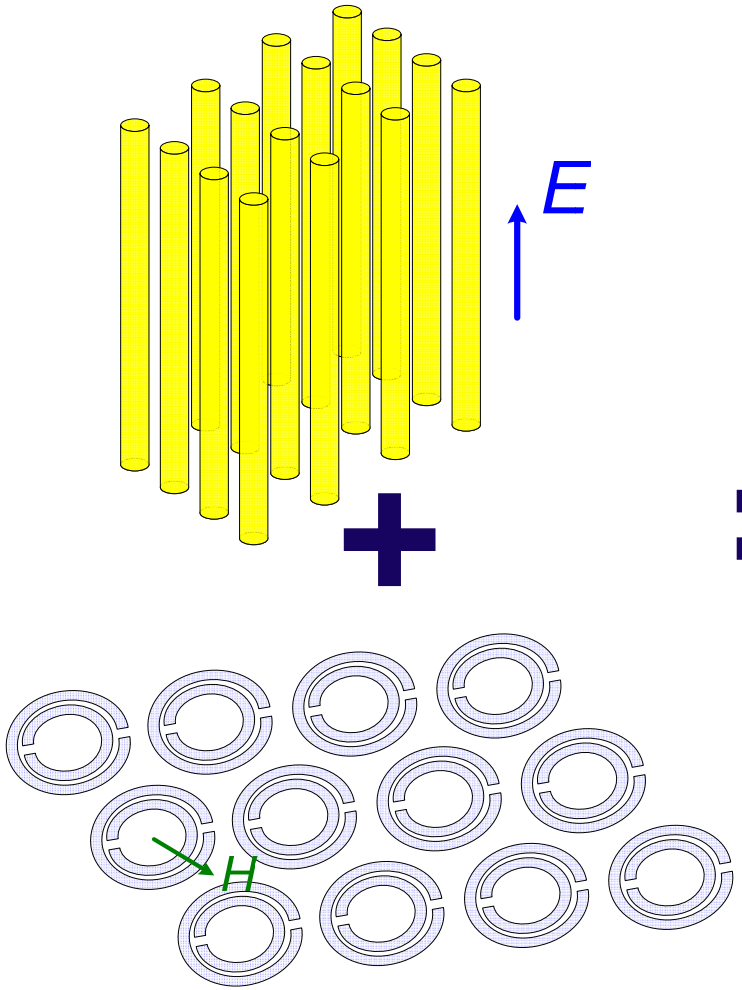
Negative index metamaterials

Negative electrical metamaterial + Negative magnetic metamaterial
= Negative index metamaterial



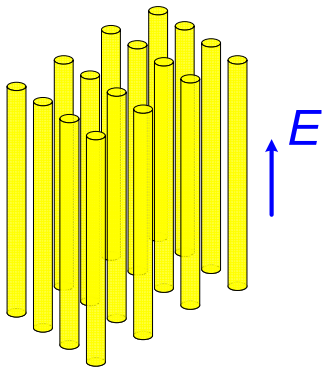
Smith, et al., UCSD, PRL (2000)

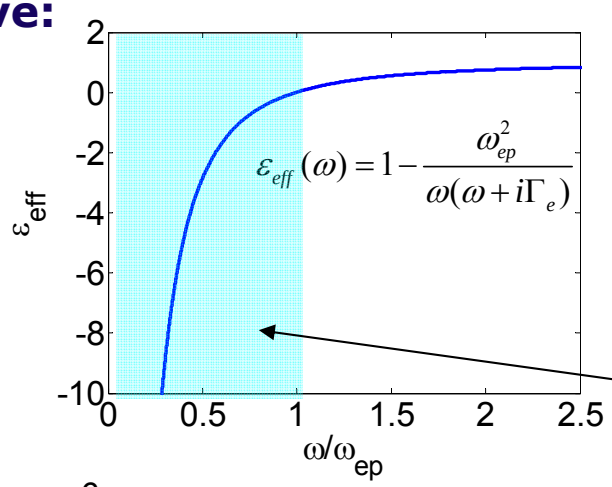
The key to obtaining a NIM

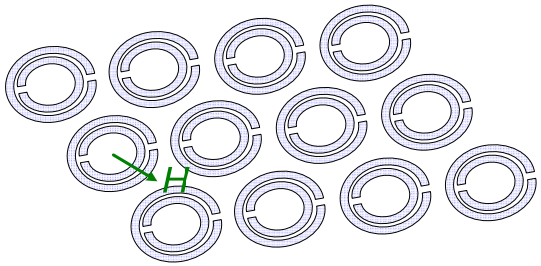
To match magnetic resonance with negative permittivity band

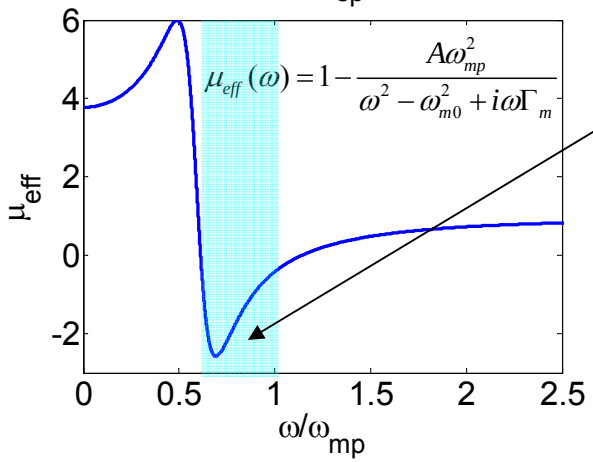
Similar magnitudes of |ε| and |μ| are desirable for impedance matching

An example in microwave:





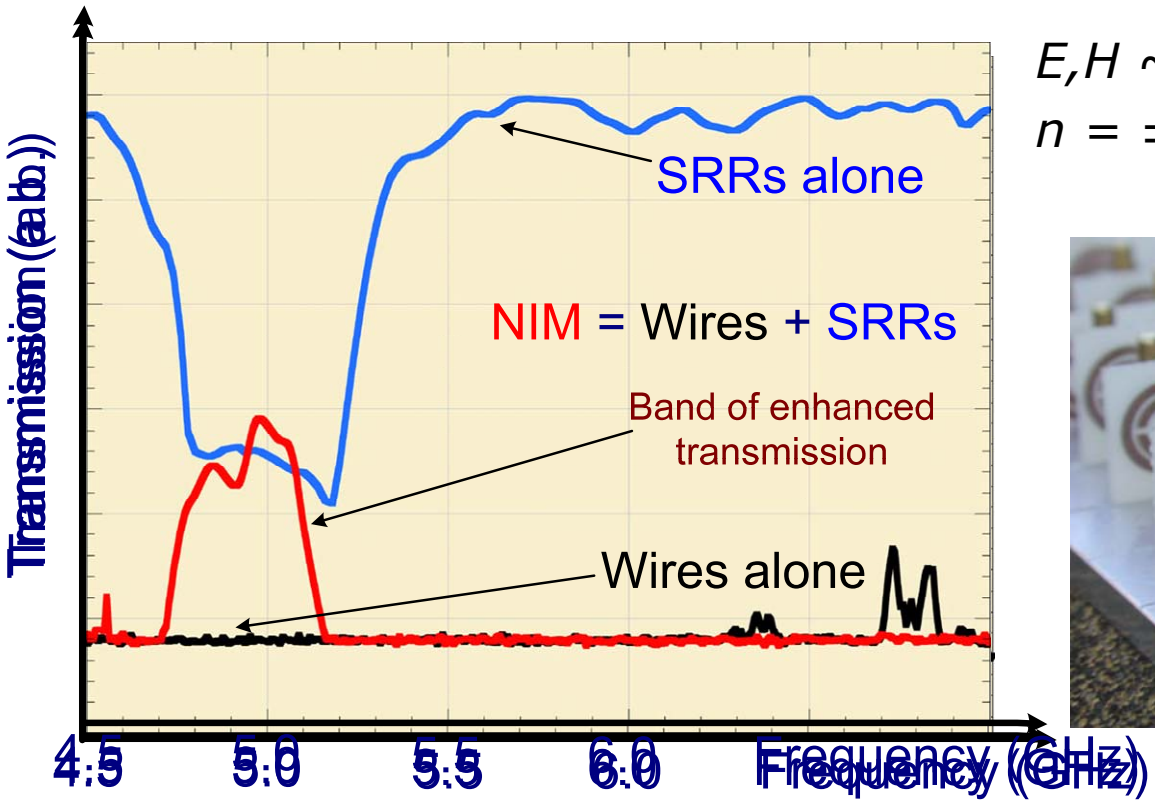




Try to match these two regions !

The first NIM in microwave

Transmission properties of the structure



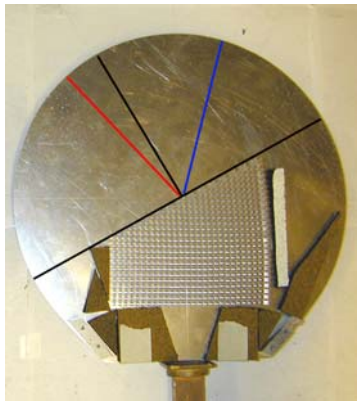
$E,H \sim \exp[in(\omega/c)z]$

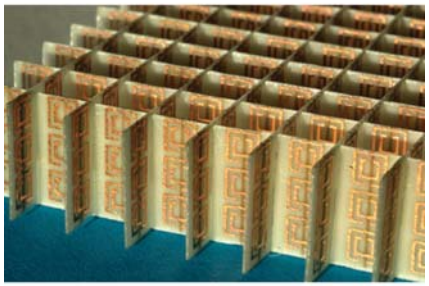
$n = \pm\sqrt{(\varepsilon\mu)}$

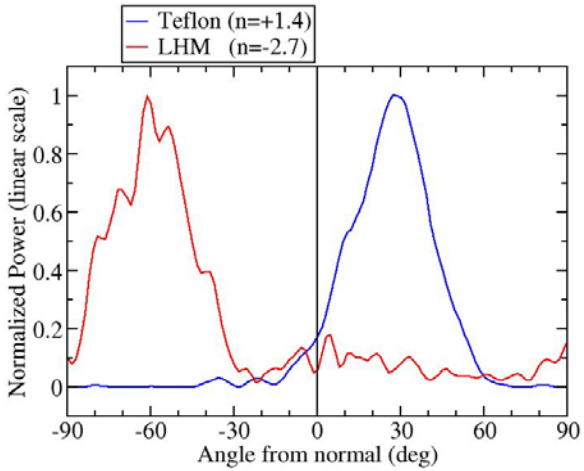
Smith, et al., UCSD, PRL (2000)

Inverses Snell's law in microwave verified

2D waveguide

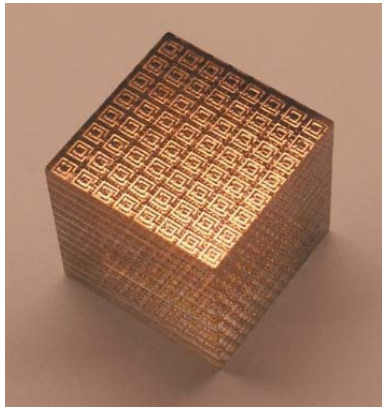




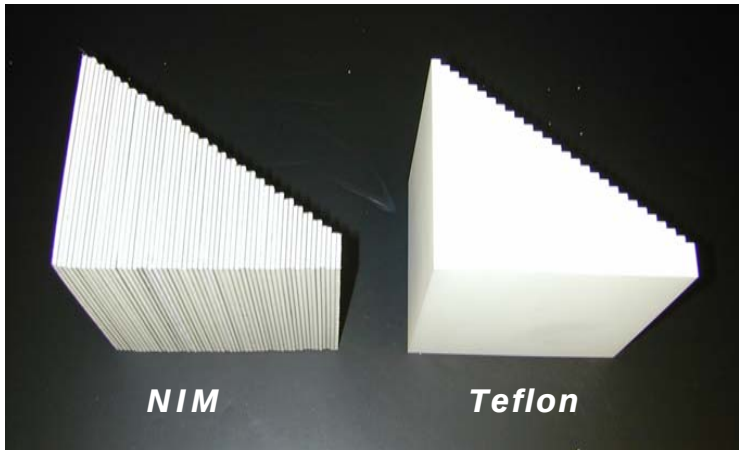


Smith, et al., UCSD, Science (2001)

3D free space



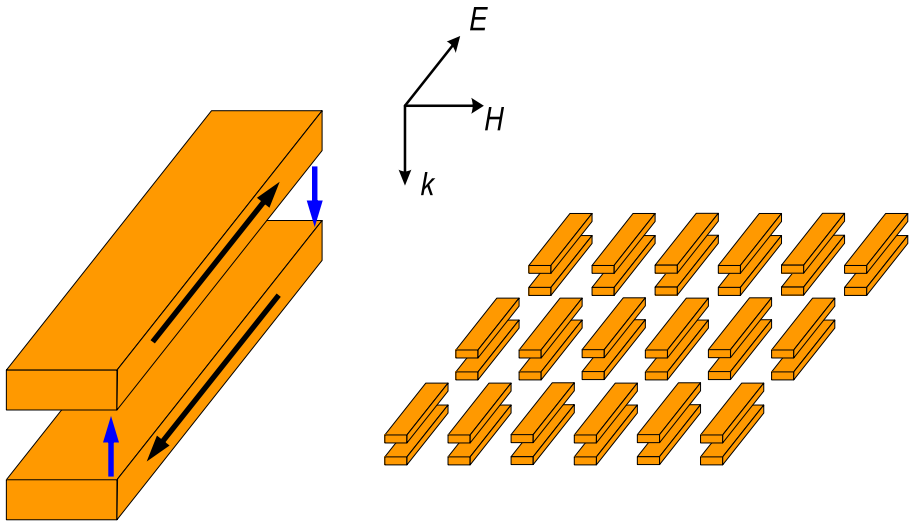
The Boeing Cube

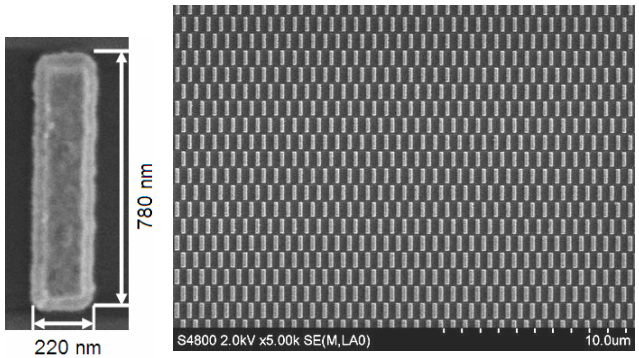


Parazzoli, et al., Boeing, PRL (2003)

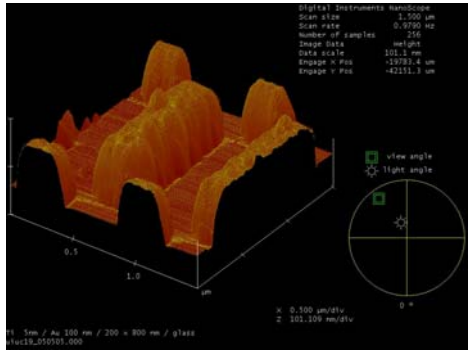
Nanorod arrays: the first optical NIM

Nanorod arrays support both electrical and magnetic resonances





SEM



AFM

The overlapping of the two resonances cannot be achieved exactly. Therefore the figure of merit is low.

@ 1.5 μm

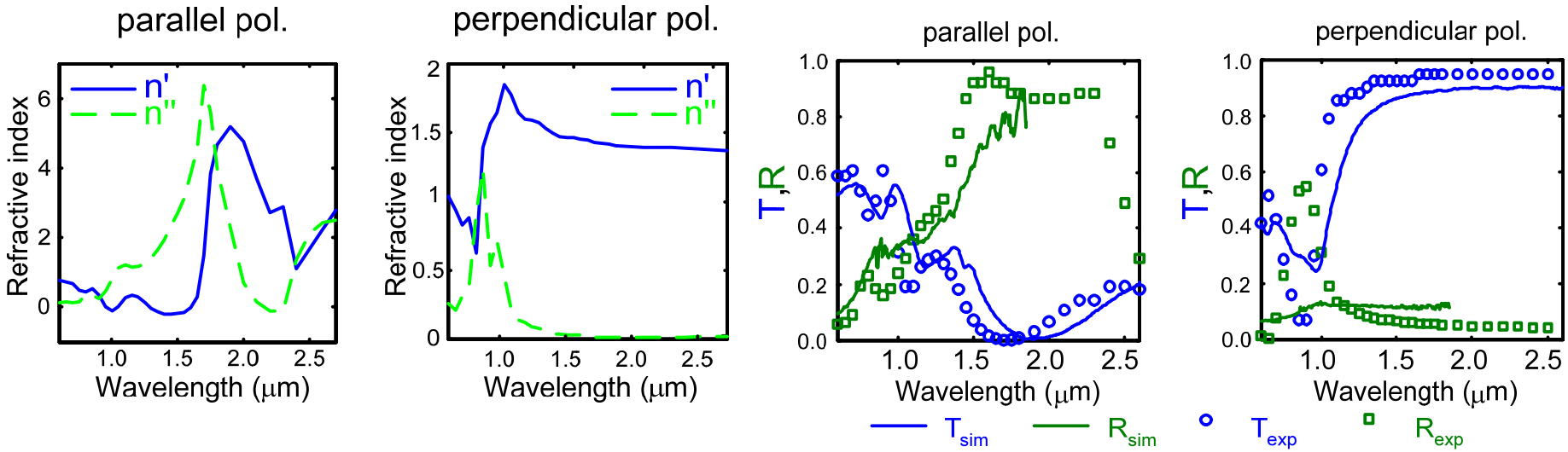
$$\mu' > 0$$

$$\varepsilon'|\mu| + \mu'|\varepsilon| < 0$$

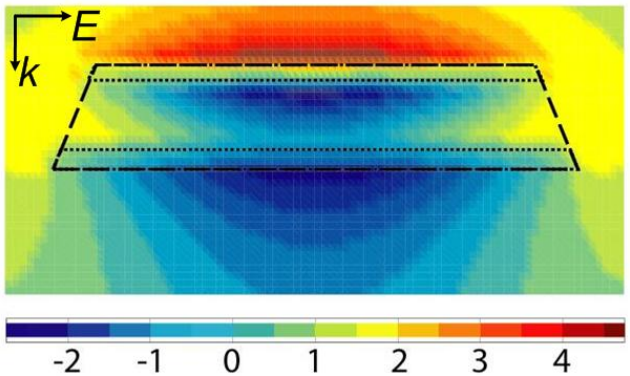
$$n' < 0$$

Shalaev, et al., OL (2005)

Optical properties of Nanorod Structure



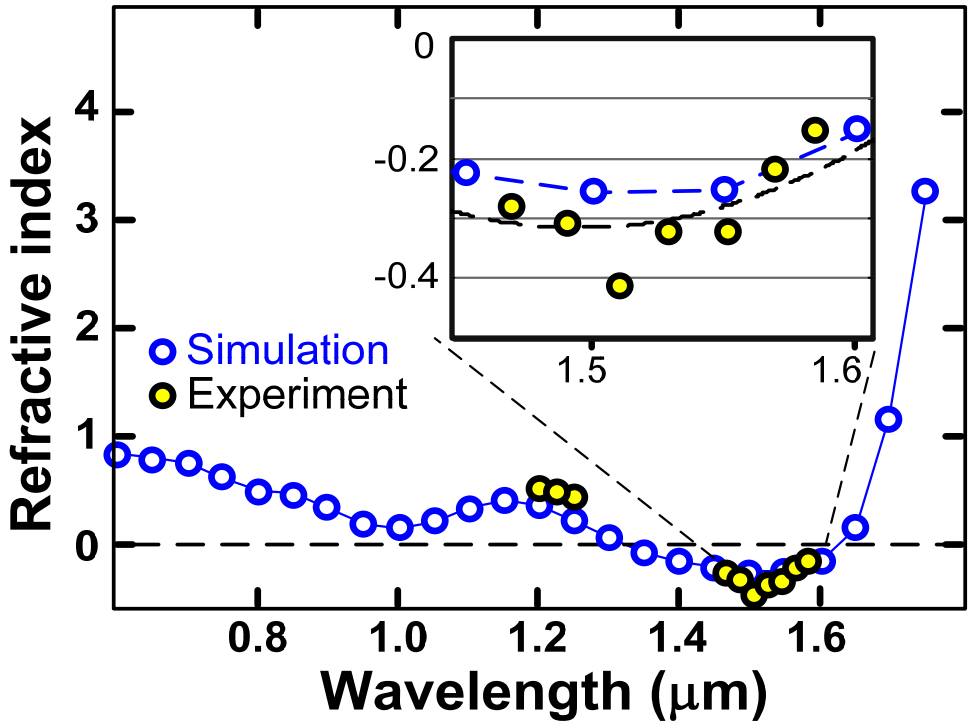
- ***Strong resonance behavior for parallel pol.; Substrate-like for perpendicular pol.***
- ***In consistency with the T, R spectra***



Simulated cross-sectional field map of the magnetic field

Re(n) = -0.3 ± 0.1 at ~1.5 μm is obtained

- (Opt. Lett. 30, 3356 (2005); first reported in arXive/physics/0504091, Apr 13, 2005;)

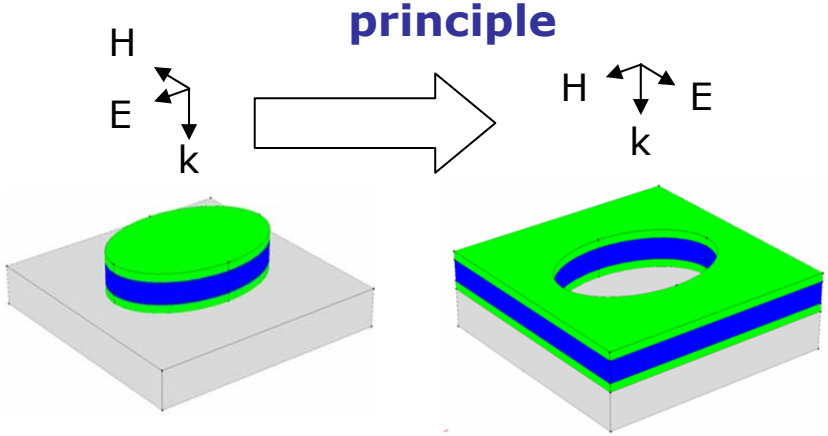


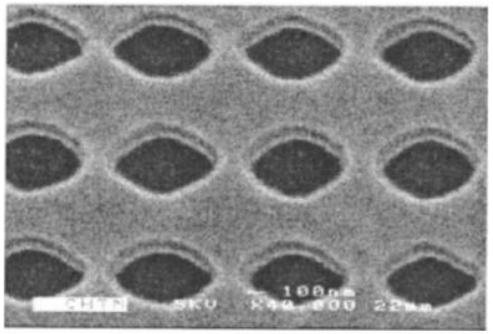
$$\cos nk\Delta = \frac{1 - r^2 + n_s t^2}{(n_s + 1)t + rt(n_s - 1)}$$

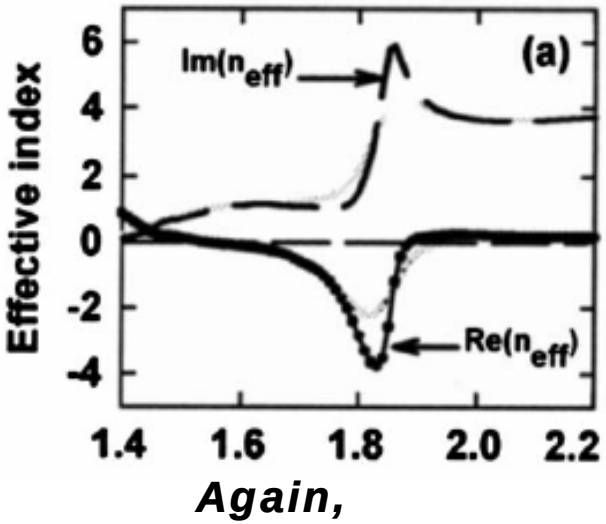
Refractive index is retrieved from direct measurement of complex r & t coefficients

The inverted system: coupled void pairs

The Babinet principle







Experimental demonstration of negative n at ~ 1.8 μm.

Zhang, et al., UNM and Columbia group, 2005

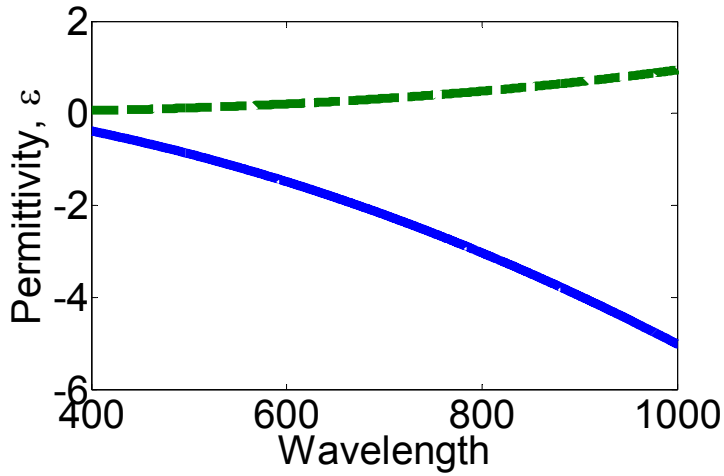
$$\mu' > 0$$

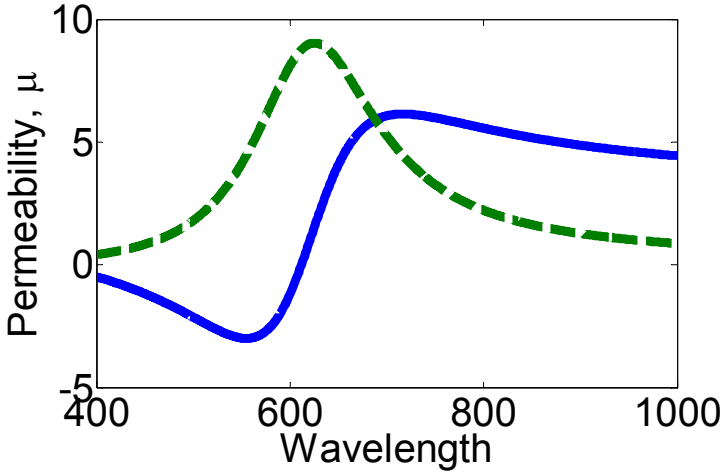
$$\varepsilon'|\mu| + \mu'|\varepsilon| < 0$$

$$n' < 0$$

The coupled voids arrays structure is the prototype of the optical "Fishnet", the state-of-the-art NIM design.

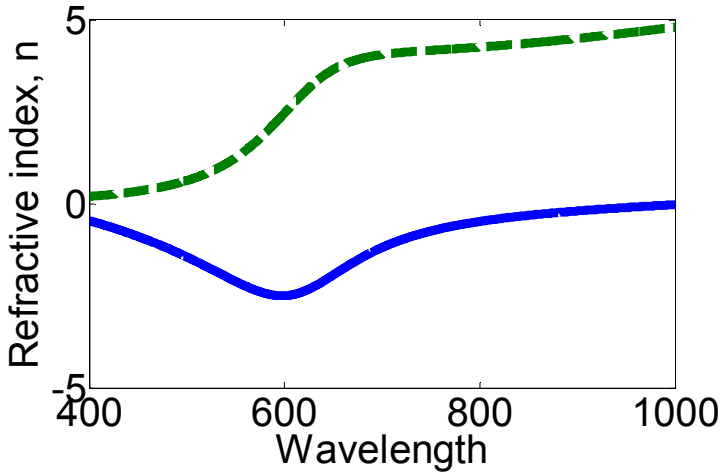
General guideline for optical NIM design



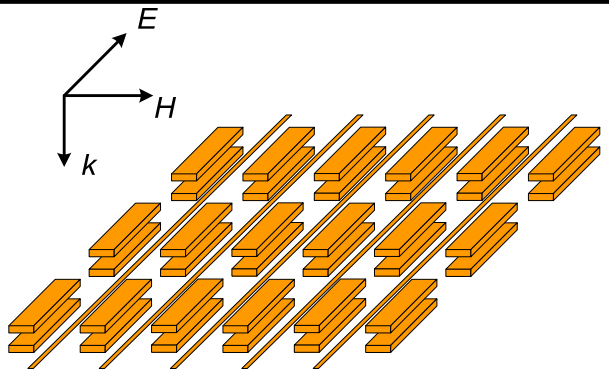


- **Problem:**
- **Magnetic and electric resonances occur at different wavelengths**

- **Solution:**
- **Use broadband, non-resonant, diluted metal for negative ε**



Examples of optical NIM designs ***(resonant μ + broadband ε)***

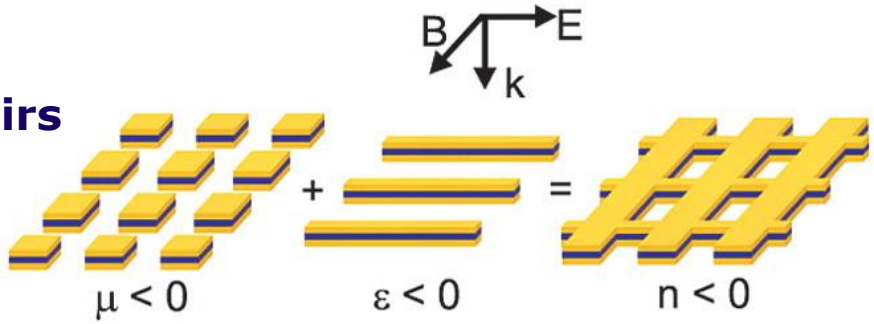


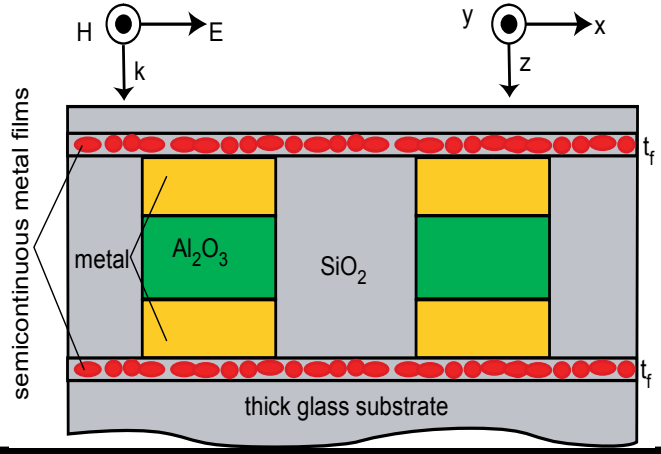
Nanorod pairs + thin metal wires

Soukoulis, et al., 2006

Nanor-plate pairs + thin metal wire pairs = "optical fishnet"

Zhang, et al., UNM & Columbia, 2006

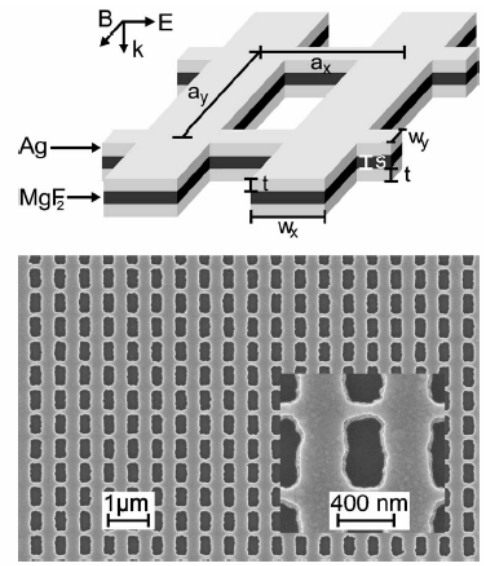


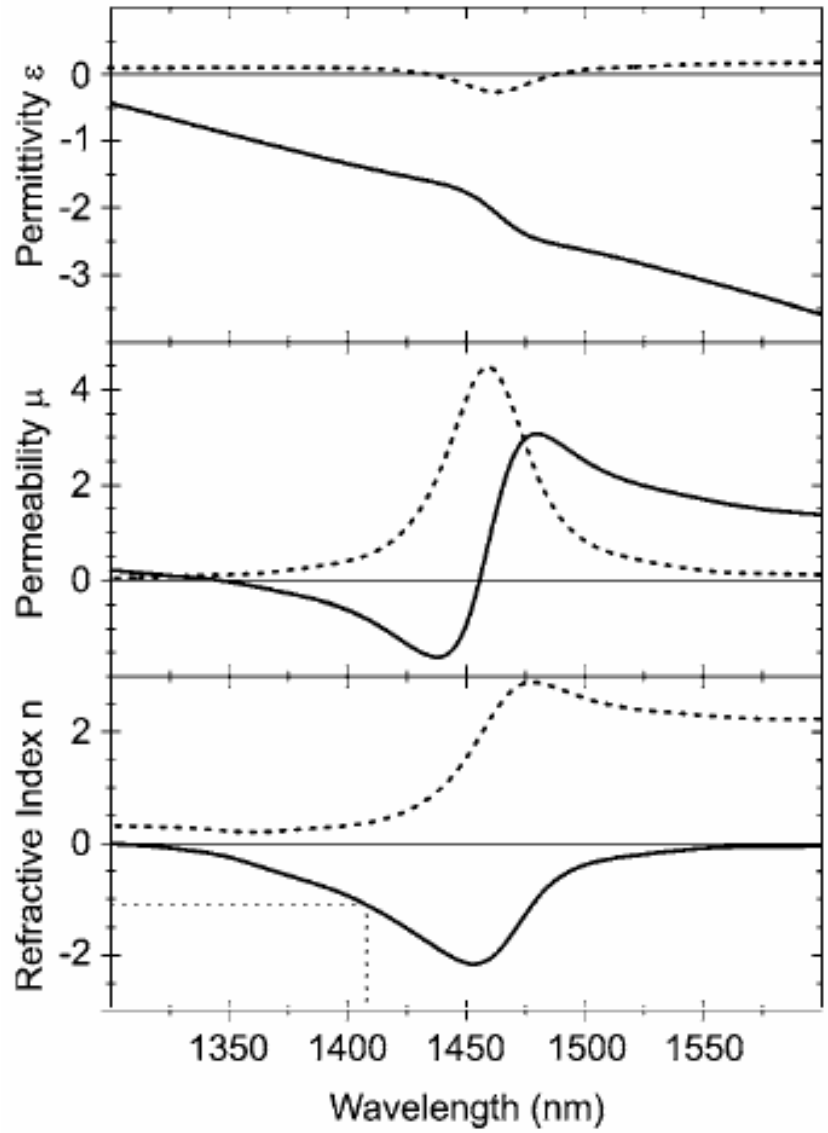


Nano-strip pairs + semicontinuous film

Chattier, et al (Purdue); OE (2006)

Optical fishnet: a double-negative structure

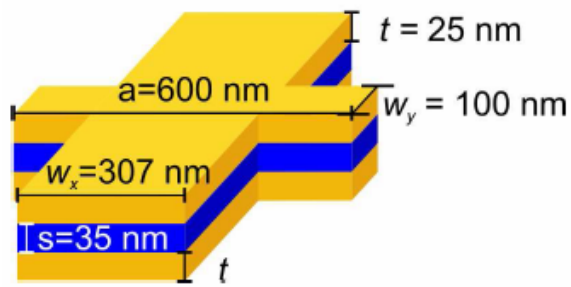


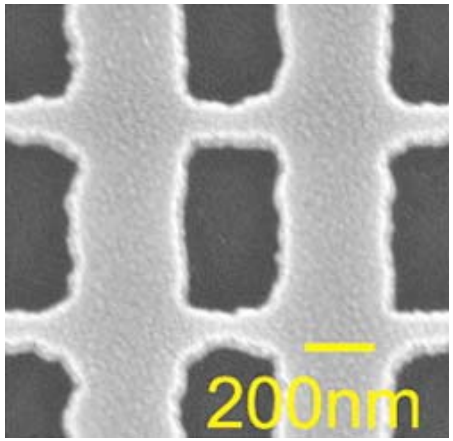


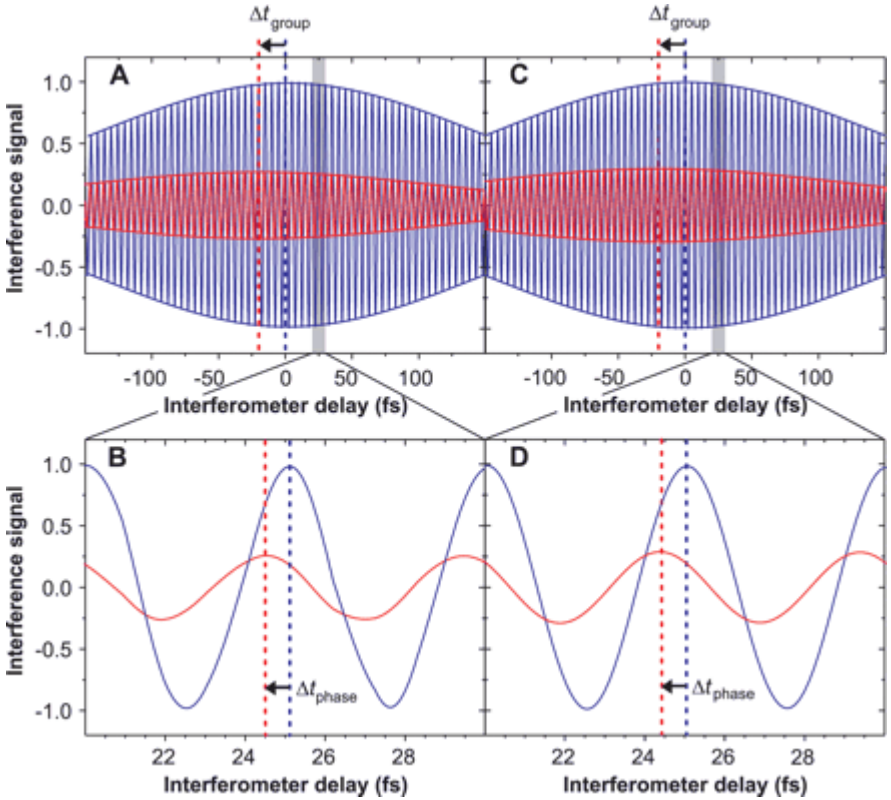
An optical NIM with both negative ε and negative μ obtained in optical "Fishnet".

Dolling, et al., 2006

Simultaneously negative *Vp* and *Vg* in Fishnet







Dolling, et al., Science, 2006

Progress in optical NIMs

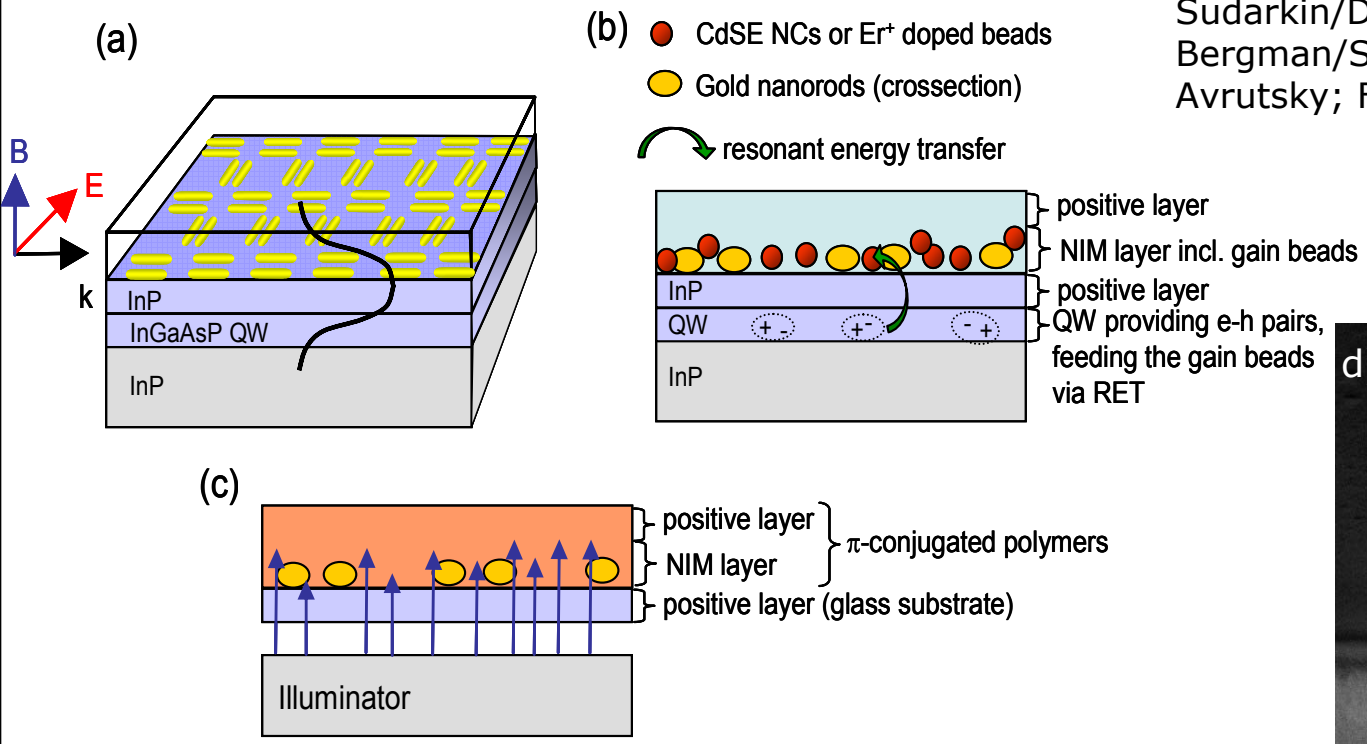
Year and Research group	*1st time posted and publication*	*Refractive index, n′*	*Wavelength λ*	*Figure of Merit F=|n′|/n″*	*Structure used*
2005:					
Purdue	April 13 (2005) arXiv:physics/0504091 Opt. Lett. (2005)	–0.3	1.5 μm	0.1	Paired nanorods
UNM & Columbia	April 28 (2005) arXiv:physics/0504208 Phys. 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	Opt. Lett. (2006)	–1 *	1.4 μm	3.0	Nano-fishnet with rectangular voids
Karlsruhe & ISU	In press	–0.6	780 nm	0.5	Nano-fishnet with rectangular voids

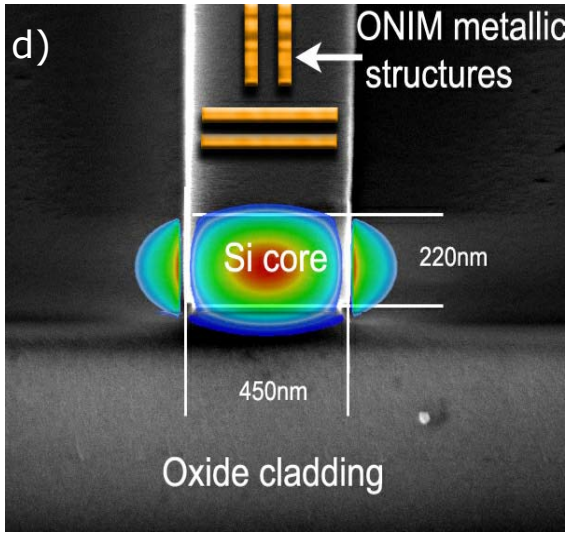
* Minimum n′ is –2 occurring at 1.45 μm with F=1.5

From Low- to no Loss NIMs: Is it for Real?

Gain components compensating losses in NIMs (Required gain ~ 10^2 to 10^4 cm^{-1})

Lasers with plasmonic structures:
Capasso; Feldmann
plasmon+gain (theory):
Sudarkin/Demkovich;
Bergman/Stockman;
Avrutsky; Fainman; Lawandy; Pendry



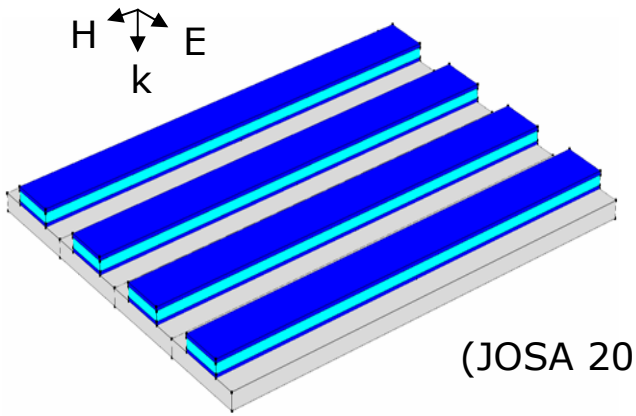


a) SOA gain (low confinement factor)
b) NC gain beads
c) π-conjugated polymer
d) dyes

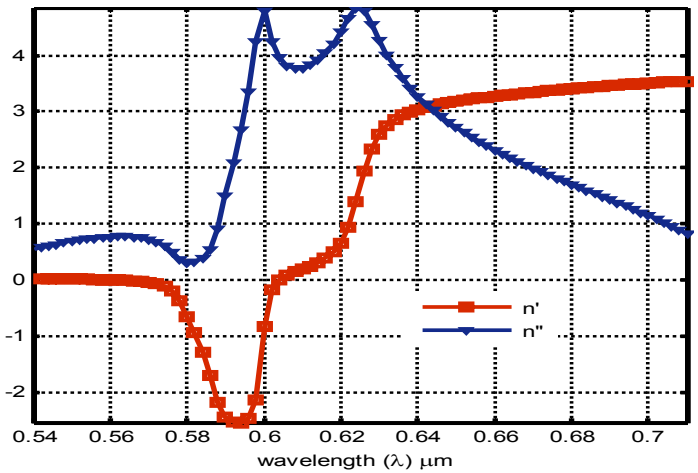
d) Vlasov:
Raman amplification in Si waveguide with metal-nanorod ONIM on top
g~100cm^{-1} at P~1mW

Inverse Design Problem: from Desired Functionality to Optimized Design

Paired Metal Strips

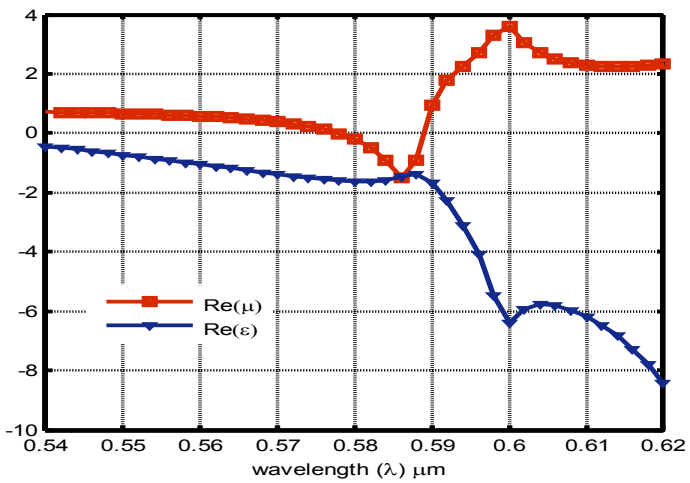


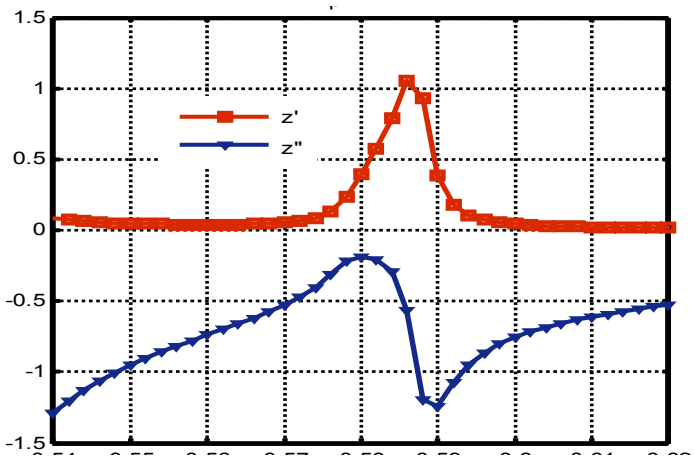
(JOSA 2006)

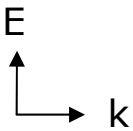


Negative μ and ε

Optimum at λ = 584 nm, n = - 1.30 + 0.39i





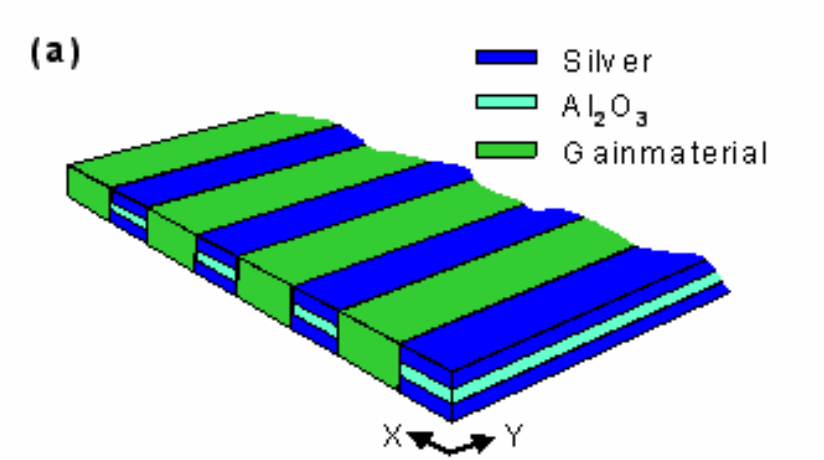


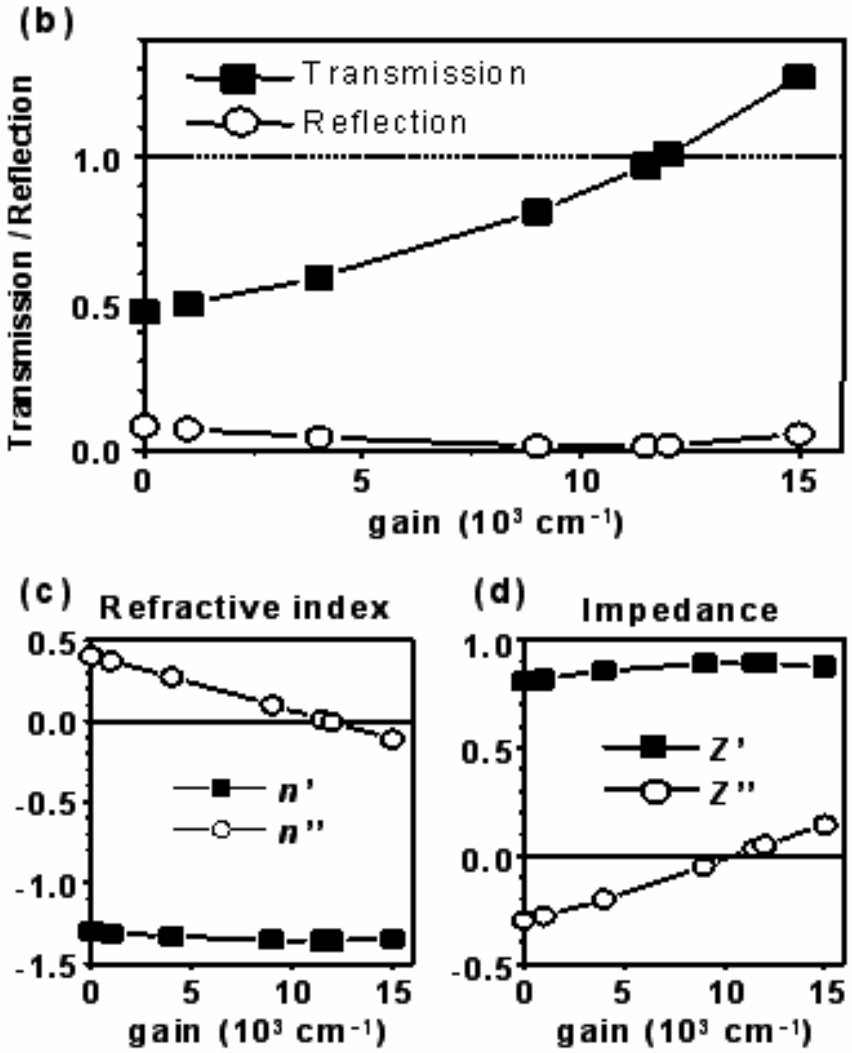
NIMs with no Losses

Optical NIM slab with gain inclusions:

at λ= 584 nm, n = -1.3 + 0·i (!)

n″ = 0 (!); R ≈ 0% and T ≈ 100%





T. Klar, A. V. Kildishev,
V. P. Drachev, and V. M. Shalaev
IEEE- J. of Selected Topics in
Quantum Electronics, November issue (2006)

Compensating loss with gain in
Ag colloids/dyes, Noginov et al, OL **31**, 3022 (2006)

Outline

- What are metamaterials?
- Electrical metamaterials
- Magnetic metamaterials
- Negative-index metamaterials
- Perfect lens, superlens, & other
- Optical cloaking

Imaging with NIM-lens:
Amplification of Evanescent Waves Enables sub-λ Image!

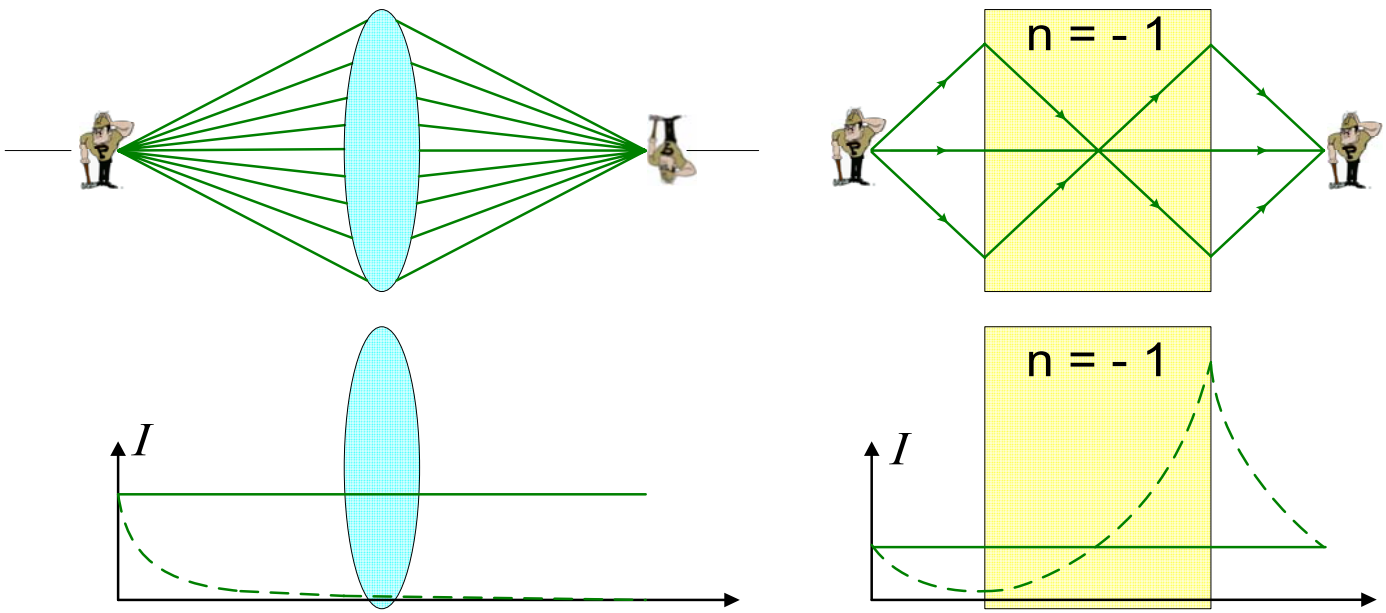
Waves scattered by an object have all the Fourier components $k_z = \sqrt{k_0^2 - k_x^2 - k_y^2}$

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***

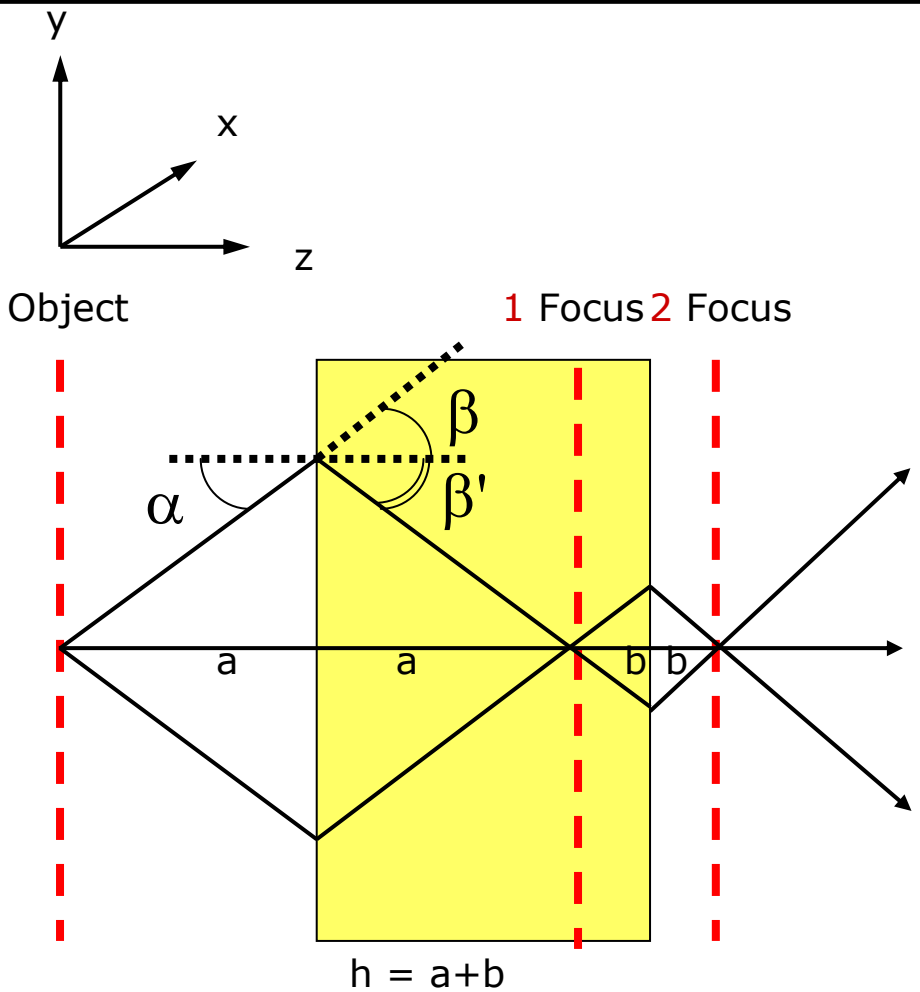


Propagating waves

Evanescent waves

Pendry, PRL, 2000

Perfect Lens



$n = -1$ (ε = -1; μ = -1)

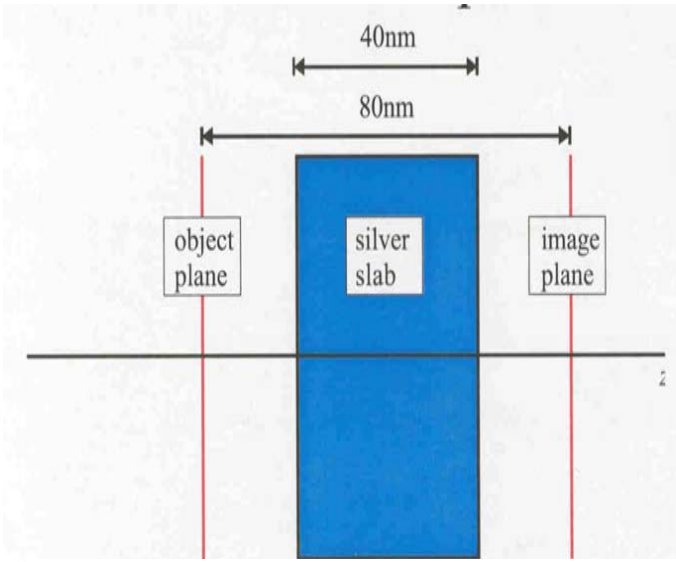
$$\sin(\alpha) = n\sin(\beta') = -\sin(\beta') = \sin(\beta)$$

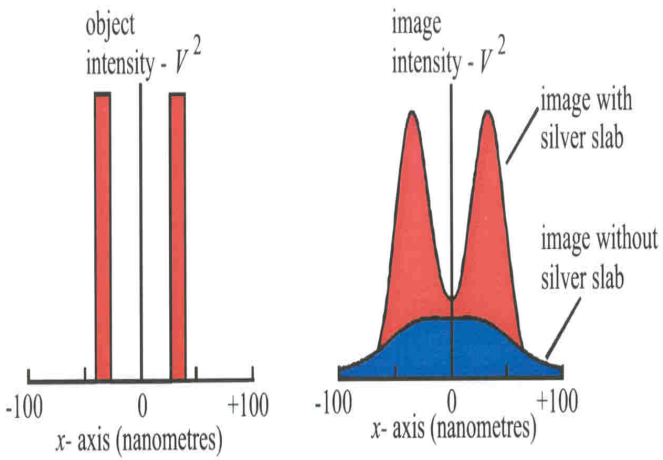
$$E(y,z) = \sum_q A_q \exp\left(iqy + i\sqrt{(nk)^2 - q^2}\ z \right)$$

$$Phase\,shift =$$

$$\left(iqy + i\sqrt{k^2 - q^2}\ z \right) + \left(-iqy - i\sqrt{(-k)^2 - q^2}\ z \right) = 0$$

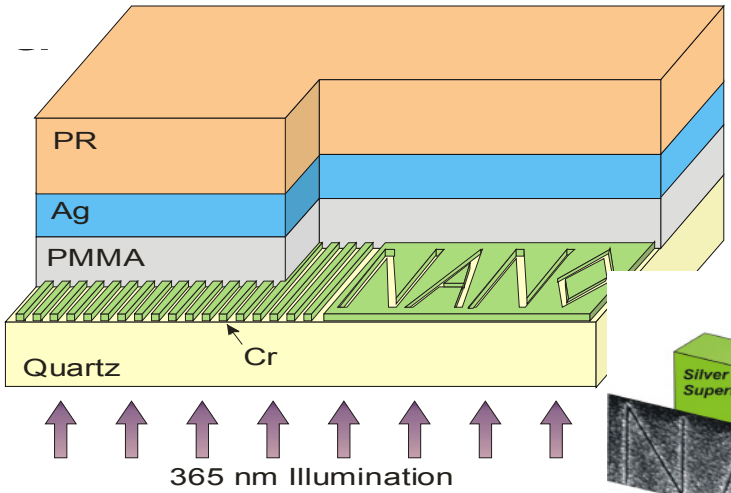
The Poor Man's (Near-Field) Superlens ($\varepsilon < 0$, $\mu = 1$)

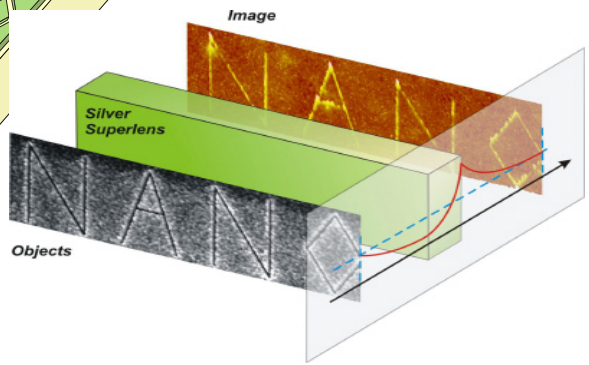




Original implementation by Pendry: use a plasmonic material (silver film) to image 10 nm features with hw = 3.48 eV;

$$\varepsilon = 5.7 - 9^2/\omega^2 + 0.4i \quad (= -\varepsilon_h)$$





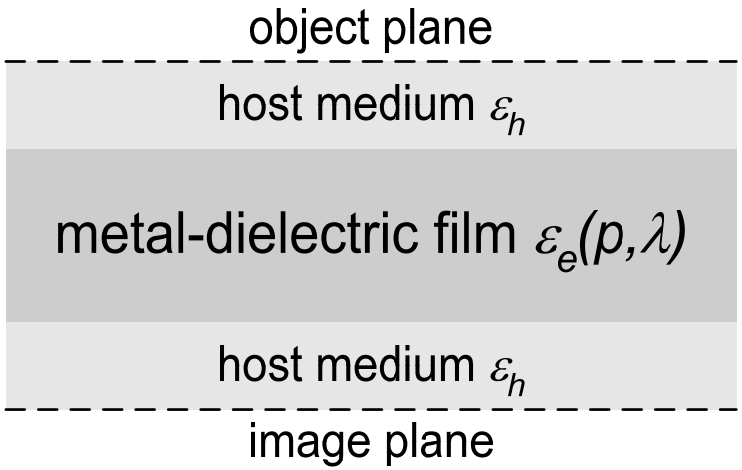
Near-field super-lens (NFSL)

super-resolution with superlens: Zhang et al. (2005); Blaikie, et al (2005)

Mid-IR: Shvets et al. (2006)

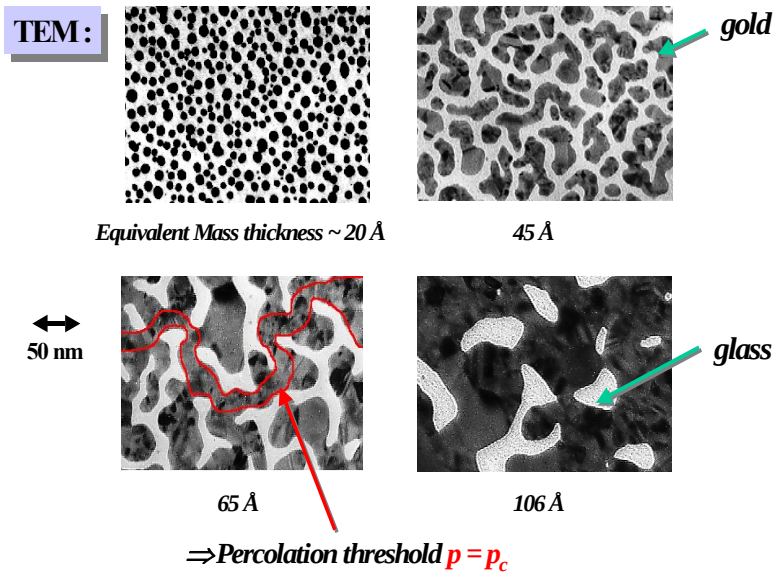
Near-Field Tunable Super-Lens Based on Metal-Dielectric Composites

$$p\frac{\varepsilon_m-\varepsilon_e}{\varepsilon_m+(d-1)\varepsilon_e}+(1-p)\frac{\varepsilon_d-\varepsilon_e}{\varepsilon_d+(d-1)\varepsilon_e}=0$$



- For a metal-dielectric composite the NFSL can work <u>at any desired wavelength</u>

$$\mathrm{Re}[\varepsilon_e(\varepsilon_m,\varepsilon_d,p,\lambda)]=-\varepsilon_h$$

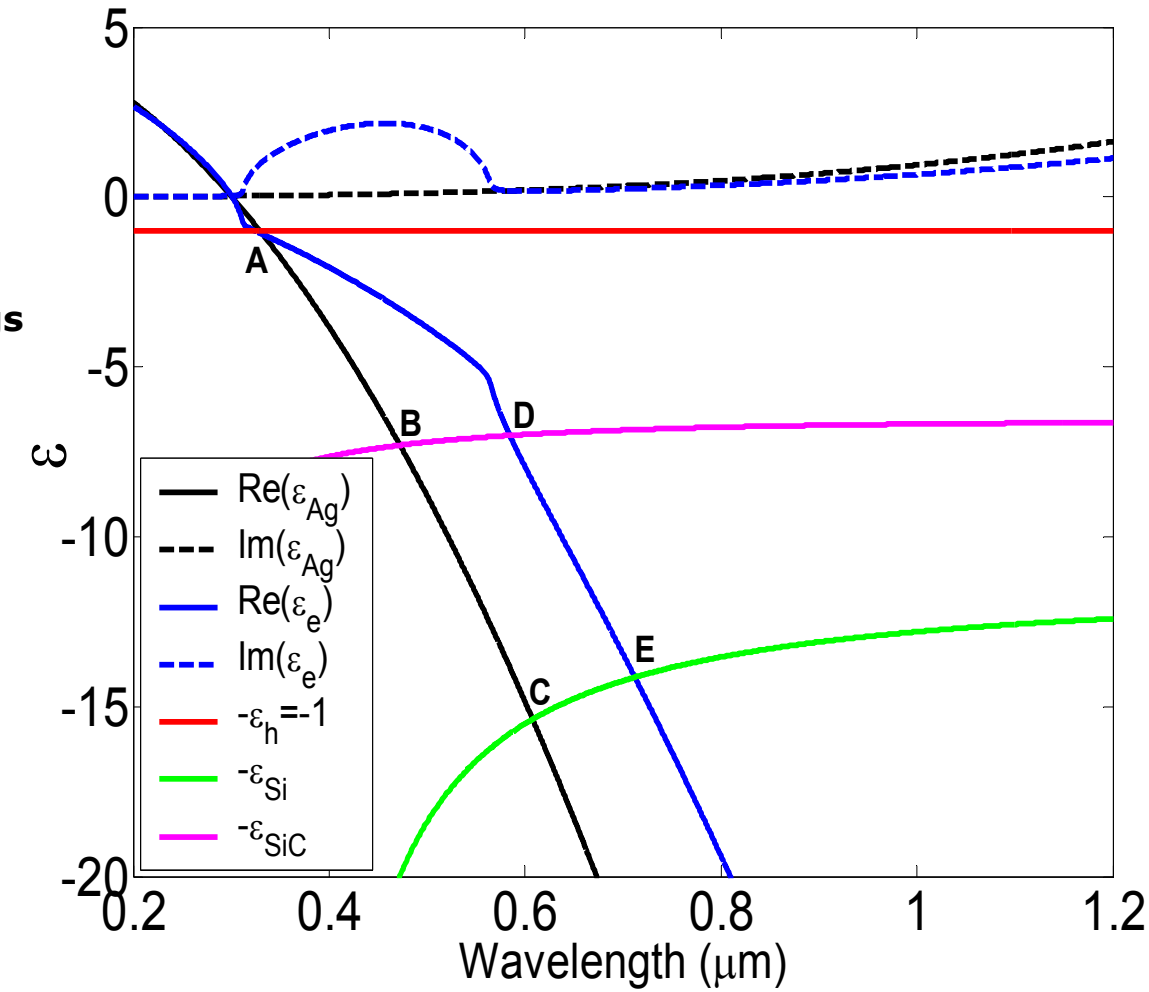


PRB 72, 193101 (2005)

Tunable Superlens: Controlling Operational λ

Operation condition:

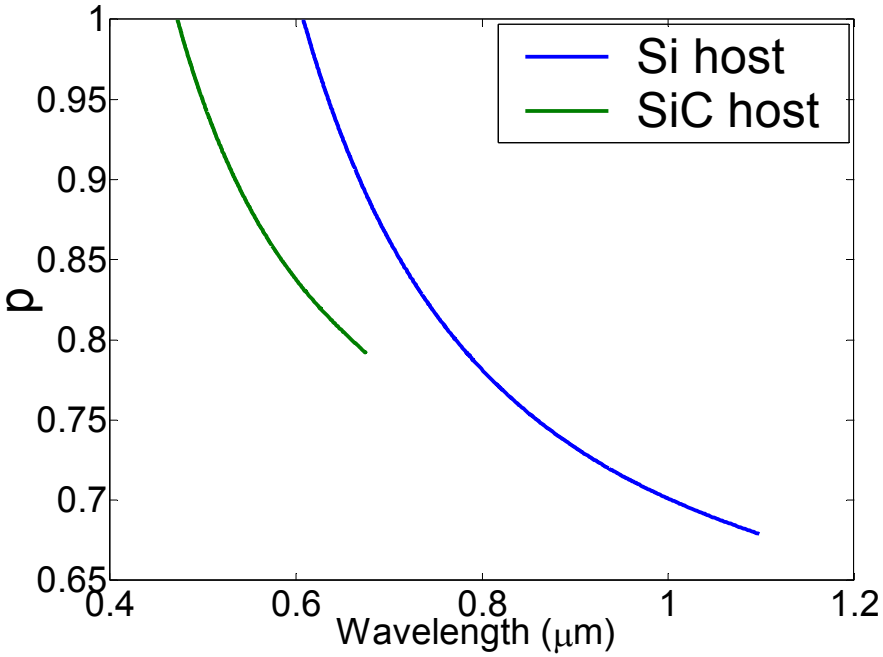
$\varepsilon_{film}(\omega, p) = -\varepsilon_{surroundings}$



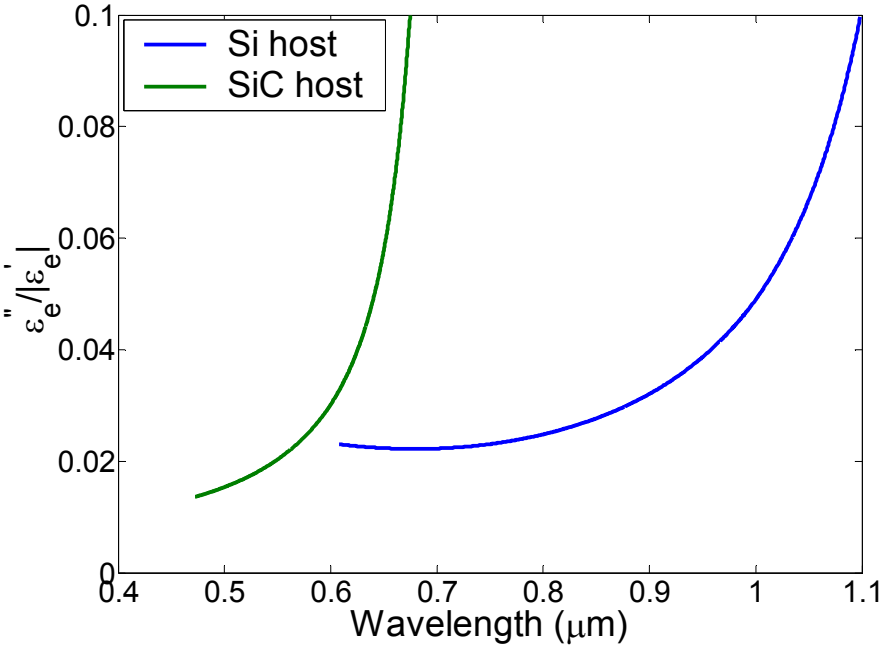
Example: Ag-SiO_2 lens (p=0.85) with Si or SiC as host

Performance of Composite NFSL with Si or SiC as Host

The required filling factor for different wavelengths:

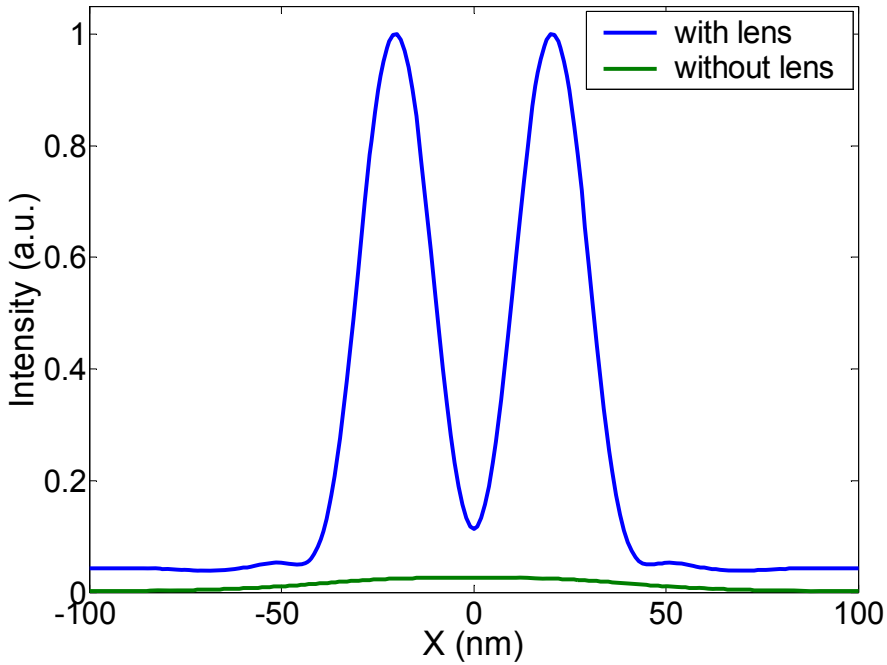


The value $\varepsilon_e''/|\varepsilon_e'|$ for different wavelengths:



- The upper limit of the operational range is taken such that $\varepsilon_e''/|\varepsilon_e'| = 0.1$
- The whole possible spectral range is $[0.47, 0.67] \cup [0.61, 1.10] = [0.47, 1.10]\mu m$

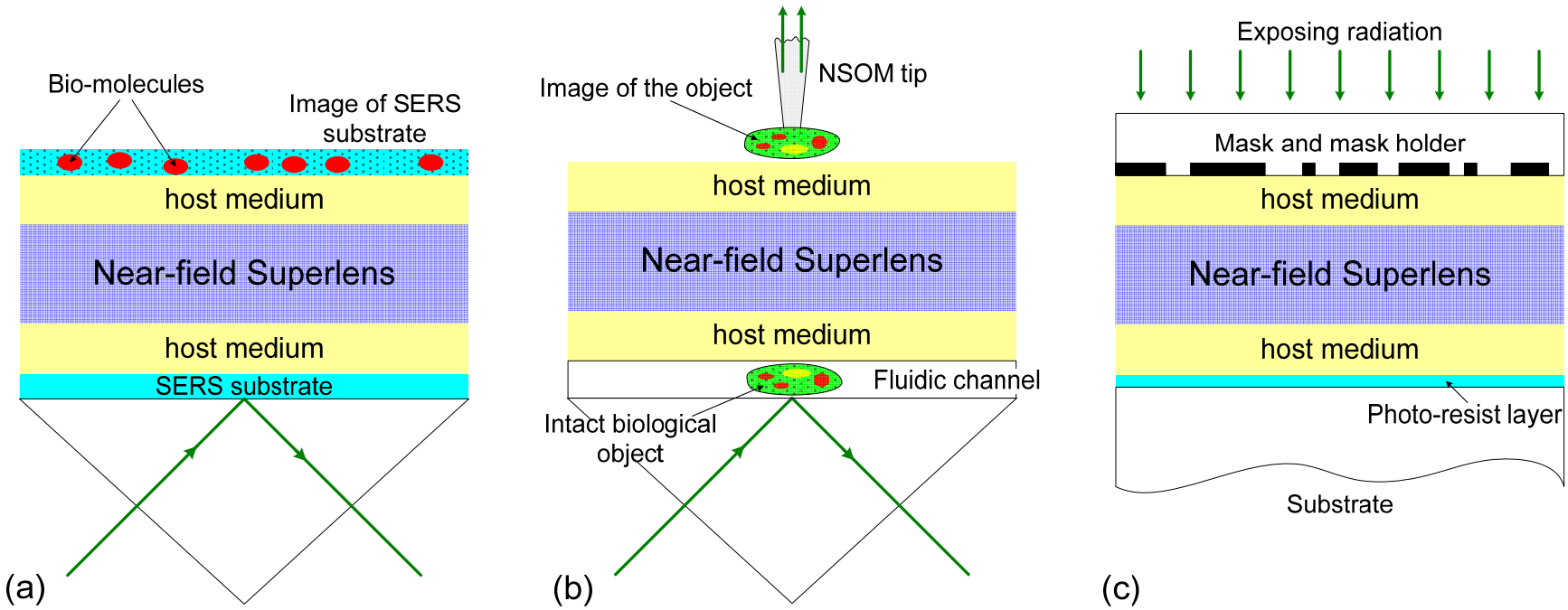
Imaging with a Composite Superlens



Example:

Wavelength:	**632.8nm (He-Ne)**
Host medium:	**SiC**
	p=0.82; ε_h=6.94; ε_e= -6.94+0.31i
Lens thickness:	**d=20nm**
Object:	**slit-pair** with 20nm width and 40nm center-to-center separation

Possible applications of the near-filed superlens



Remote SERS sensing

Non-contact bio-molecule probing

Nanoscale lithography

Outline

- What are metamaterials?
- Electrical metamaterials
- Magnetic metamaterials
- Negative-index metamaterials
- Perfect lens and superlens
- Optical cloaking - intro

Optical metamaterials: A route to invisibility?

Optical metamaterials provide unprecedented control of electromagnetic fields

If we can change the path of light at will…

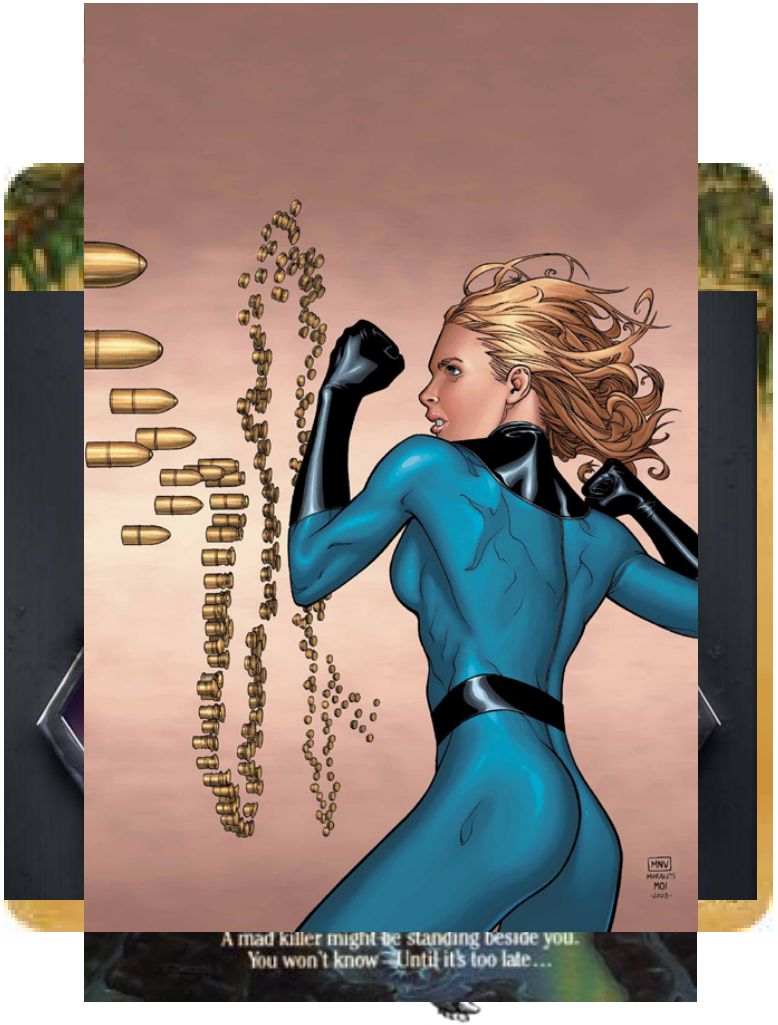
Invisibility in Mythology, Folklore and Fictions

Ancient time:

- **Perseus' helmet in Greek Mythology**
- **The ring of Gyges in Plato's *The Republic***
- **…**

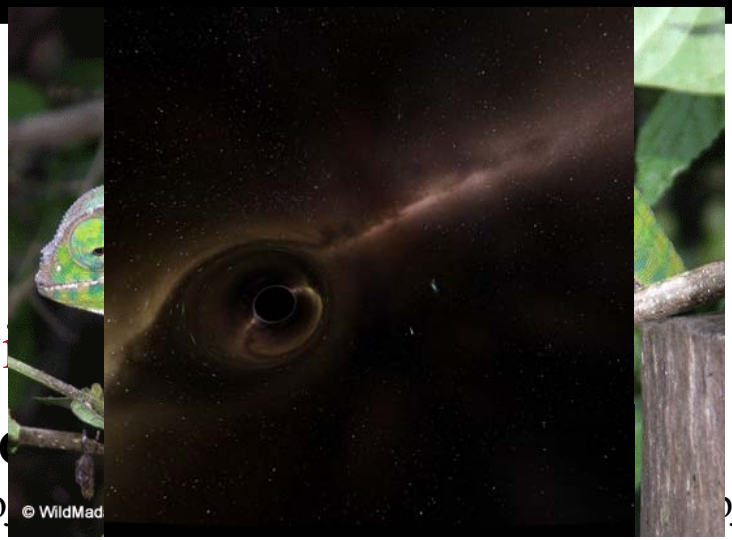
Modern time:

- **Harry Potter's invisibility cloak**
- **The stealth shield of NOD in Command & Conquer**
- **The Invisible Man by H. Wells**
- **The Invisible Woman by Lee & Kirby**
- **…**



Invisibility in nature, physics and technology

- Natural camouflage
- Black hole
- …



Current technologies to achieve invi

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

➢ **C**
Pro ject.

F-117 "Nighthawk" Stealth Fighter

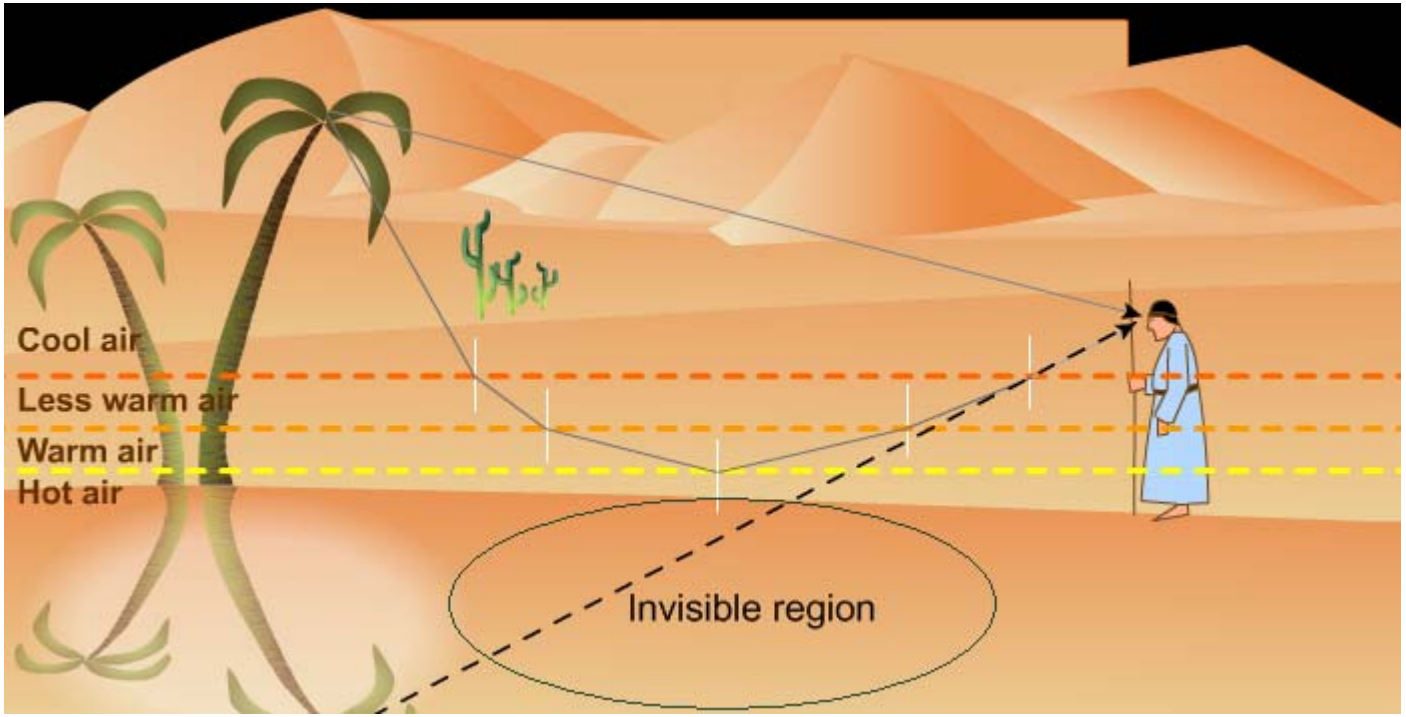
Optical Camouflage, Tachi Lab, U. of Tokyo, Japan

Cloaking ≠ Invisibility

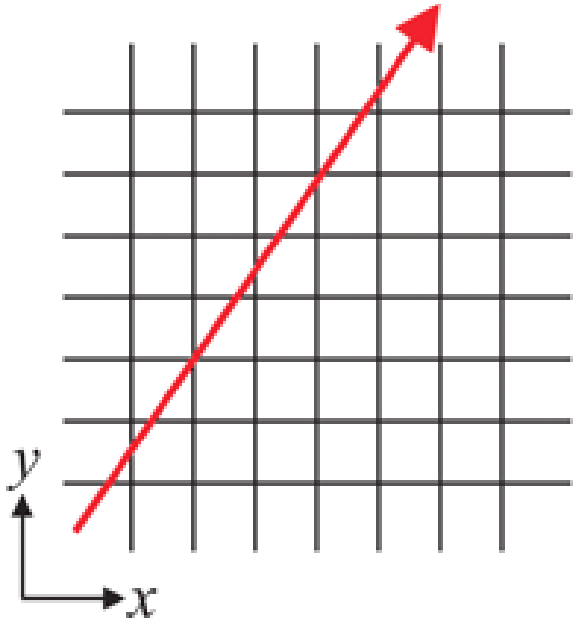
- **Cloaking is more than invisibility or camouflage**
  - **Camouflage: an adaptation to the surrounding environment**
  - **Cloaking: No need to adapt to a particular environment, with the ultimate goal of transparency — no scattering; no shade**
- **Criteria for an ideal cloak**
  - **Macroscopic, no limit to subwavelength size or near field region**
  - **Independent of object to be cloaked**
  - **Minimized absorption and scattering**
  - **Broadband**
  - **…**

A similarity in Mother Nature

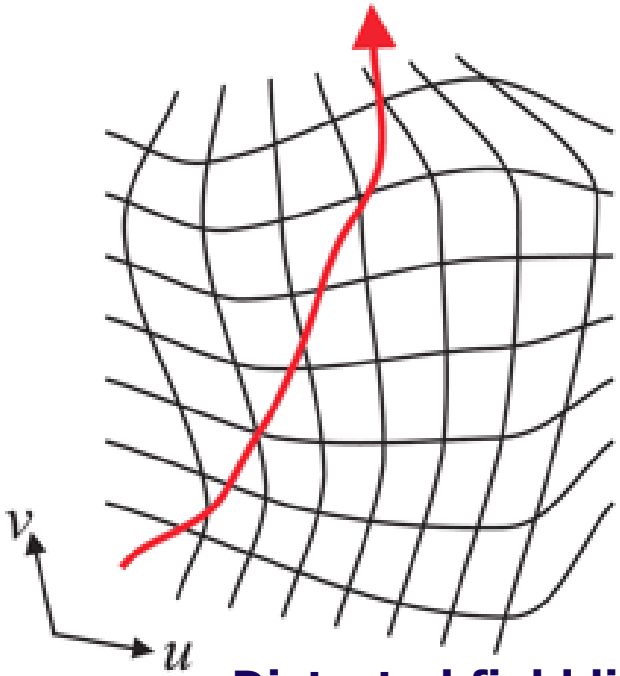
The bending of light due to the gradient in refractive index in a desert mirage



Transformation of Maxwell's equations



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

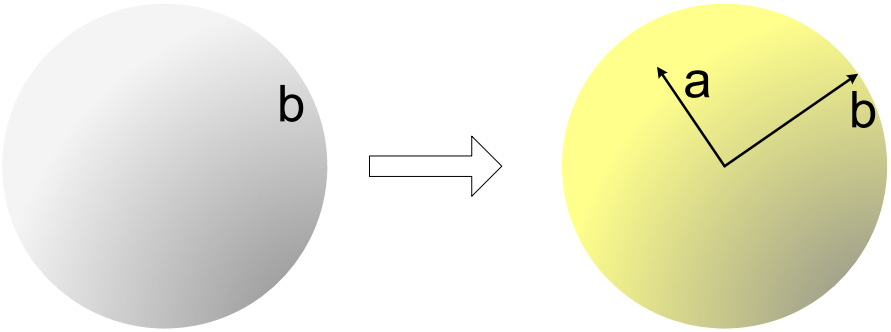
Cloaking in spherical system

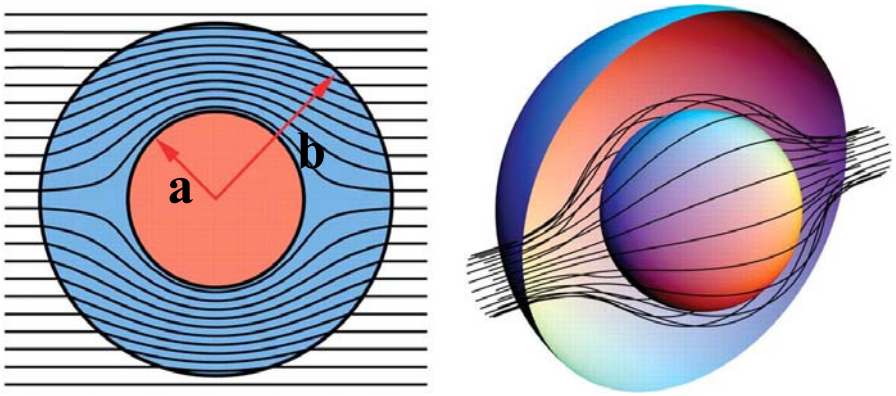
The transformation in spherical system:

$$0 < r < b \Longrightarrow a < r' < b$$

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

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

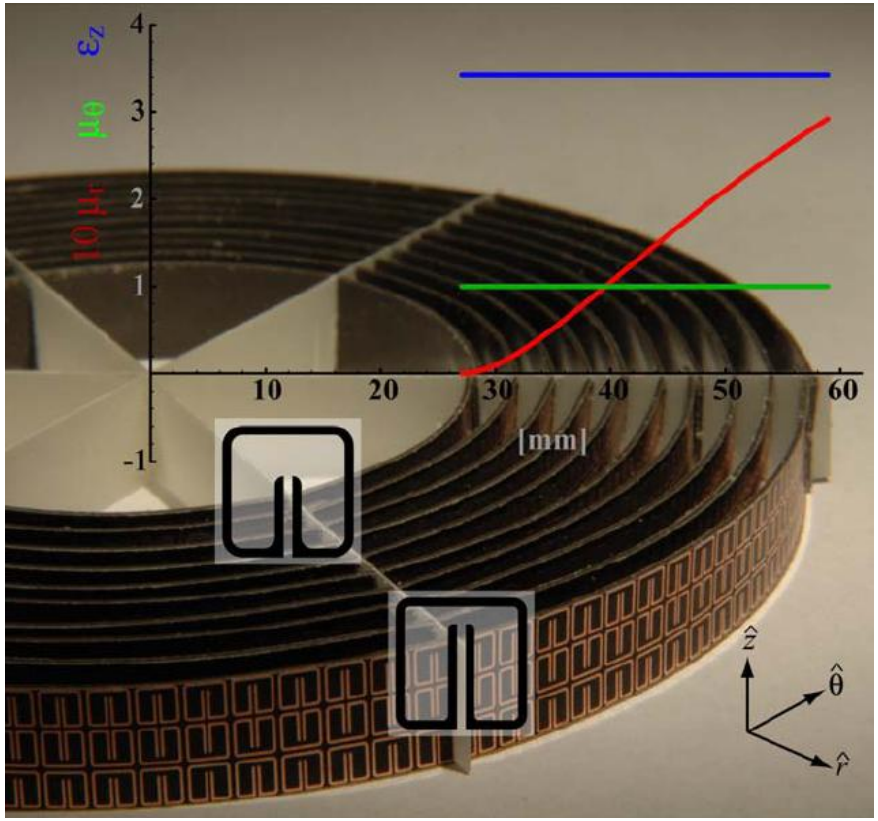


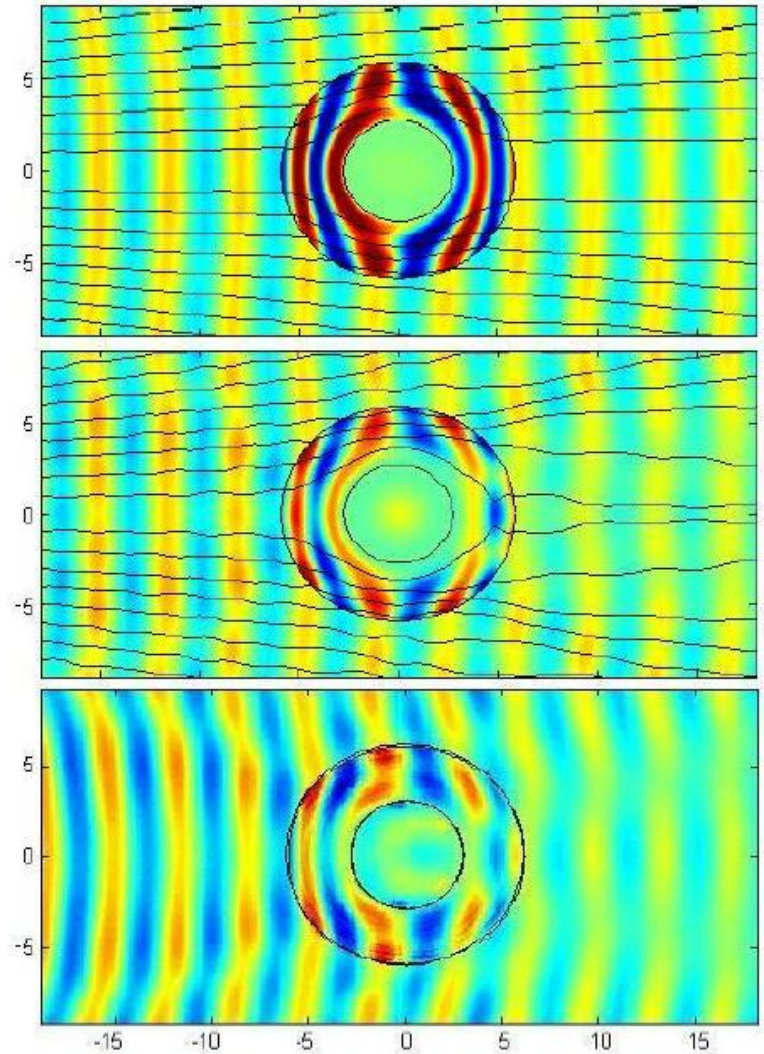


Pendry et al., Science, 2006

Similar idea was proposed by Leonhardt, Science, 2006

Experimental demonstration at microwave frequency





Structure of the cloak

Ideal case

Reduced parameter

Experimental data

Schurig et al., Science, 2006

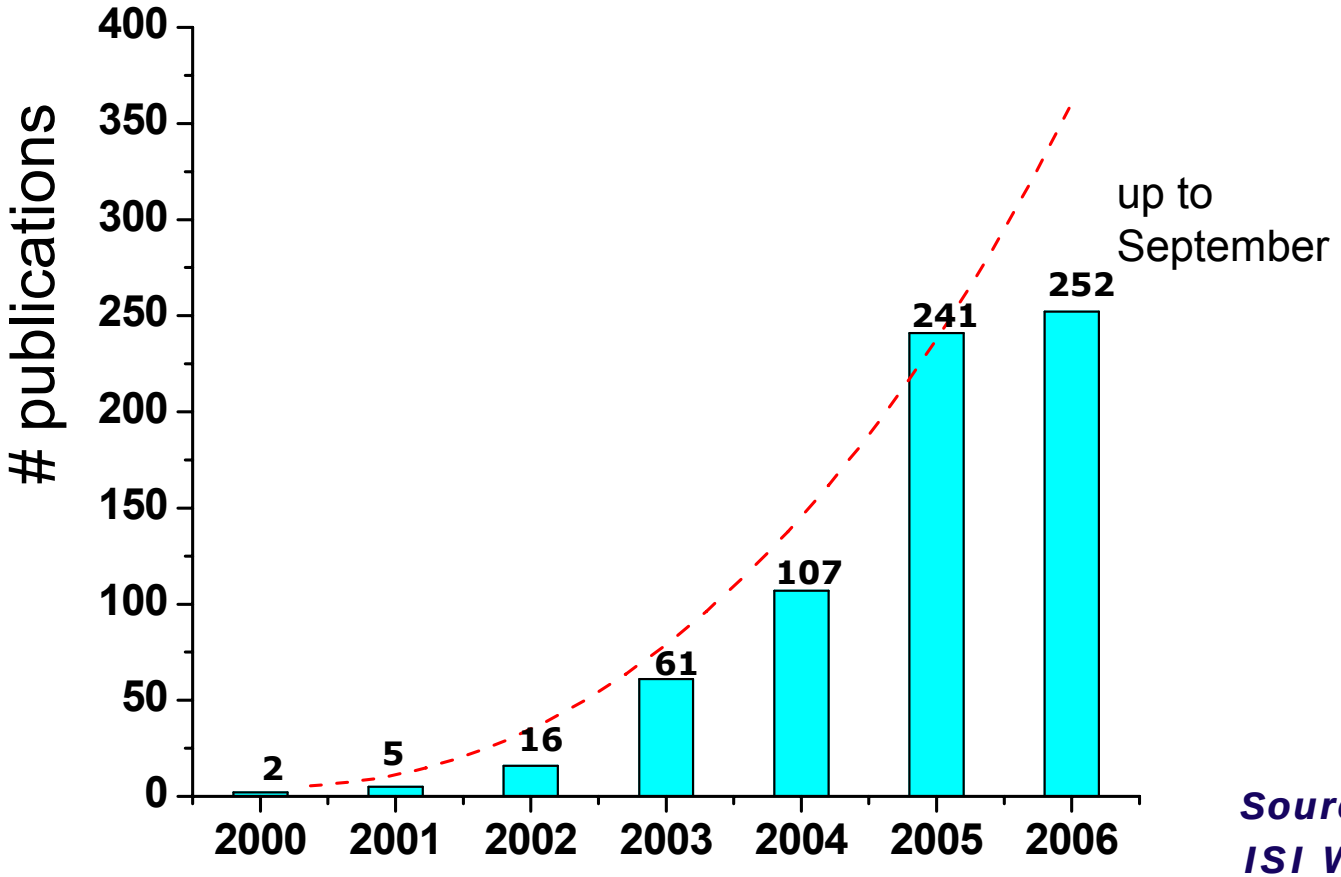
Making objects invisible in the visible

Cloaking in the visible range: Invisibility in the visible?

work is in progress….stay tuned

Increasingly keen interest to the topic

Journal articles with "metamaterial" in titles, abstracts or keywords



Source: ISI Web of Science

Take-Home Messages

- **NIMs with μ<0 and and n<0 in the visible and in the optical range**
  -> Metamaterials make light "two-handed"

- **Superlens and tunable composite NF superlens**

- **Major problem of losses can be addressed by using gain materials**

- **Novel NLO in NIMs**

- **"n<0-physics" is fun with lots of potential applications:**
  Nanoscale imaging
  Photolithography
  Sensing
  Nano-Photonics (sources, waveguides, switches, etc.)
  Cloaking