Some recent advances in the metamaterial research,

and *where we are going?*

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FP7 NMP *Metamaterials* Workshop
December 2009

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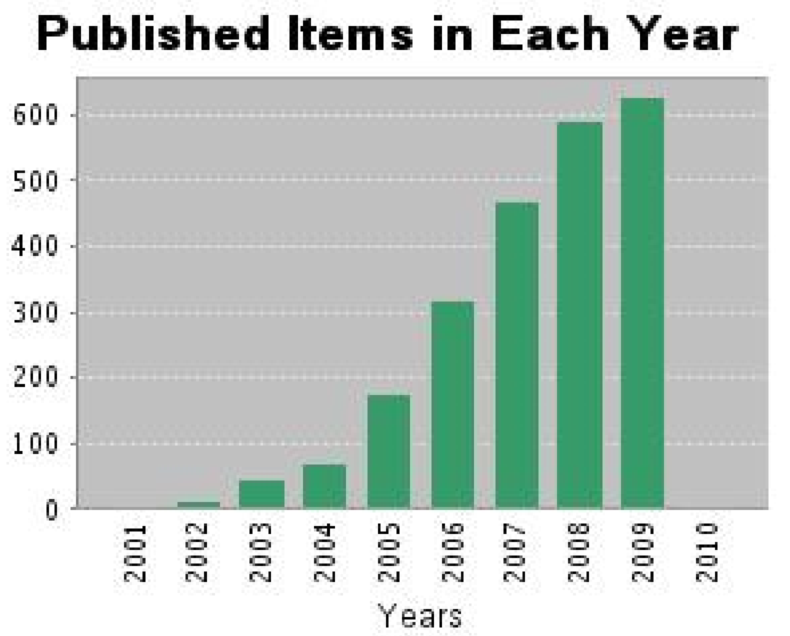
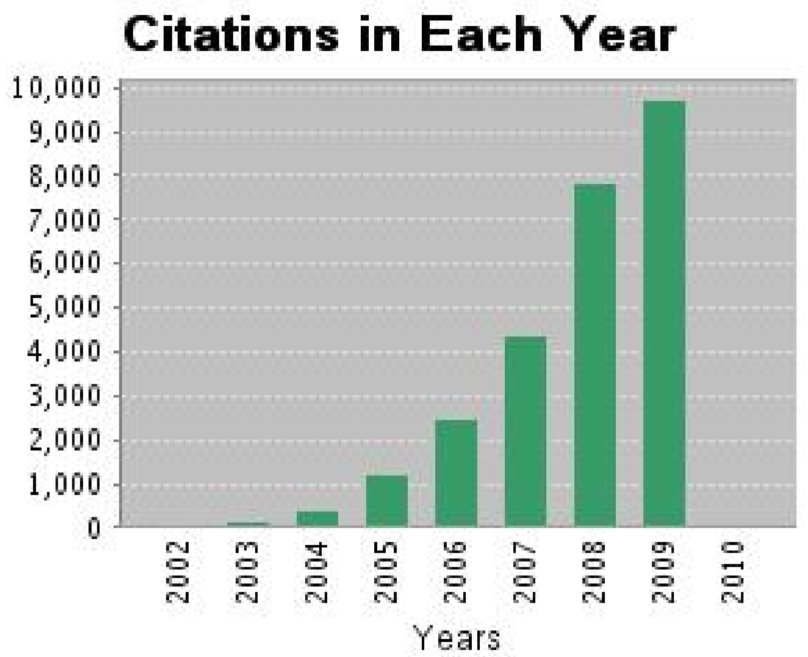
- Exotic material properties
- Chiral nanostructures
- Exotic boundaries
- Cloaking
- Nanocircuits
- Superlenses, hyperlenses

- And what next?

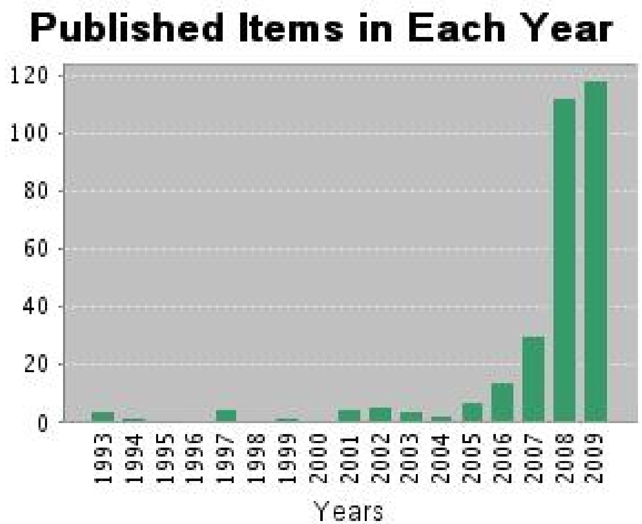
Metamaterials

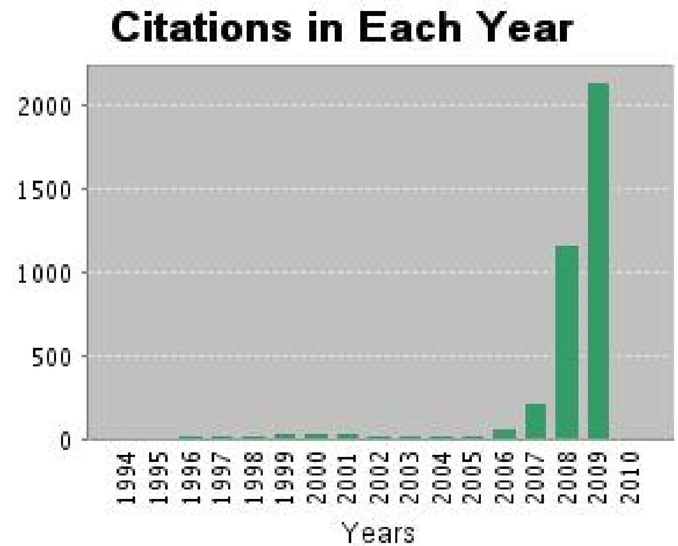




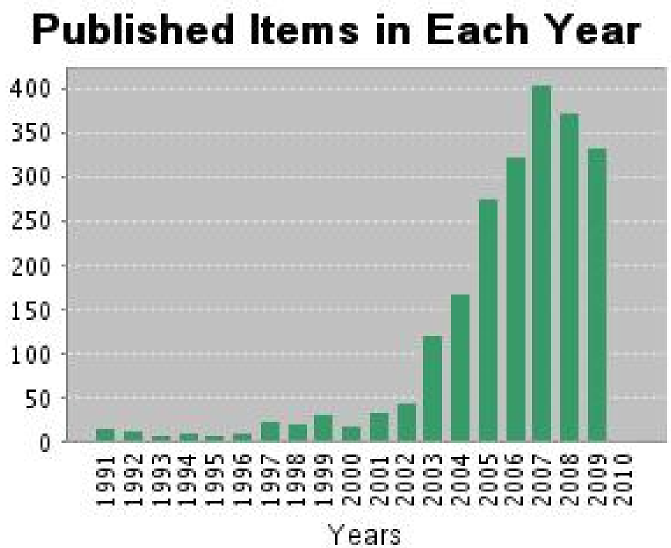
Steadily growing field

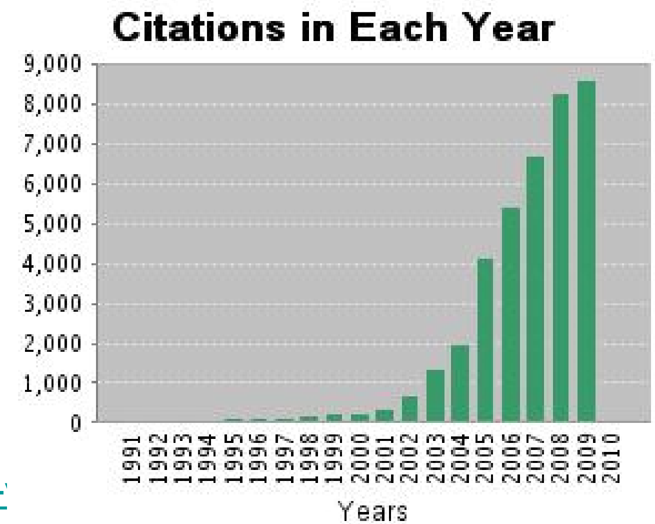
Cloaking – *exposive growth*



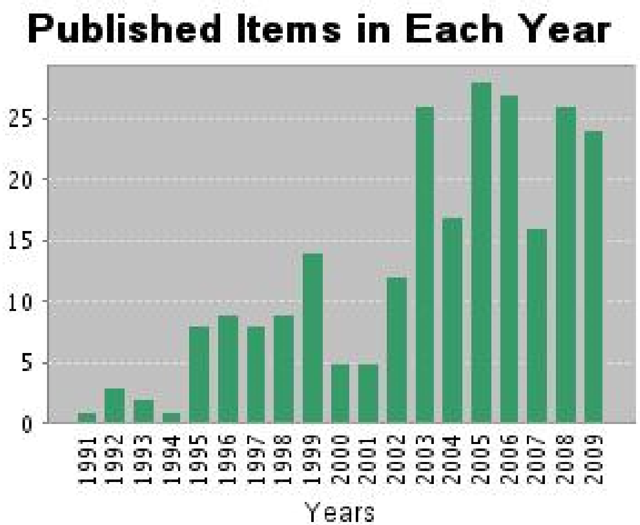


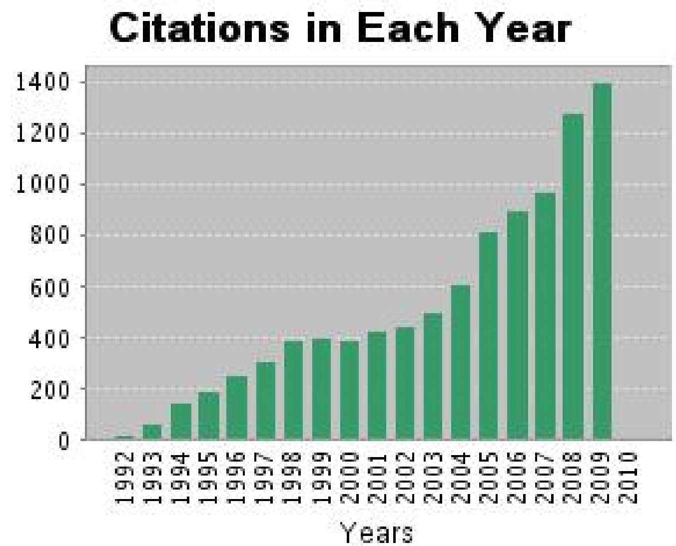
Negative refraction – *going down*



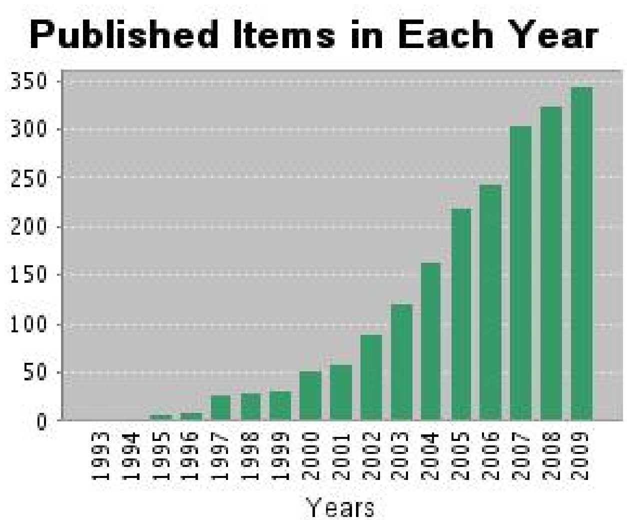


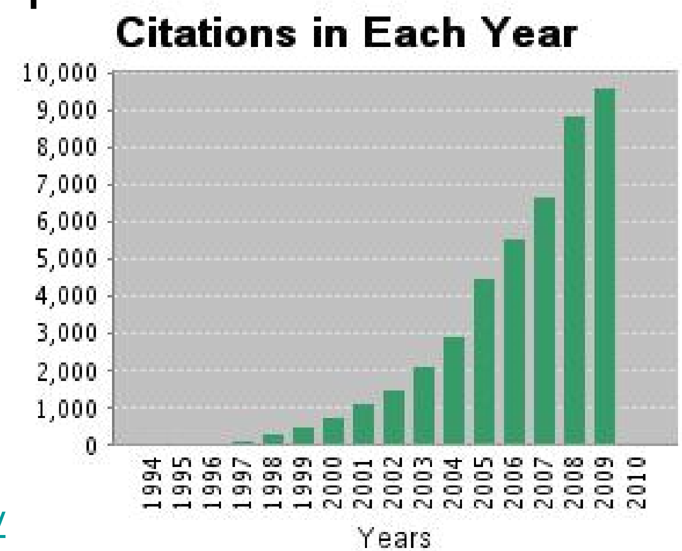
For comparison: nanochemistry





Self-assembly nano particle





Some examples of recent results

Truly exotic material properties

Can we realize material properties that REALLY cannot be found in Nature?
(something which is FORBIDDEN by basic physics?)

No physical medium can move faster than light...

$$\mathbf{D} = \frac{1}{\sqrt{1 - v^2/c^2}} \left(\epsilon_0 \mathbf{E} + \frac{1}{c^2} \mathbf{v} \times \mathbf{H} \right)$$

$$\mathbf{B} = \frac{1}{\sqrt{1 - v^2/c^2}} \left(\mu_0 \mathbf{H} - \frac{1}{c^2} \mathbf{v} \times \mathbf{E} \right)$$

$$\mathbf{D} = \epsilon\epsilon_0 \mathbf{E} + a\mathbf{z}_0 \times \mathbf{H}$$

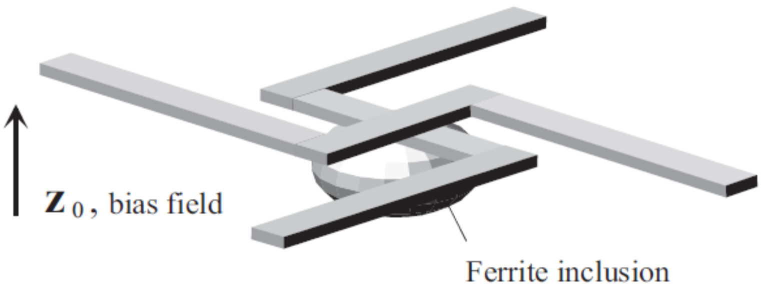
$$\mathbf{B} = \mu\mu_0 \mathbf{H} - a\mathbf{z}_0 \times \mathbf{E}$$

with $\epsilon = \mu = \pm j|\beta|, \quad a = \pm jv|\beta|/c^2.$

Purely imaginary permittivity and permeability, and also "imaginary velocity"

Meta-design

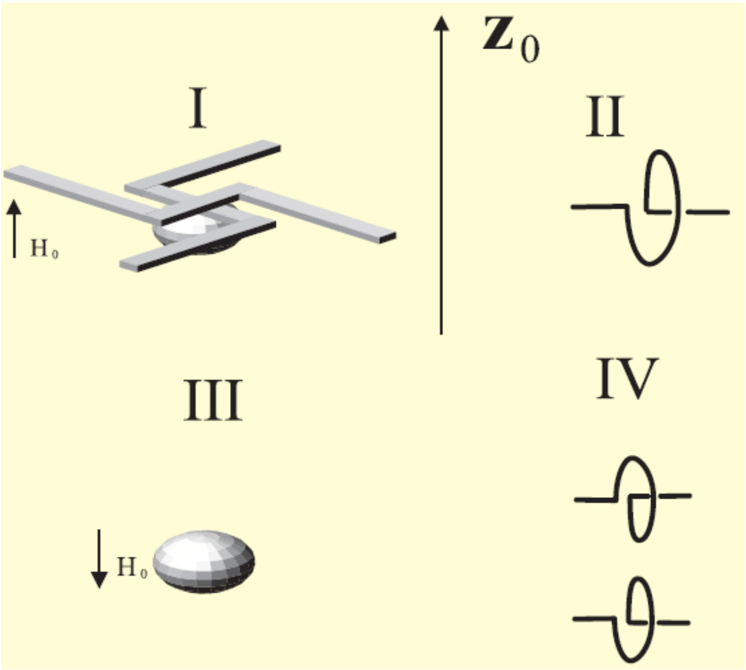
of a metamaterial which ”moves faster than light”...



Cross-coupling terms become (cross-multiplication by $-\mathbf{z}_0$)

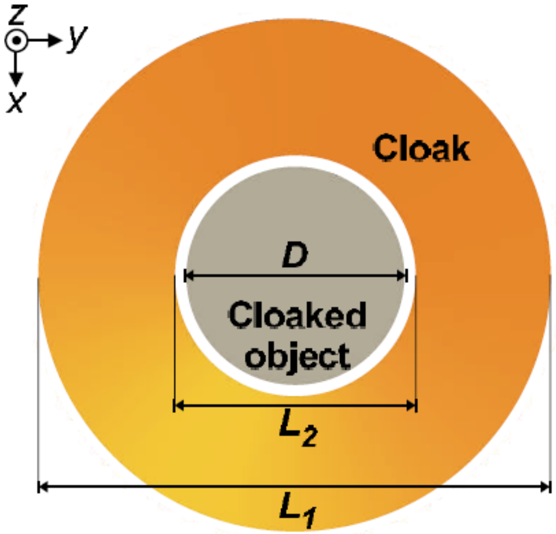
$$\mathbf{p} = -A(-j\alpha_a \mathbf{z}_0 \times \overline{\overline{I}}_t + \alpha \overline{\overline{I}}_t) \cdot \mathbf{H}$$

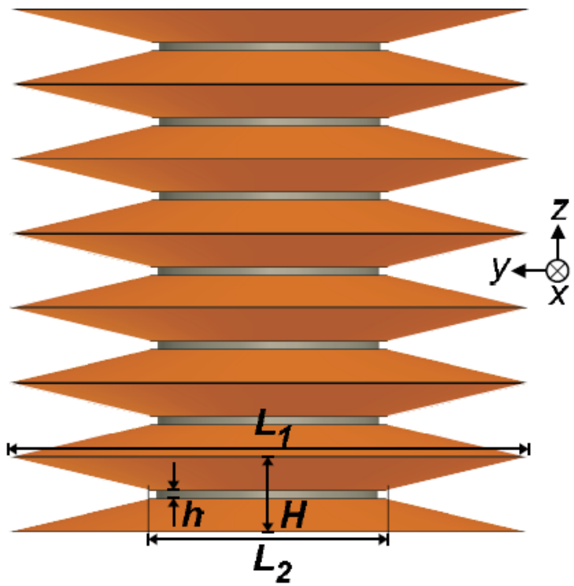
$$\mathbf{m} = -A(j\alpha_a \mathbf{z}_0 \times \overline{\overline{I}}_t - \alpha \overline{\overline{I}}_t) \cdot \mathbf{E}$$

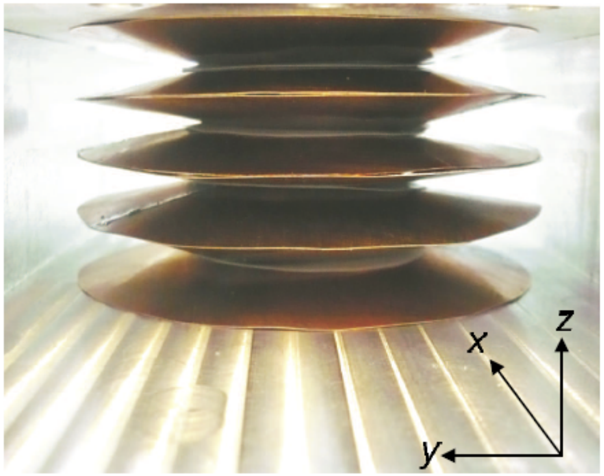


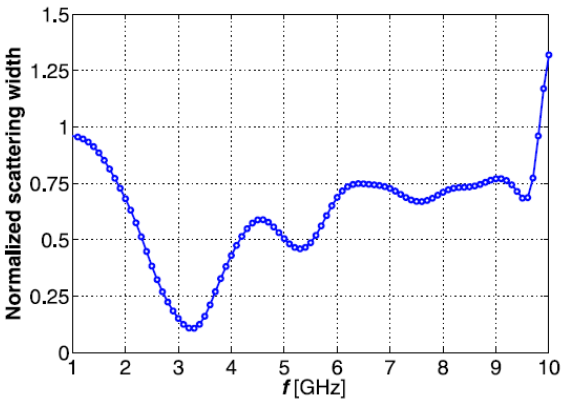
S.A. Tretyakov and I.S. Nefedov, On a possibility to imitate media moving with superluminal velocity, Proc. of 3rd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (*Metamaterials'2009*), pp. 114-116, 30.08-4.09.2009, London, UK

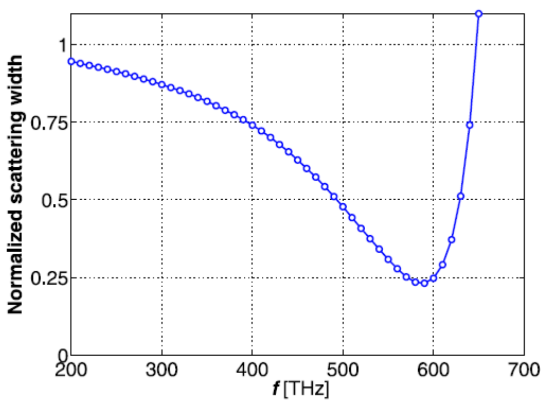
Broadband cloaks for cylindrical objects





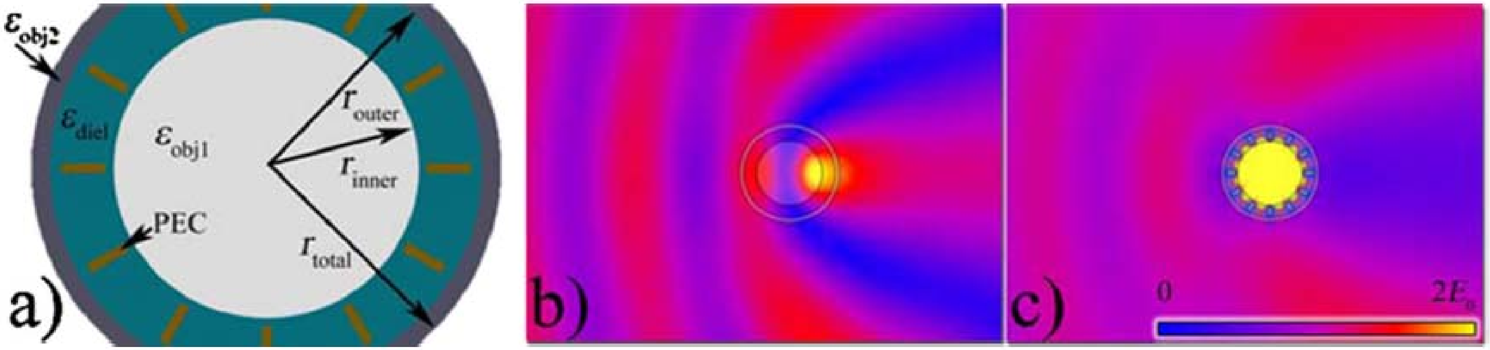


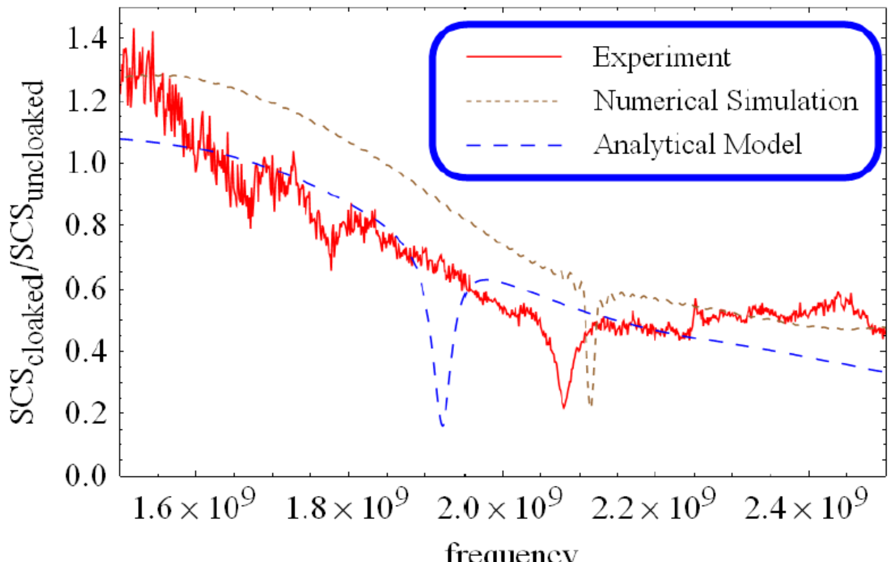




S. Tretyakov, P. Alitalo, O. Luukkonen, and C. Simovski, *Phys. Rev. Lett.*, **103**, 103905, 2009.

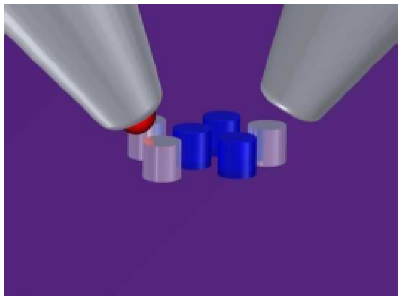
Plasmonic cloaking

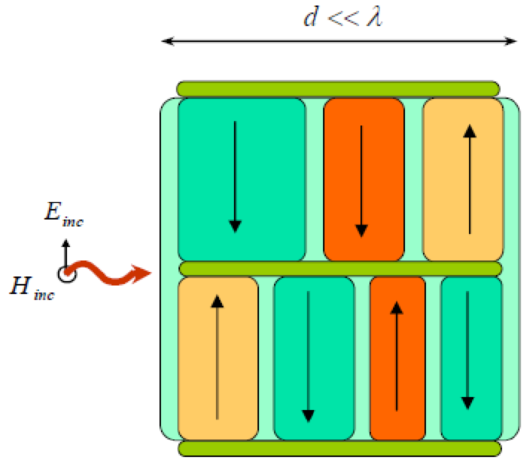


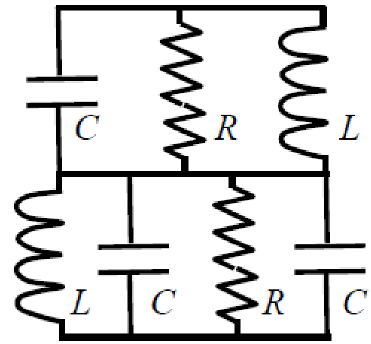


Experimental Verification of Plasmonic Cloaking at Microwave Frequencies with Metamaterials
B. Edwards, A. Alu, M.G. Silveirinha, and Nader Engheta, PRL 103, 153901 (2009)

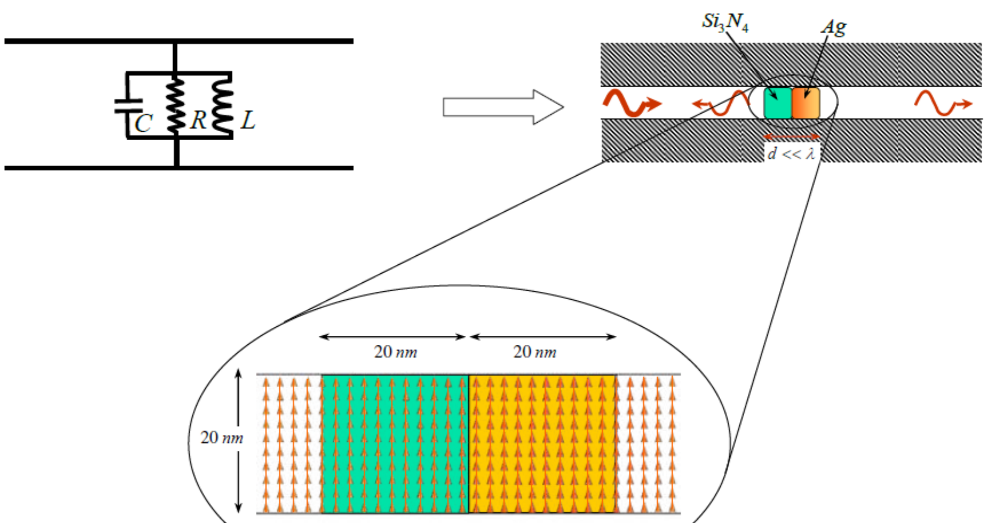
Meta-nanocircuits (group of N. Engheta)

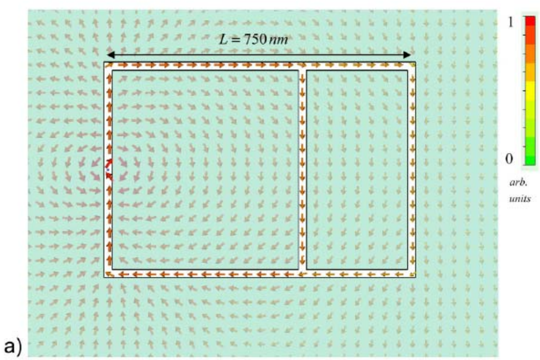




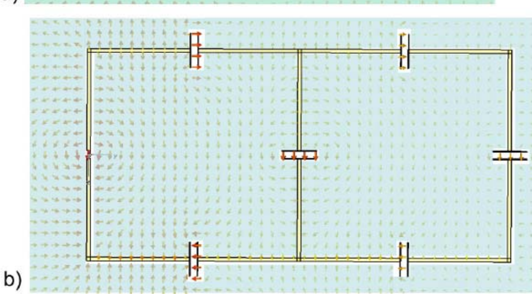


PRL 103, 143902 (2009)

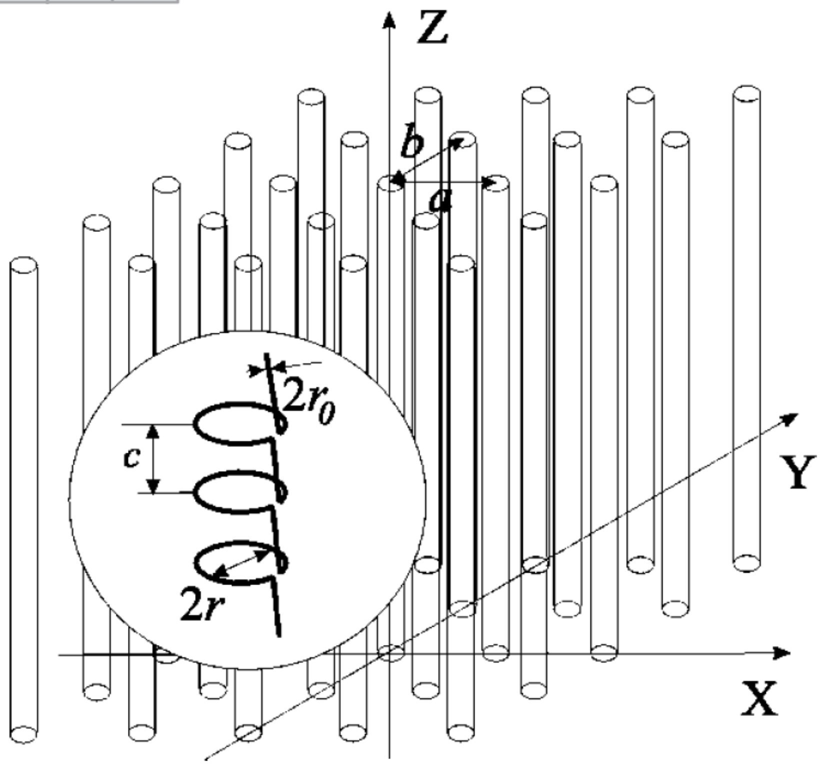


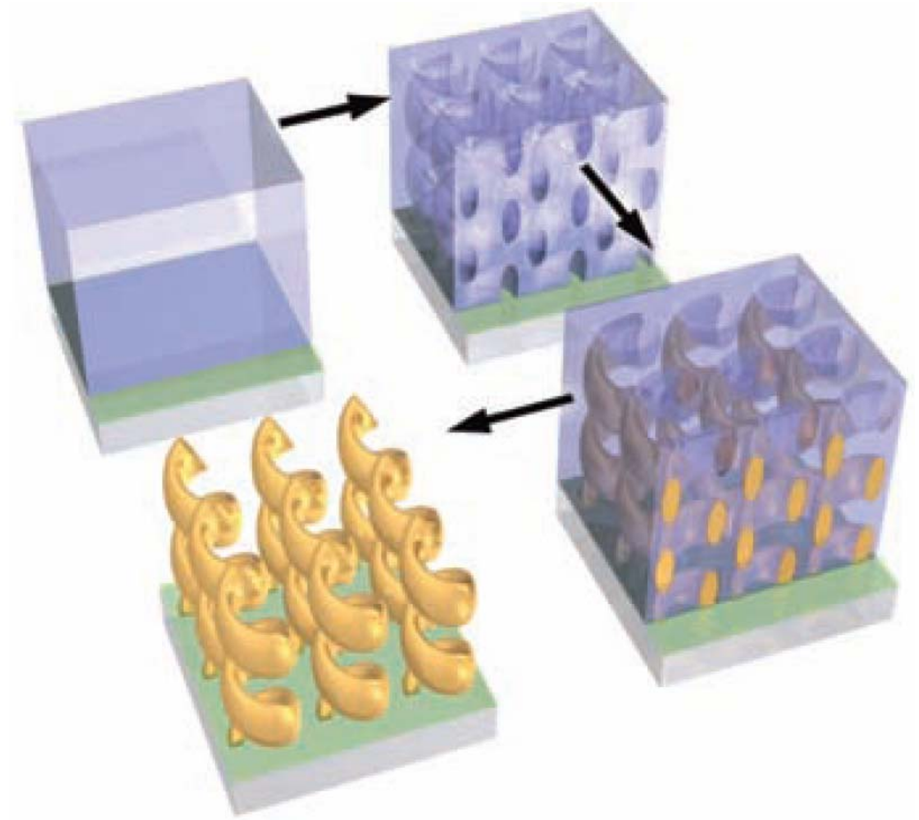


a)


b)

Chiral nanostructured metamaterials



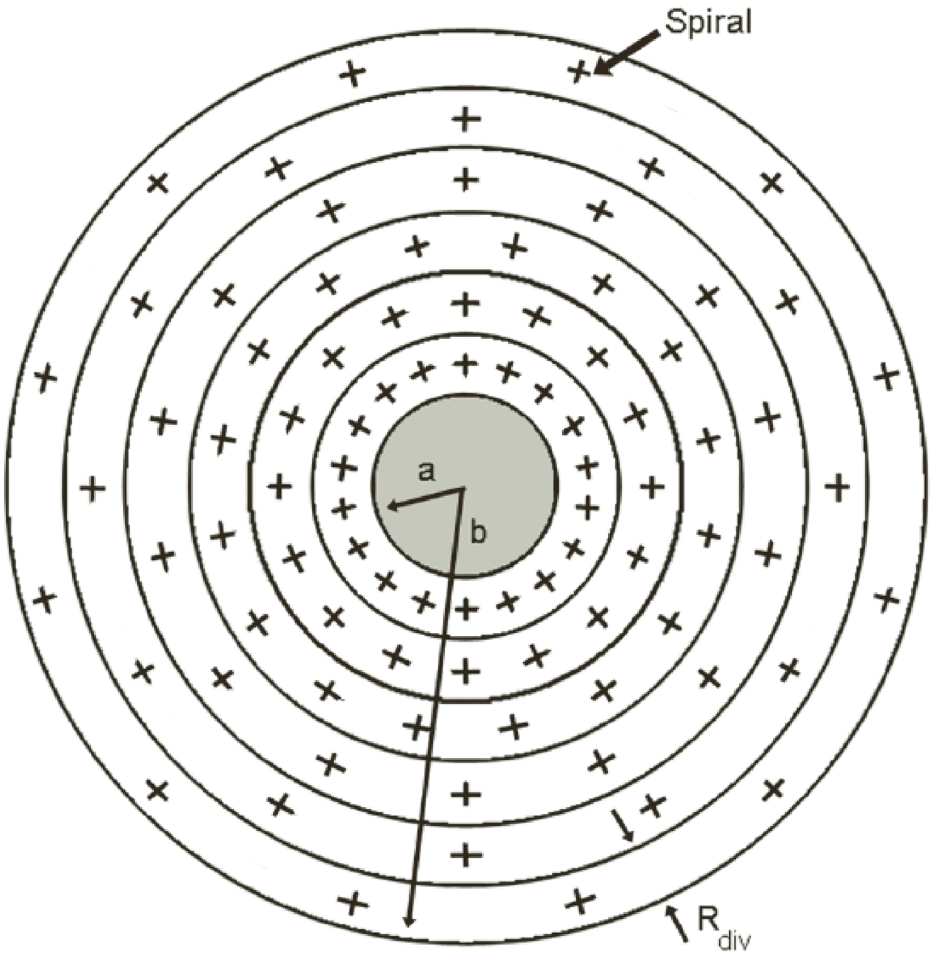


Theory: E.g., P.A. Belov, C.R. Simovski, S.A. Tretyakov, Example of bianisotropic electromagnetic crystals: The spiral medium, *Physical Review E,* 67, 056622, 2003 (left).

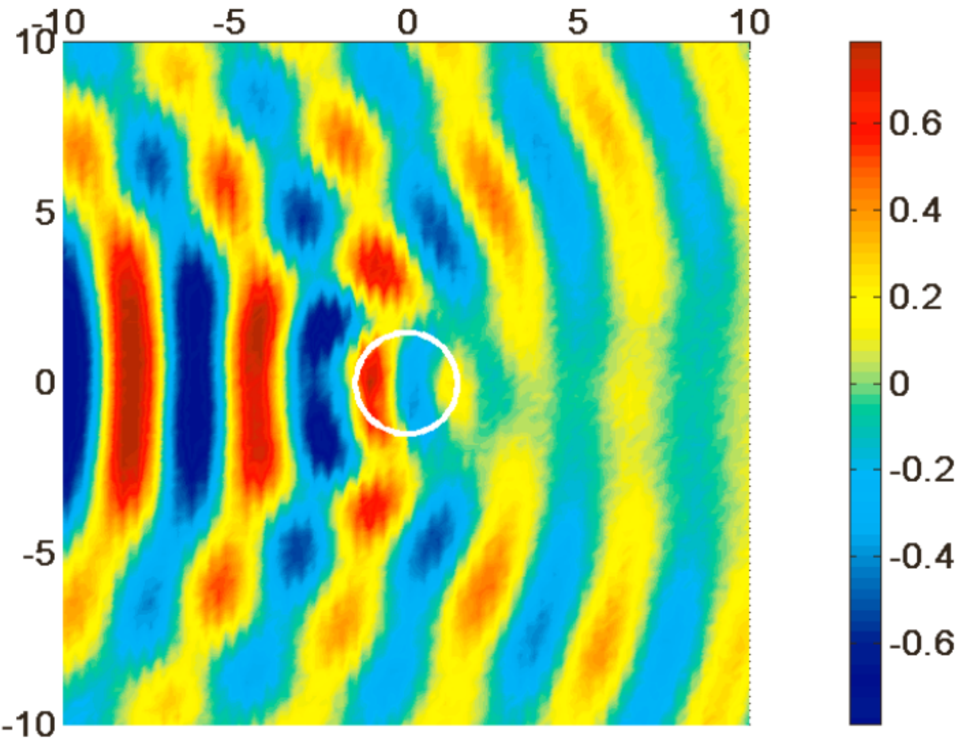
Experiment: J.K. Gansel et al, *Science* 325, 1513, 2009 (right).

Using chirality for cloaking

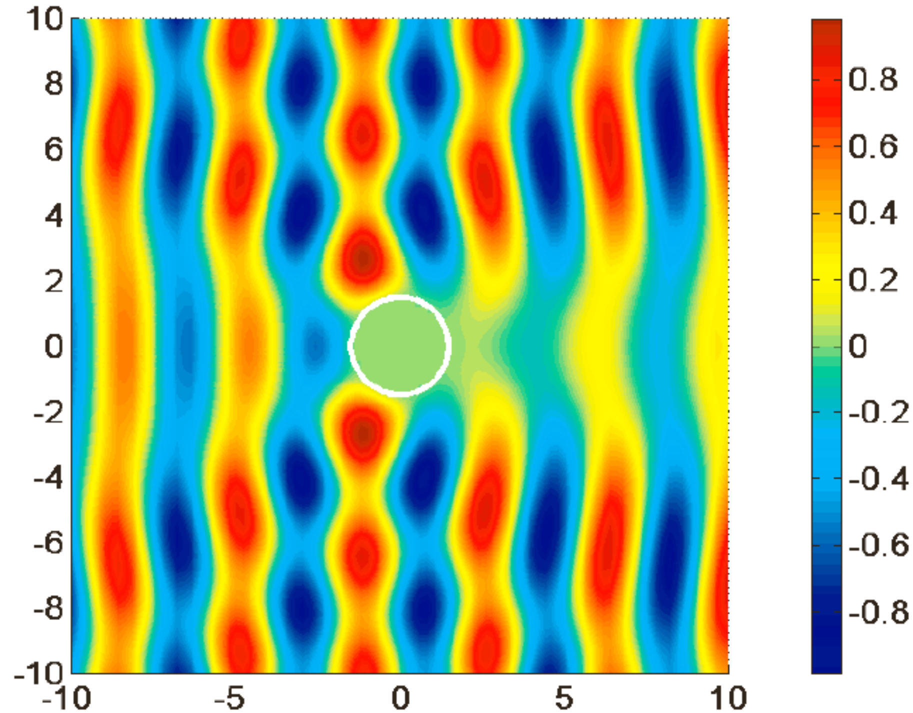
ε=μ medium



Experimental results



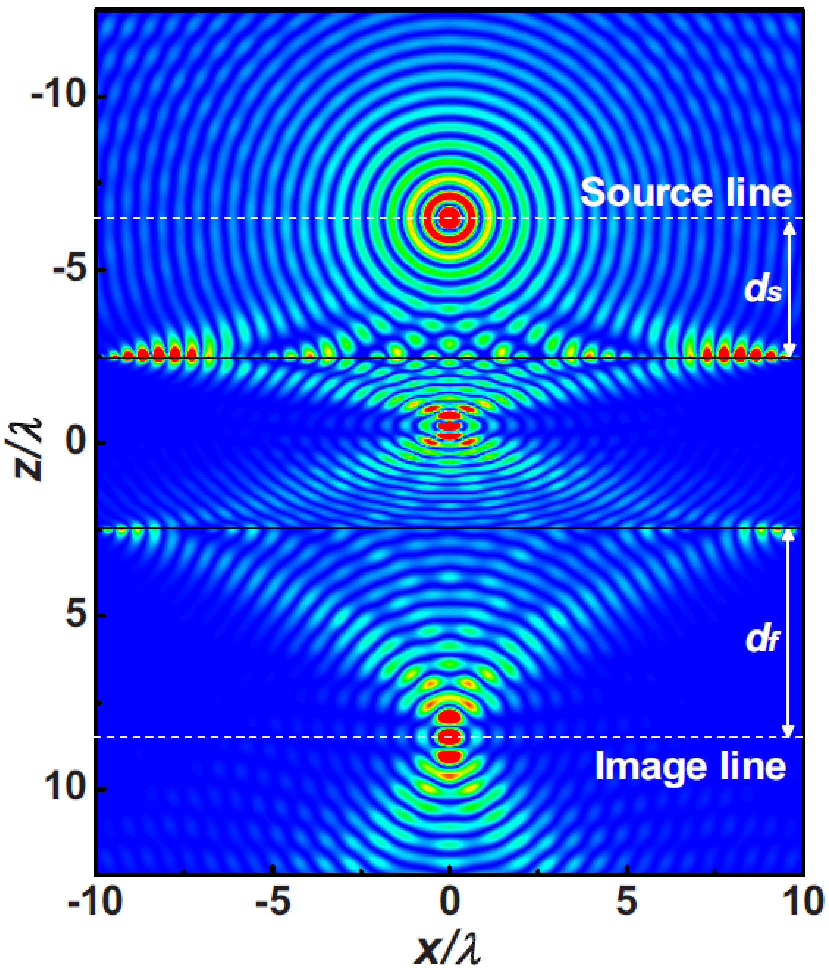
Bare cylinder



Cloaked cylinder

K. Guven, E. Saenz, R. Gonzalo, E. Ozbay, and S. Tretyakov, Electromagnetic cloaking with canonical spiral inclusions, *New J. of Physics,* vol. 10, no. 11, p. 115037, 2008.

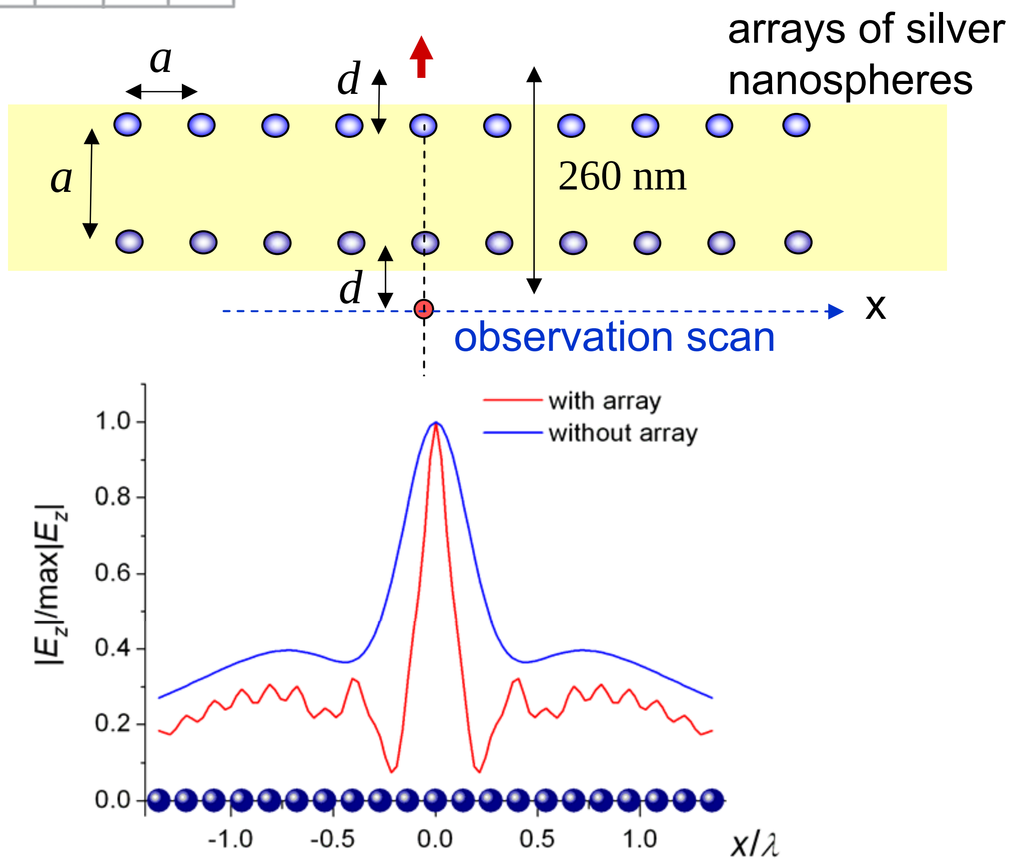
Superlenses, hyperlenses...

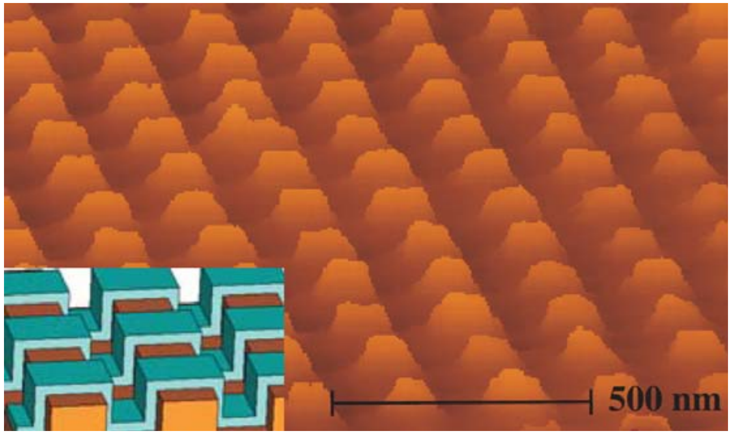


Anisotropic metamaterial lens, with parameters $\varepsilon_x=\mu_y=-2+0.001i$ and $\mu_z=-0.5+0.001i$

Compact planar far-field superlens based on anisotropic left-handed metamaterials, Nian-Hai Shen, S. Foteinopoulou, M. Kafesaki, Th. Koschny, E. Ozbay, E.N. Economou, C. Soukoulis, PHYSICAL REVIEW B **80**, 115123 2009.

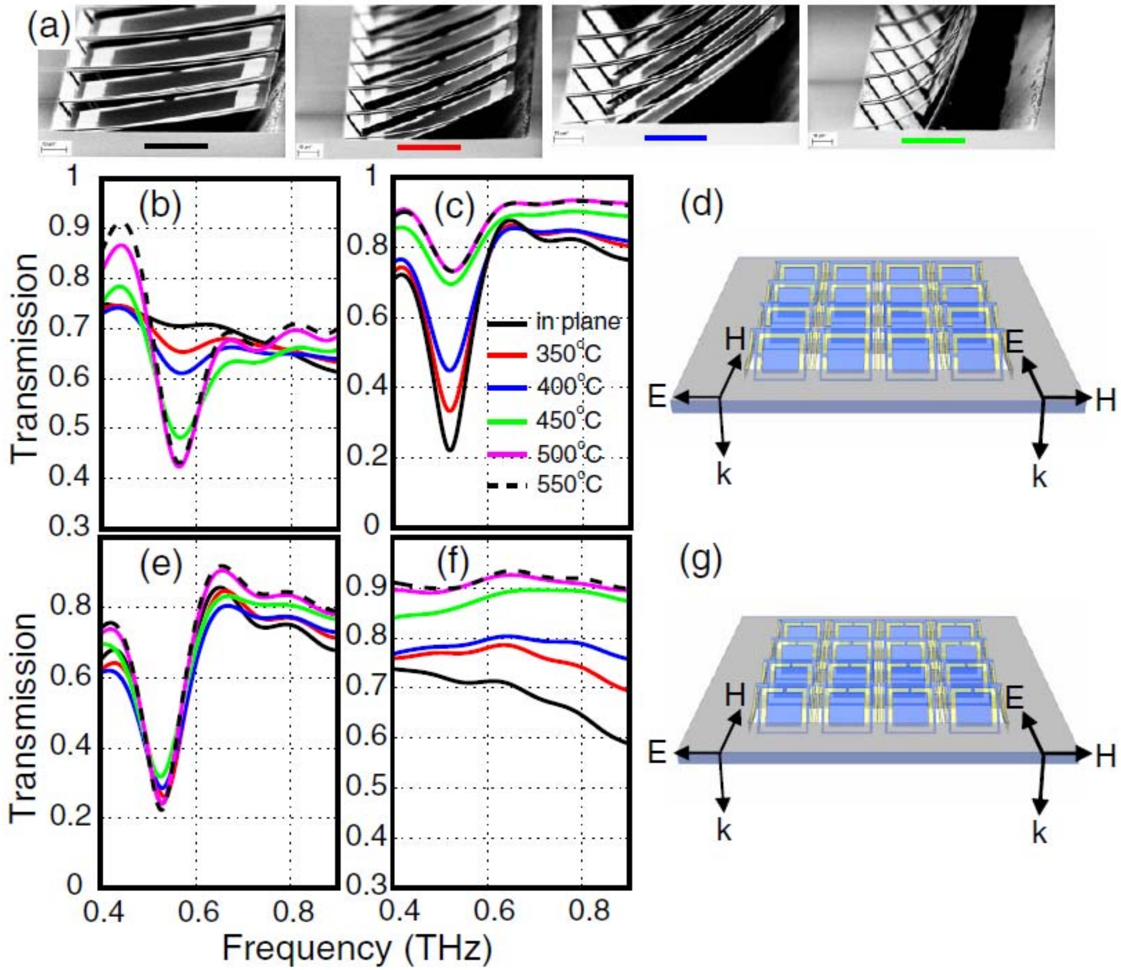
Superlenses, hyperlenses...





Theory: C.R. Simovski, A.J. Viitanen, S.A. Tretyakov, *J. of Applied Physics,* 101, 123102 (2007)
P. Alitalo, C. Simovski, A. Viitanen, and S. Tretyakov, *Physical Review B*, 74, 235425 (2006).
Experiment: Optical properties of metallic meanders, Fu Liwei, H. Schweizer, T. Weiss, and H. Giessen, J. Opt. Soc. Am. B, 26, No. 12/December 2009

Reconfigurable



Reconfigurable Terahertz Metamaterials, Hu Tao, A.C. Strikwerda, K. Fan, W. J. Padilla, X. Zhang, and R. D. Averitt, PRL 103, 147401 (2009)

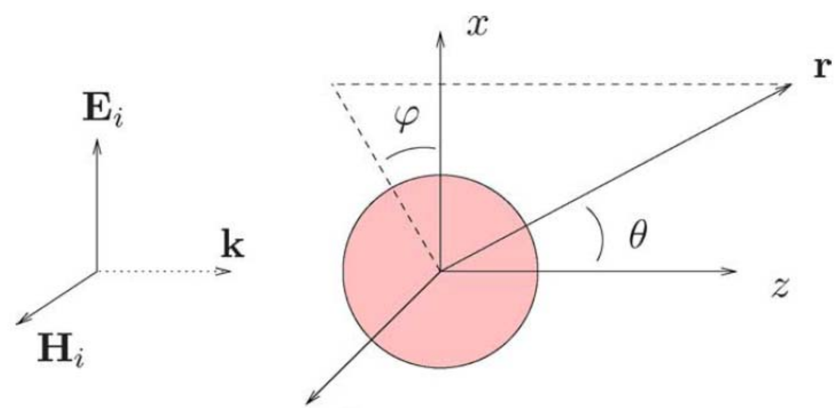
New types of boundaries

$$D_z = 0, \quad \partial_z B_z = 0$$

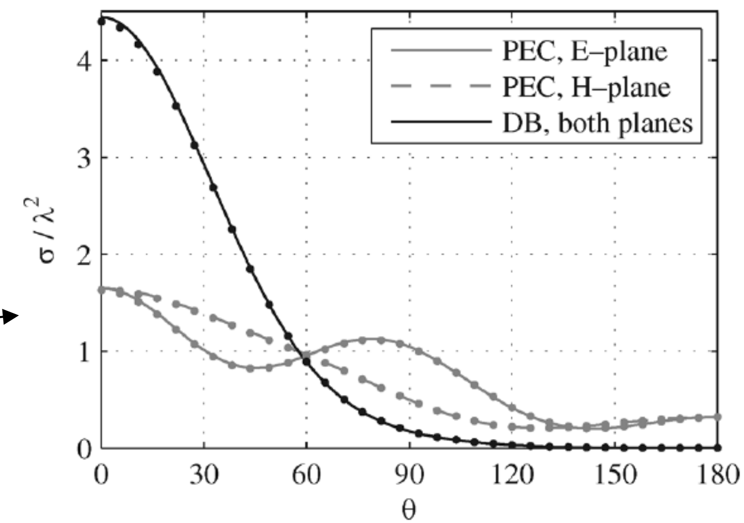
$$\partial_z D_z = 0, \quad B_z = 0$$

$$\mathbf{n} \cdot \mathbf{D} = 0, \quad \mathbf{n} \cdot \mathbf{B} = 0$$

$$\nabla \cdot (\mathbf{nn} \cdot \mathbf{D}) = 0, \quad \nabla \cdot (\mathbf{nn} \cdot \mathbf{B}) = 0$$



Zero back-scattering from a DB sphere

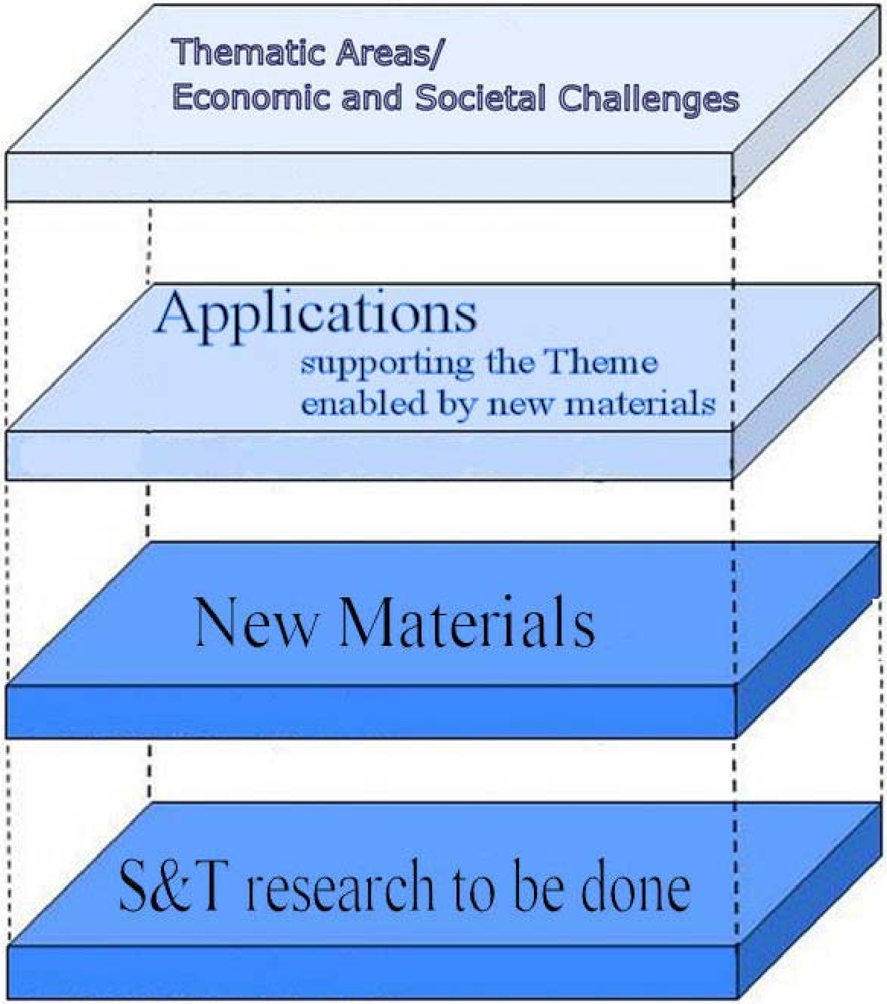


General Electromagnetic Boundary Conditions Involving Normal Field Components,
I.V. Lindell, H. Wallen, and A. Sihvola,
IEEE Antennas and Wireless Propagation Letters, 8, 877-880, 2009.

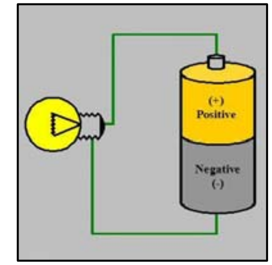
Outline of the metamaterials research road map

Metamorphose VI

Four-layer structure of the RRM



(After Anne de Baas)



Top level - strategy

***Thematic areas** (chalenges):*

- **Nanosciences, Nanotechnologies, Materials** (materials with superior and unusual electromagnetic properties, targeted design of electromagnetic materials, new technologies to manufacture these materials, including self-assembly and nanochemistry)
- **Information and communication technologies** (low-cost low power consumption communication and control systems)
- **Energy** (low-loss components, advanced solar cells,...)
- **Health** (sensors, on-body communication systems, implanted actuators...)
- **Environment** (monitoring devices,...)
- **Transport** (car radars, sensors,...)
- **Security** (security control devices, sensors, monitoring devices,...)
- **Dual applications** (especially in aviation - not for the FP)

Middle level (systems)

- **Nanosciences, Nanotechnologies, Materials**
  - **Material-science goals:**
    - **Design and realization of electromagnetic materials with unusual and extreme electormagnetic properties**
    - **Targeted design of electromagnetic materials**
      - **Material architectures providing design control over material parameters, losses, spatial dispersion, nonlinearity**
      - **Electrical, magnetic, and optical control of the properties of engineered materials**
  - **Application-driven goals for the materials enabling new capabilities in:**
    - **Nanoimaging and nanosensing devices**
    - **Sub-wavelength optical information processing systems**
    - **Smart and adaptive integrated electronic and optical circuits and devices**
    - **Sensors, including biosensors**
    - **In-body drug delivery and control devices**

Bullet points at the bottom level (science and technology)

- **Material-science driven:**
  - Theoretical modelling and design of artificial materials – providing design control over material parameters, losses, spatial dispersion and non-linearity
  - Targeted synthesis of electromagnetic materials
  - Development and realization of exotic-property and non-classical optical materials
  - Reconfigurable microwave and optical materials
  - Active optical materials with compensated loss
  - In-situ and non-destructive characterisation of artificial electromagnetic materials
  - Materials with engineered non-linearity
  - Field-transforming metamaterials (cloaks, concentrators, dividers, etc.)
  - Fundamental aspects of novel fabrication technologies
  - In-situ and nondestructive characterisation of artificial electromagnetic materials
- **Application-driven:**
  - Low-loss miniaturized microwave components for devices and antennas (especially components using left- right-handed transmission line components)
  - Adaptive and reconfigurable microwave materials as enablers of multiband, multifunctional microwave devices and antennas
  - Absorbing and filtering (shielding) materials and structures
  - Resonant nanotips for nanoscopy and nanoantennas
  - Artificial materials enabling terahertz devices
  - Photonic nanocircuits
  - Nano-structured light and microwave energy harvesting materials
  - Structures for slowing and localization (storage) of light, also on quantum level

Science and technology level challenges:

Expected Impact

Design and implementation of engineered materials with the required properties: *Materials-on-demand*

– Theoretical modelling and design of artificial electromagnetic materials
– Fundamental aspects of novel fabrication technologies
– In-situ and nondestructive characterisation of artificial electromagnetic materials

Absorbing and filtering (shielding, mode-transforming) materials and structures

- Nano-structured material layers for absorption of electromagnetic radiation in extremely wide ranges of incidence angles and polarizations in pre-determinded frequency ranges.
- Subwavelength filtering metamaterial layers for applications in advanced solar cells and in nano-processing of light.

Resonant nanotips for nanoscopy, nanoantennas

- Design and practical implementation of resonant energy guiding and nanofocusing nano-structures for applications in scanning near-field optical microscopes and as nanoantennas.

Nanostructured materials for light and microwave energy harvesting

- Development, study and design of nano-structured metamaterial layers containing semiconductors for direct harvesting of light and microwave energy (transforming into electric current).

Field-transforming metamaterials (cloaks, concentrators, dividers)

- Engineered electromagnetic materials designed to perform pre-determined transformations of electromagnetic fields, for applications in cloaks, field concenrators (nanoantennas), wave splitters, storage of light, etc.

Active and reconfigurable terahertz and optical materials

- Design and realization of artificial optical materials with engineered properties (permittivity, permeabilty, chirality, surface and sheet impedances) which can provide power gain for light waves and be electronically adjusted or switched within a pre-defined parameter range.

Artificial materials enabling terahertz devices

- Artificial electromagnetic materials with engineered pre-defined properties in the terahertz frequency range, including artificial dielectrics (low-loss or absorptive), artficial magnetics, engineered anisotropy and bi-anisotropy.

Exotic-property and non-classical optical materials, optical nanocircuits

- Design and realization of artificial electromagnetic materials with exotic and extreme properties (very low or very large values of material parameters or wave impedance). Based on the use of these new materials, realization of photonic nanocircuits for nanoprocessing of light.

Structures for slowing and localization (storage) of light, also on quantum level

- Design and realization of artificial nanostrucured materials with engineered dispersion for extreme slowing and localization of light.

Engineered non-linearity of materials

- Design, realization and studies of composite materials with engineered non-linearities for applications in waveform control, signal processing of microwave and optical signals, as well as in nanoimaging, including superlenses and magnifying superlenses.