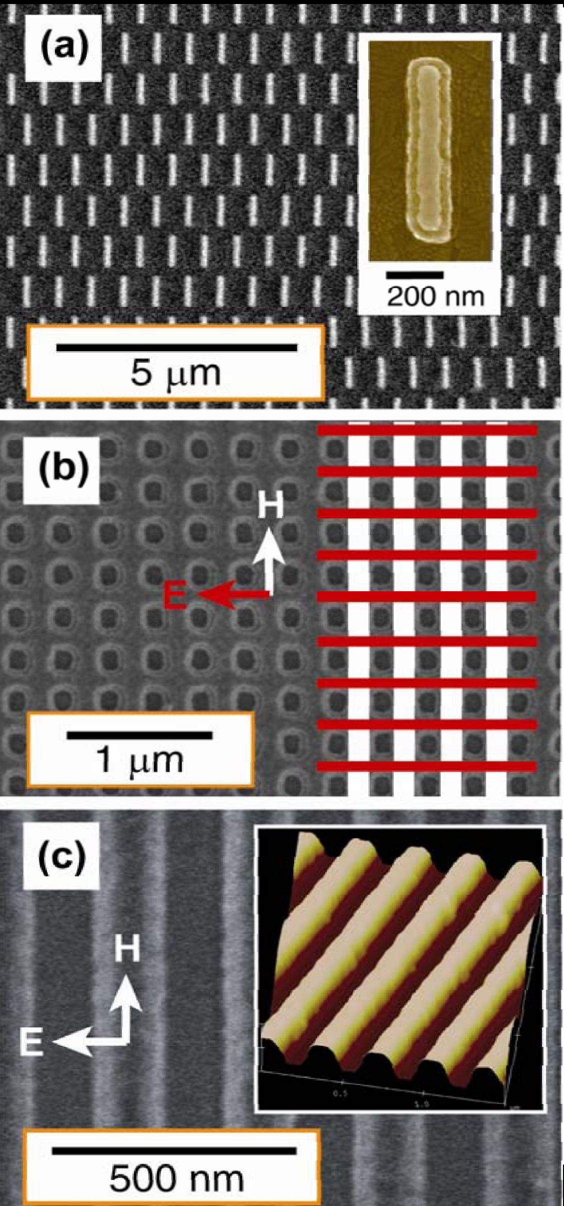
- NLO with NIMs
- Super-resolution





- Optical cloak of invisibility
- Engineered meta-space for light

Highlights of Purdue "Meta-Research"



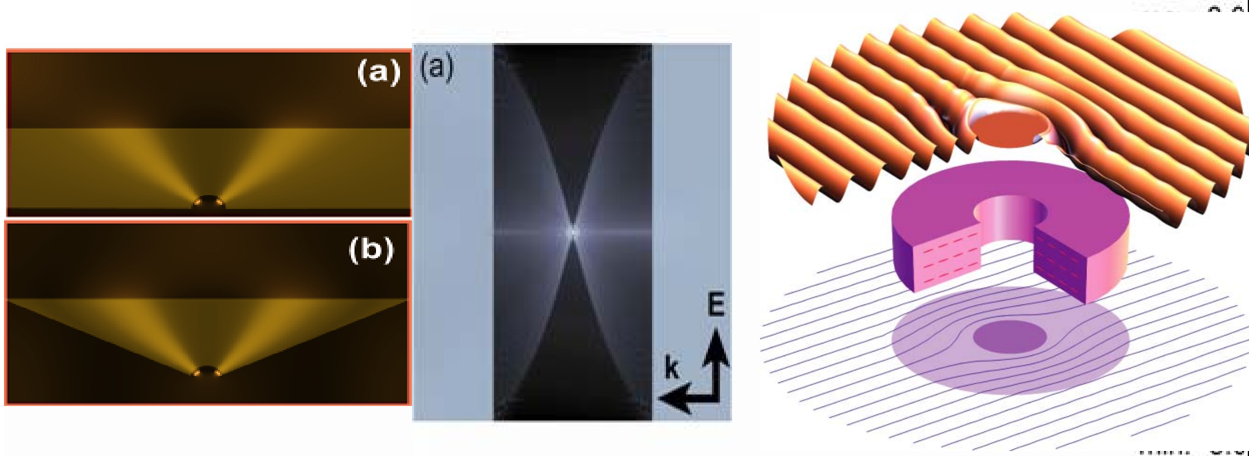
Purdue Photonic Metamaterials

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

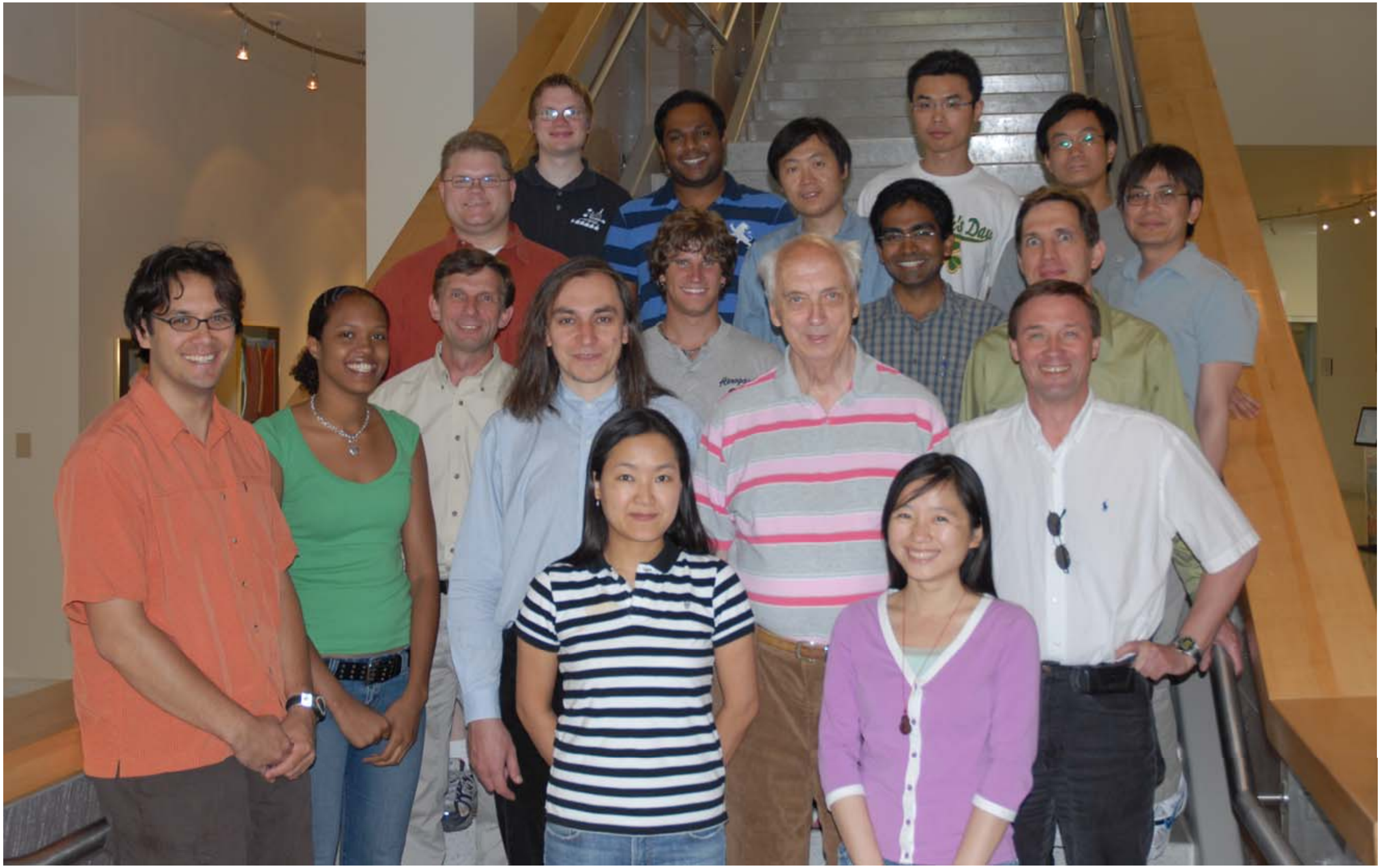
(b) double-negative MM at shortest λ (~800nm; 2007)

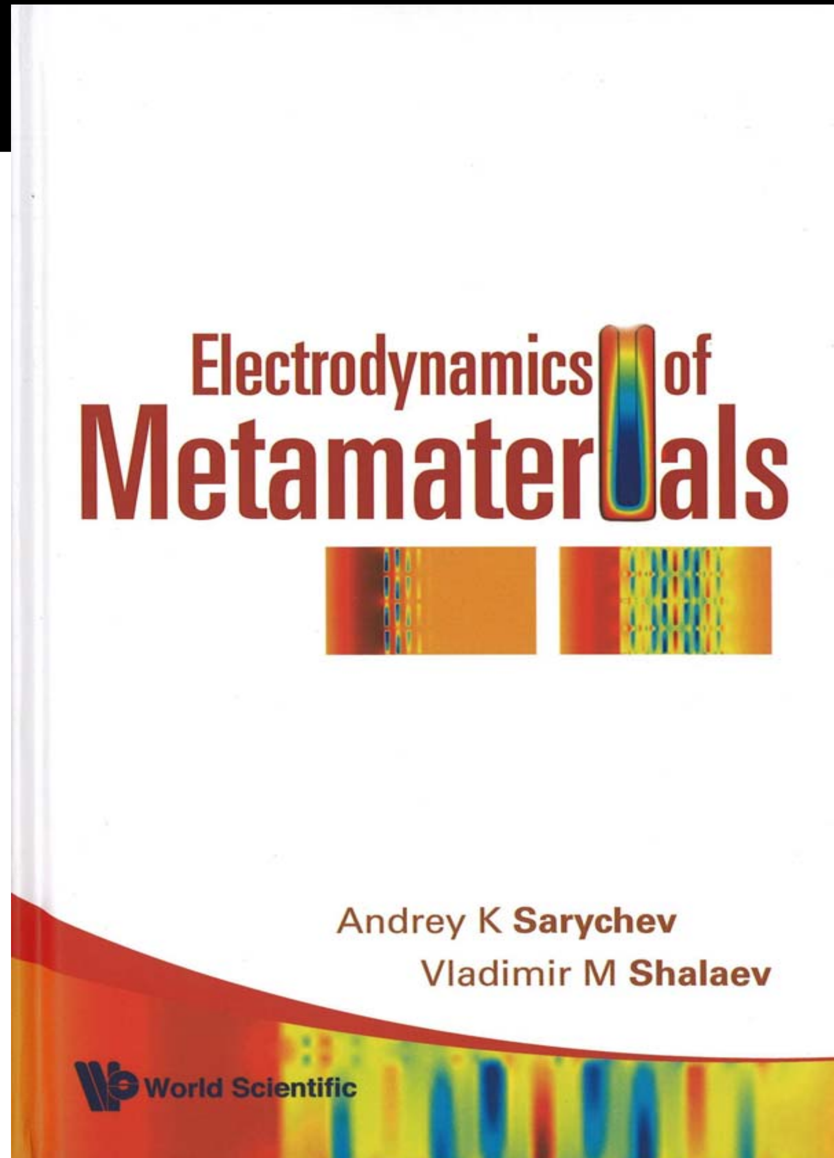
(c) 1-st magnetic MM across entire visible (2007)

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



Cast of Characters





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