Metamaterial inclusion geometries and their electromagnetic properties

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FP7 NMP *Metamaterials* Workshop

December 2009

- Introduction
- Electromagnetic properties defined by chemical composition and (or?) geometry of the micro/nanostructure
- Artificial dielectrics and relevant inclusion geometries
- Artificial magnetics and relevant inclusion geometries
- Artificial chiral and bi-anisotropic media and related geometries

Metamaterials

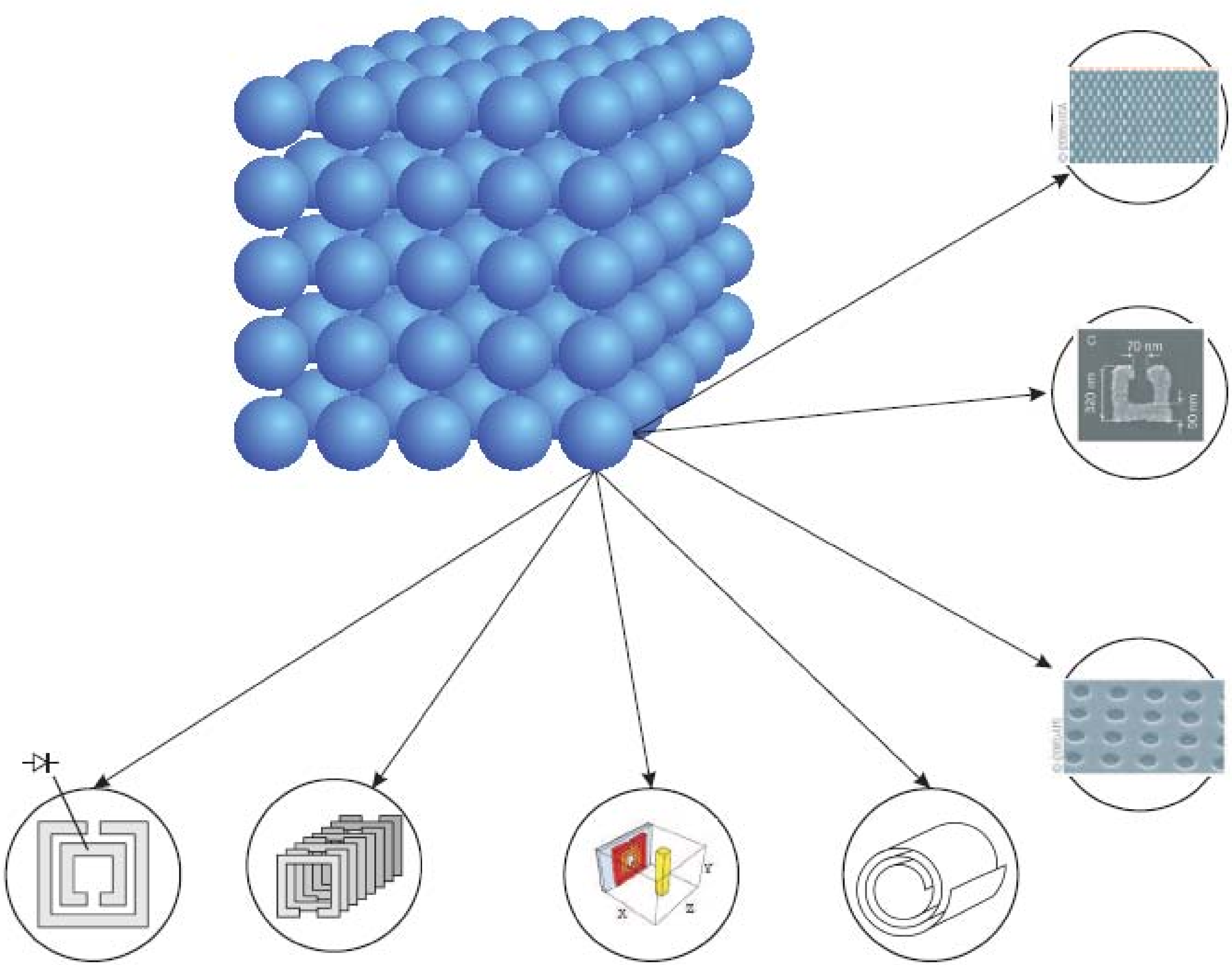
Metamaterials are artificial electromagnetic (multi-)functional materials engineered to satisfy prescribed requirements. They have new or rare properties as compared to what can be found in nature.

Wikipedia: These materials usually gain their properties from structure rather than composition, using the inclusion of small inhomogeneities to enact effective macroscopic behavior.

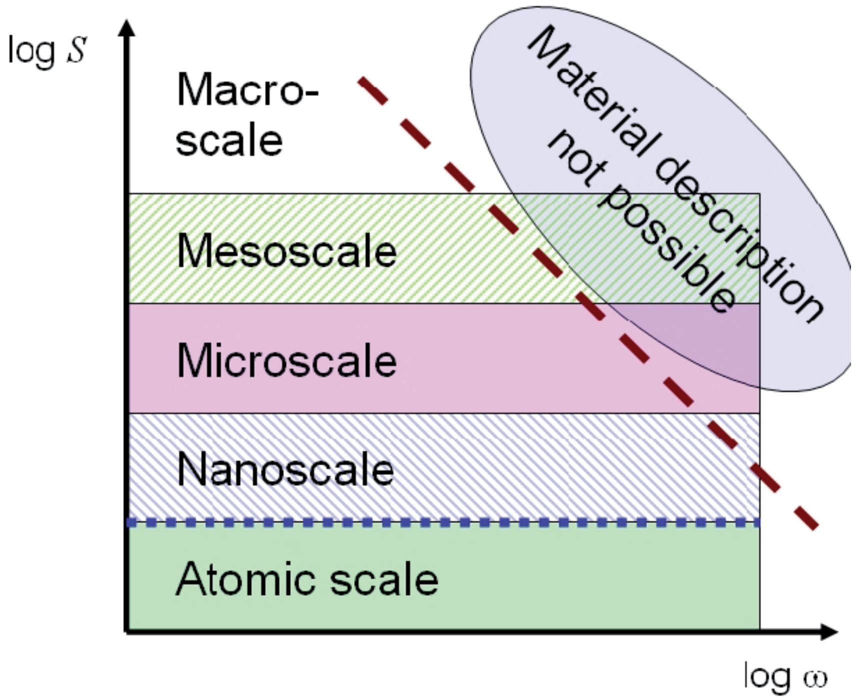
Metamaterial is a new structural material made of ordinary materials (transgressing from chemical composition to geometrical structures)

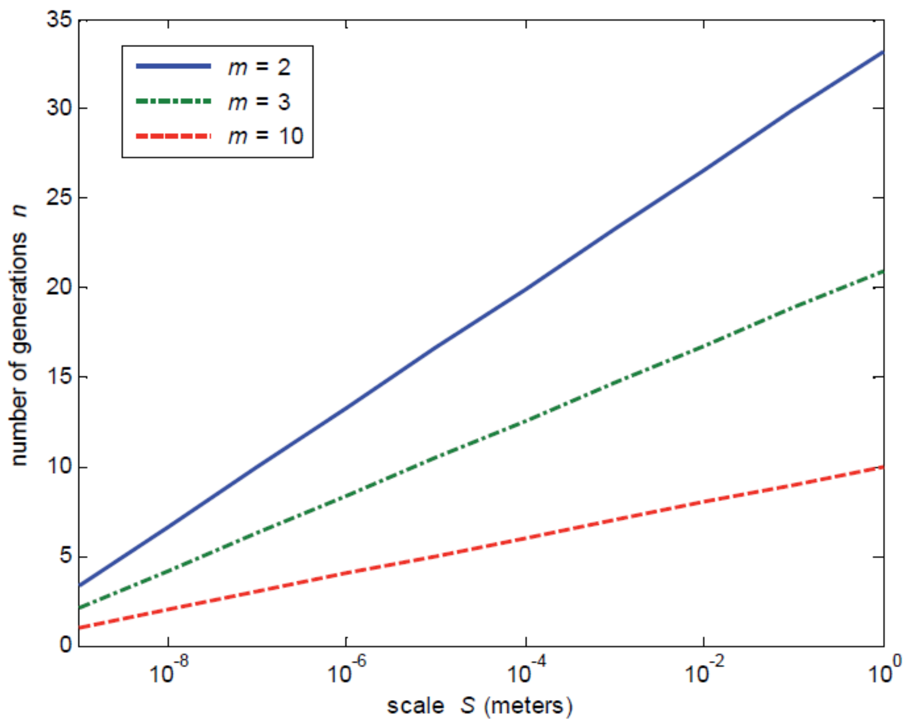
Metalanguage is a language used to make statements about statements in another language…

Metamaterial concept



Metameta...metamaterials





m = metamaterialization period.

m is the ratio between the scale
where the emergent (metamaterialistic) effect can be distinguished
and the size of the average molecule dimension in the microscale.

A. SIHVOLA, METAMATERIALS: A PERSONAL VIEW,
RADIOENGINEERING, VOL. 18, NO. 2, JUNE 2009

Control question

- **Is the following sentence telling about metamaterials or about something else?**
- *Advanced materials with properties tailored on the molecular and mesoscales are expected to stimulate evolutionary advances and revolutionary breakthroughs in emerging key-technology areas such as information and communication as well as catalysis, energy, and transportation.*

Artificial dielectrics and relevant inclusion geometries

- **Electrically polarizable inclusions (e.g. dielectric or metallic spheres...)**
  - Electrically small inclusions: non-resonant inclusions or complex-shaped particles or plasmonic nanoparticles...

Artificial dielectrics: geometries

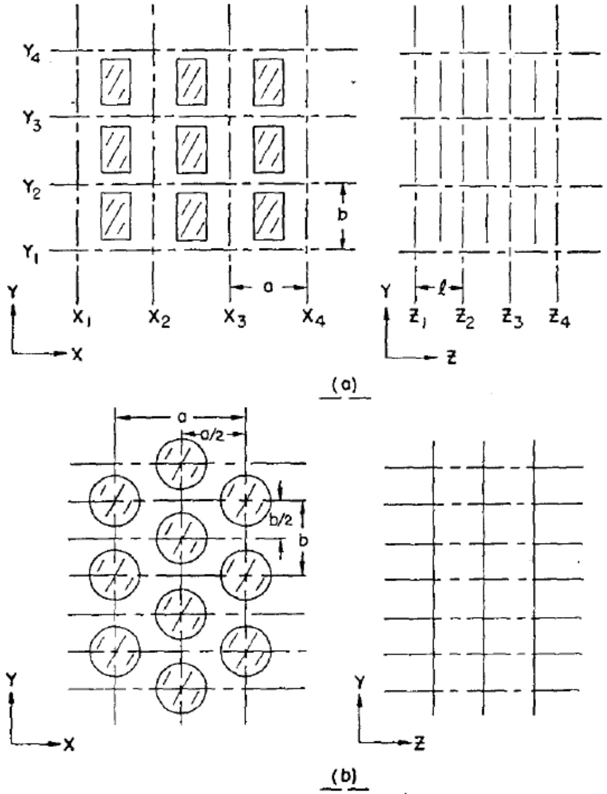
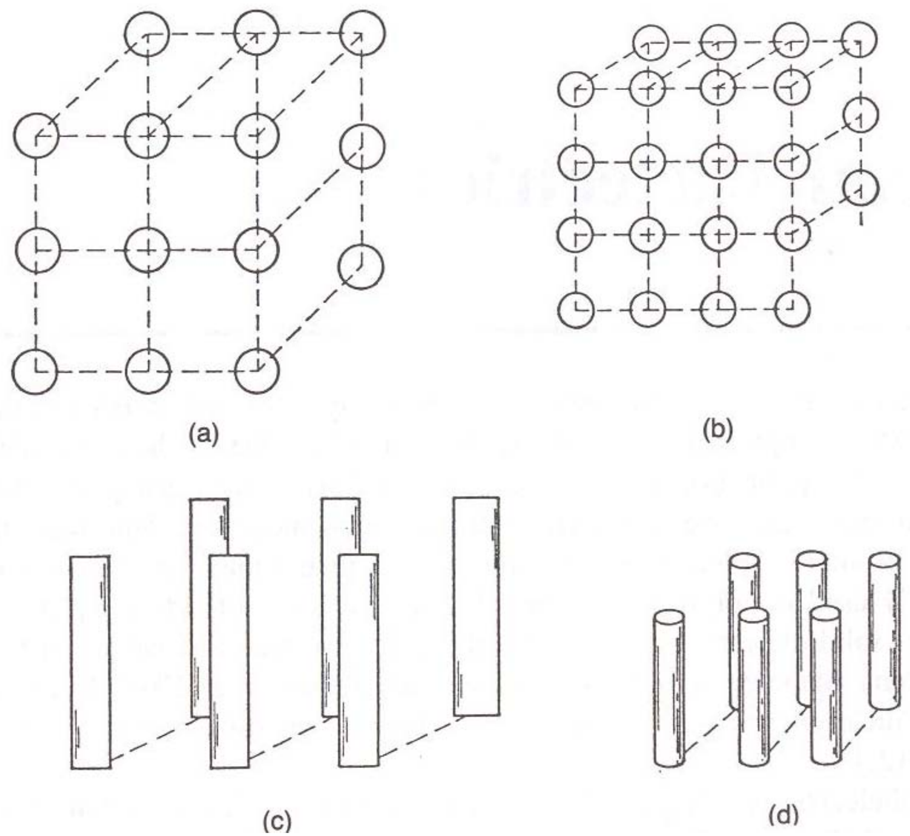


FIG. 1. Delay-lens media.



W.E. Kock, Metallic delay lenses, Bell Syst. Tech. J. vol. 27, pp. 58-82, 1948.

Left picture from: S.B. Cohn, J. Applied Phys., vol. 21, pp. 674-680, 1950.

Right picture from: R.E. Collin, *Field theory of guided waves,* 2nd ed., The IEEE Press, 1991.

Voids in homogeneous host

Artificial Dielectrics Utilizing Cylindrical and Spherical Voids*

H. T. WARD†, ASSOCIATE MEMBER, IRE, W. O. PURO†, ASSOCIATE MEMBER, IRE, AND D. M. BOWIE†

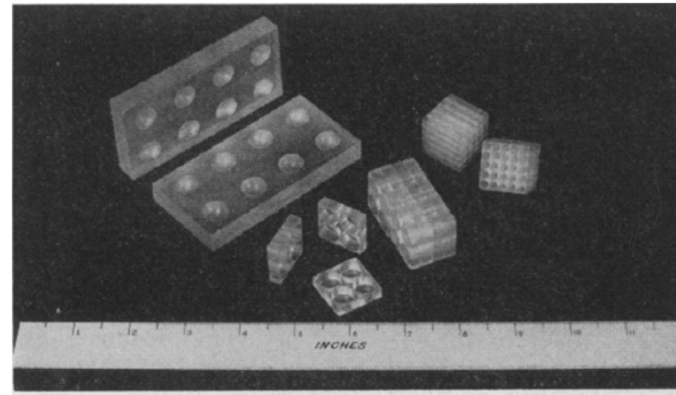
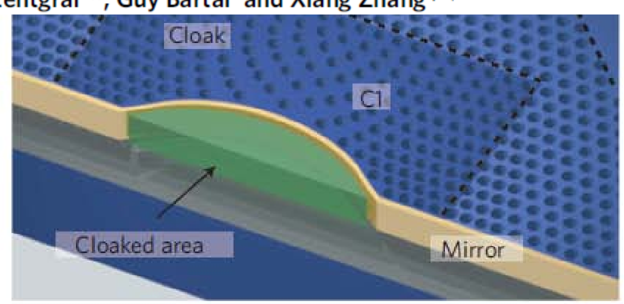


Fig. 1—Samples of materials containing spherical and cylindrical voids.

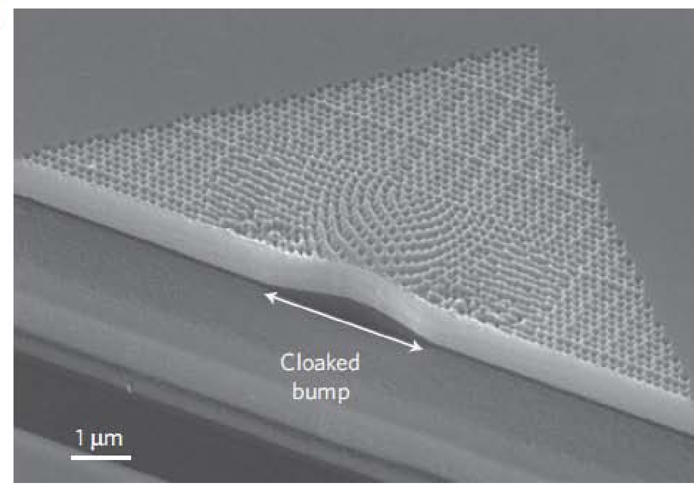
LETTERS
PUBLISHED ONLINE: 29 APRIL 2009 | DOI: 10.1038/NMAT2461
nature materials

An optical cloak made of dielectrics

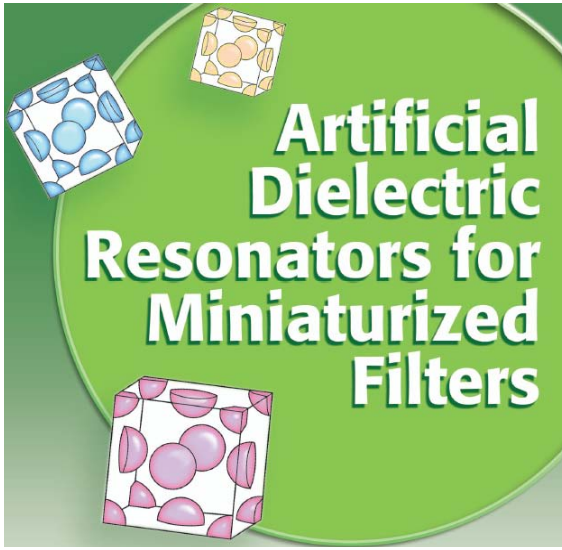
Jason Valentine[1]*, Jensen Li[1]*, Thomas Zentgraf[1]*, Guy Bartal[1] and Xiang Zhang[1,2]†



b



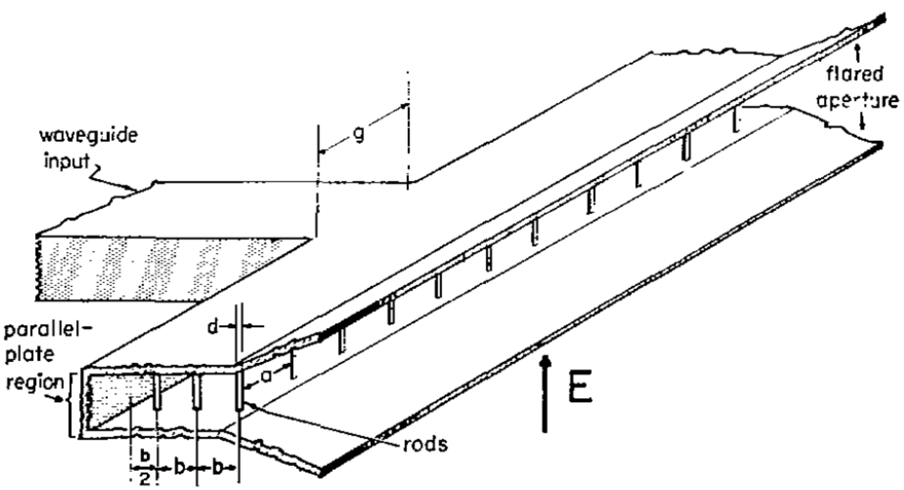
Modern applications
of artificial dielectrics at microwaves

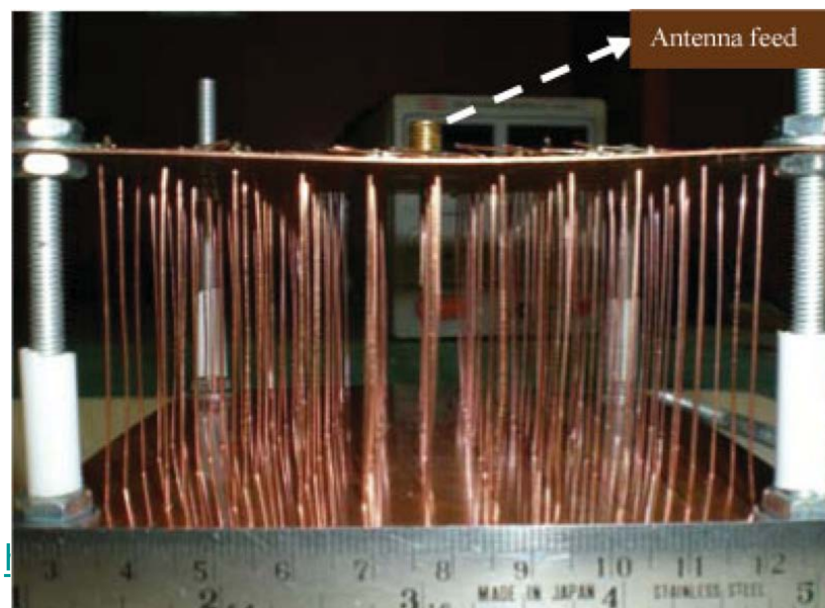


Ikuo Awai, IEEE Microwave Magazine, October 2008

Lens antennas...

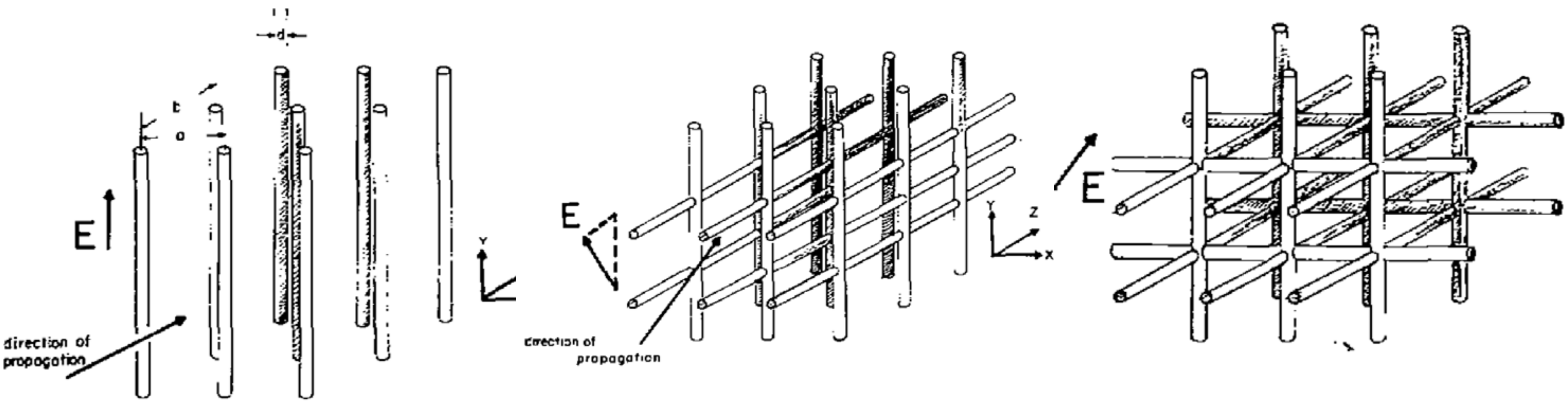
Left: Rotman, 1962. Right: R. Zhou, H. Zhang, and Hao Xin, Microwave and Optical Techn. Lett., Vol. 50, no. 9, 2008.





Wire media

- Originally proposed as an artificial dielectric



$$\epsilon_p = \epsilon_0 \left(1 - \frac{{\omega_p}^2}{\nu^2 + \omega^2} + j \, \frac{{\omega_p}^2 \nu / \omega}{\nu^2 + \omega^2} \right)$$

W. Rotman, Plasma simulation by artificial dielectrics and parallel-plate media,
IRE Trans. Antennas Propag., pp. 82-95, Jan. 1962.

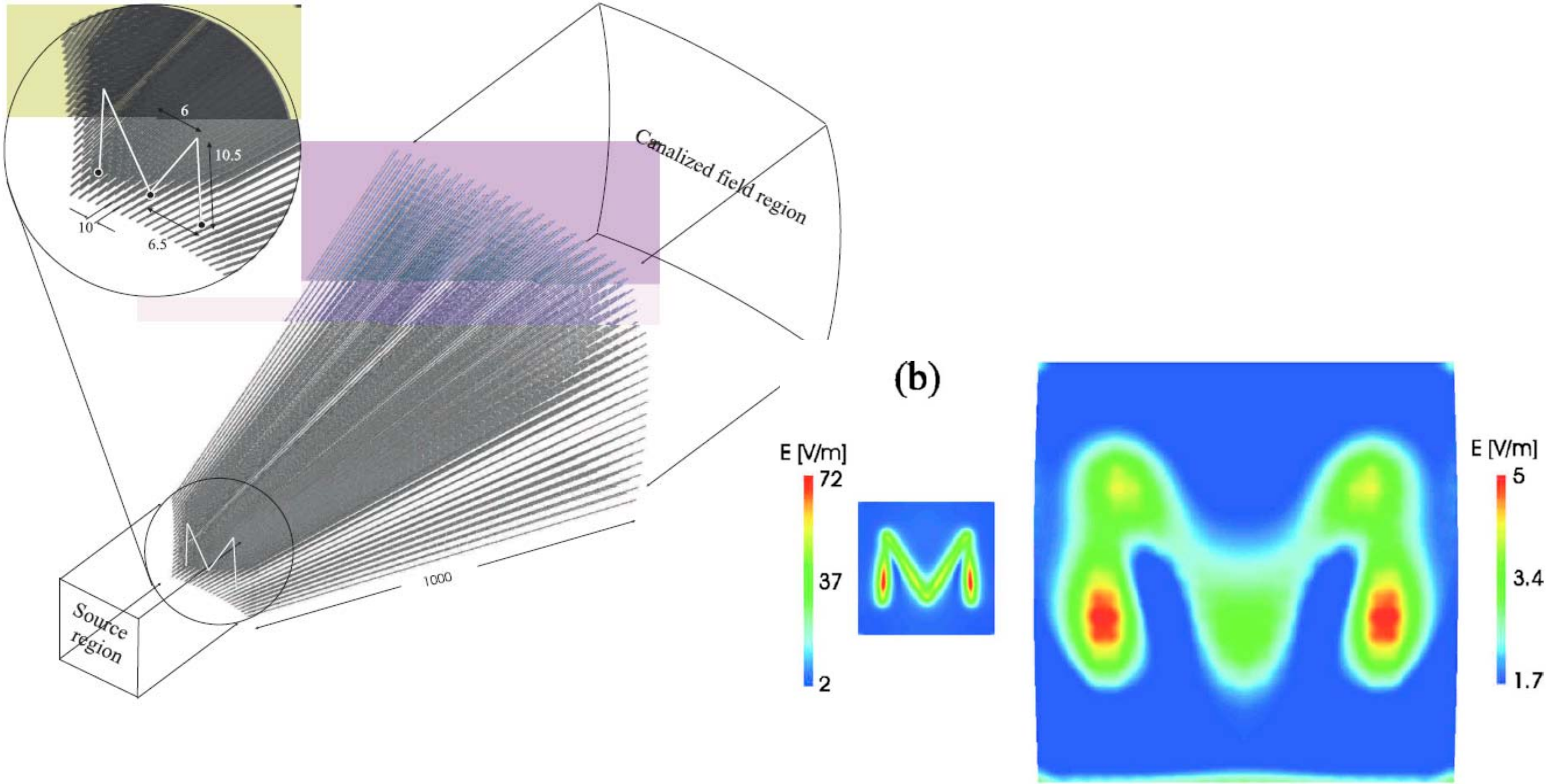
Wire media – new properties

- Wire media are fundamentally different from artificial dielectrics

$$\epsilon_{zz}(\omega, k_z) = \epsilon_0 \left(1 - \frac{k_p^2}{k^2 - k_z^2} \right)$$

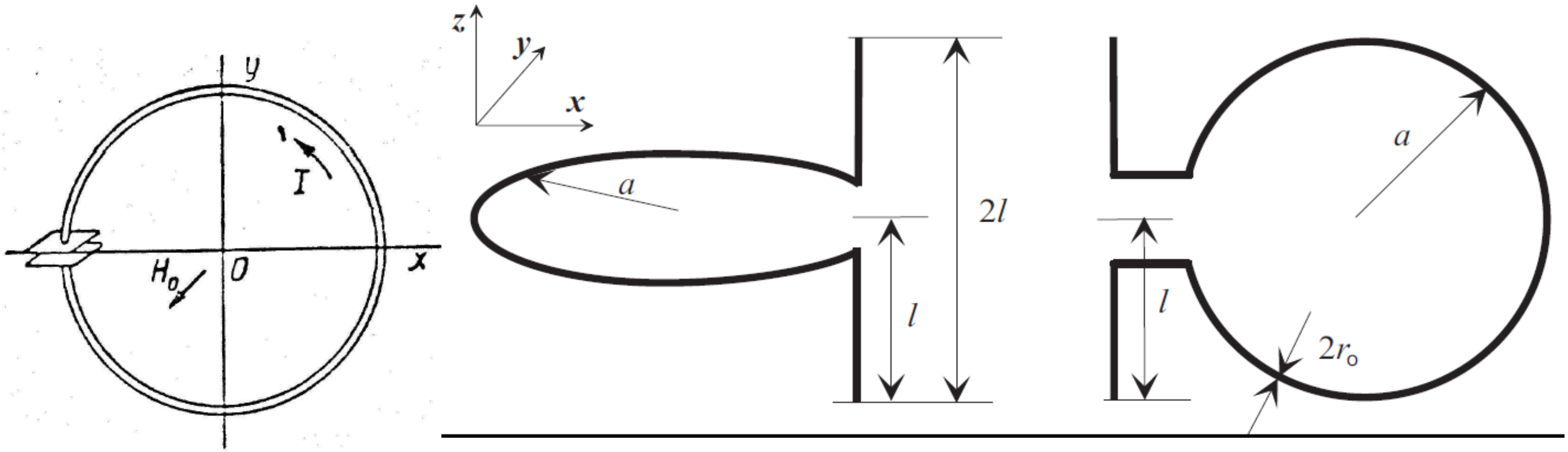
G. Shvets, *Advanced Accelerator Concepts: Tenth Workshop,* edited by C. E. Clayton and P. Muggli, 2002;
P. A. Belov, R. Marqués, S. I. Maslovski, I. S. Nefedov, M. Silverinha, C. R. Simovski, and S. A. Tretyakov, Phys. Rev. B **67**, 113103, 2003.

Canalization and superlensing



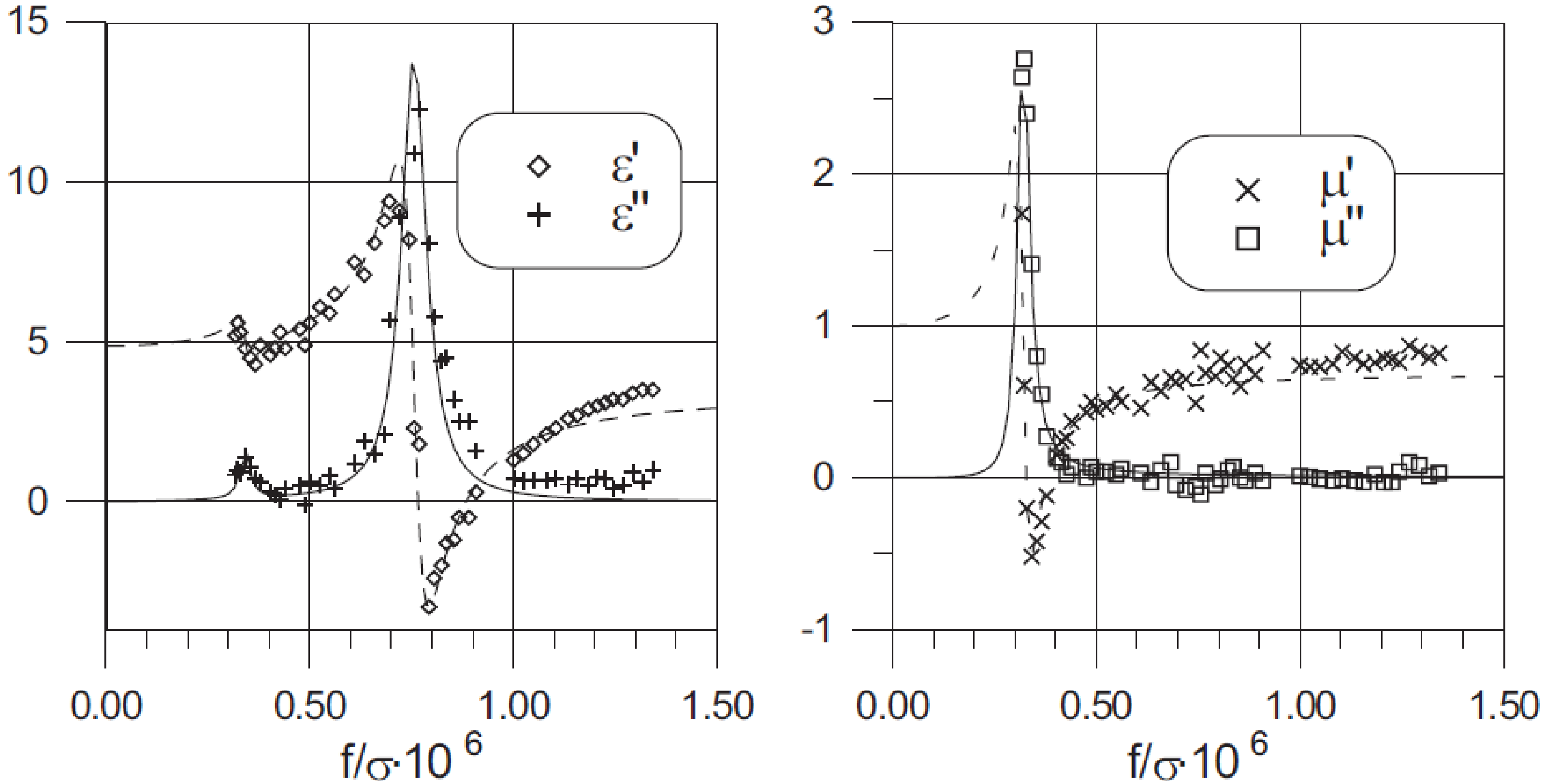
P. Ikonen, C. Simovski, S. Tretyakov, P. Belov, and Y. Hao,
Applied Physics Letters, vol. 91, p. 104102, 2007

Artificial magnetics: Split rings



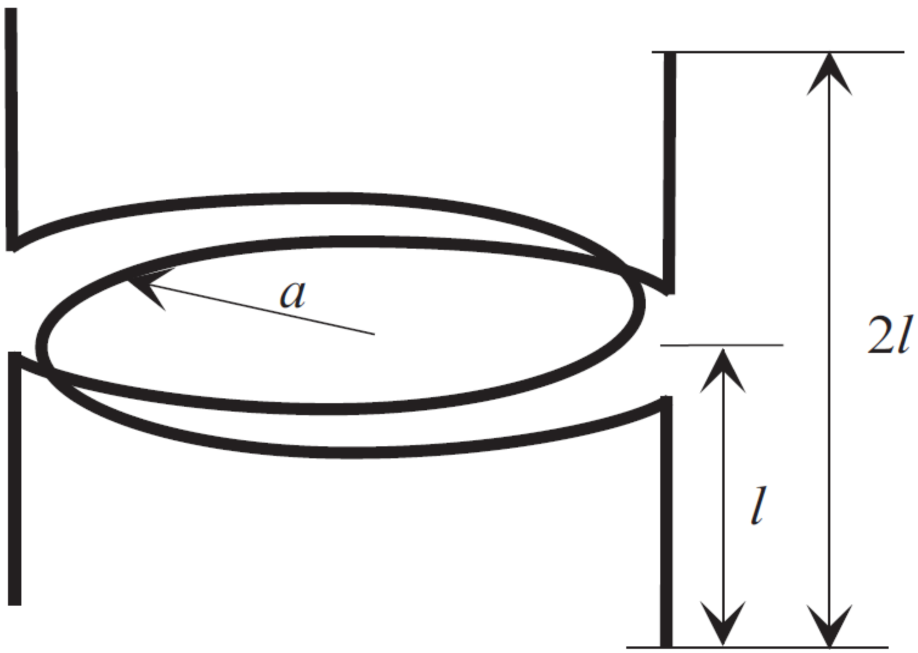
S.A. Schelkunoff, H.T. Friis, 1952; Many authors, 198x–199x

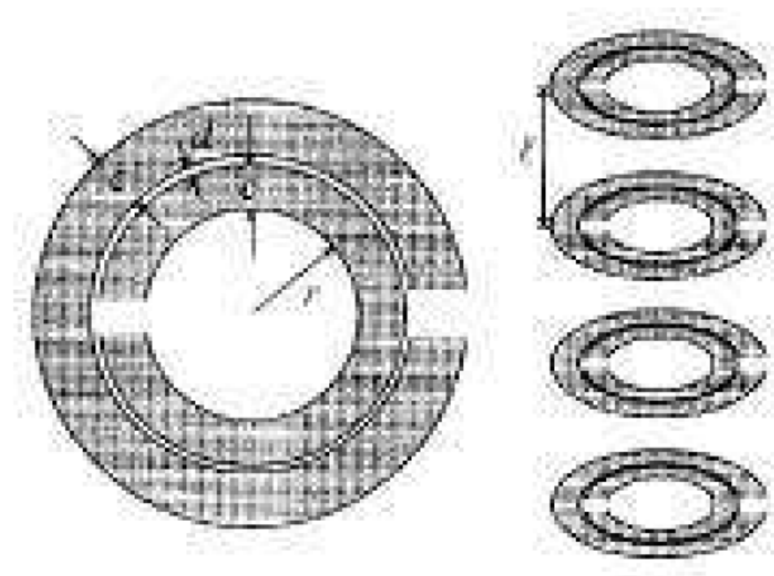
Negative permeability: First (?) experiment



A.N. Lagarkov, et al., *Electromagnetics,* vol. 17, no. 3, pp. 213-237, 1997.

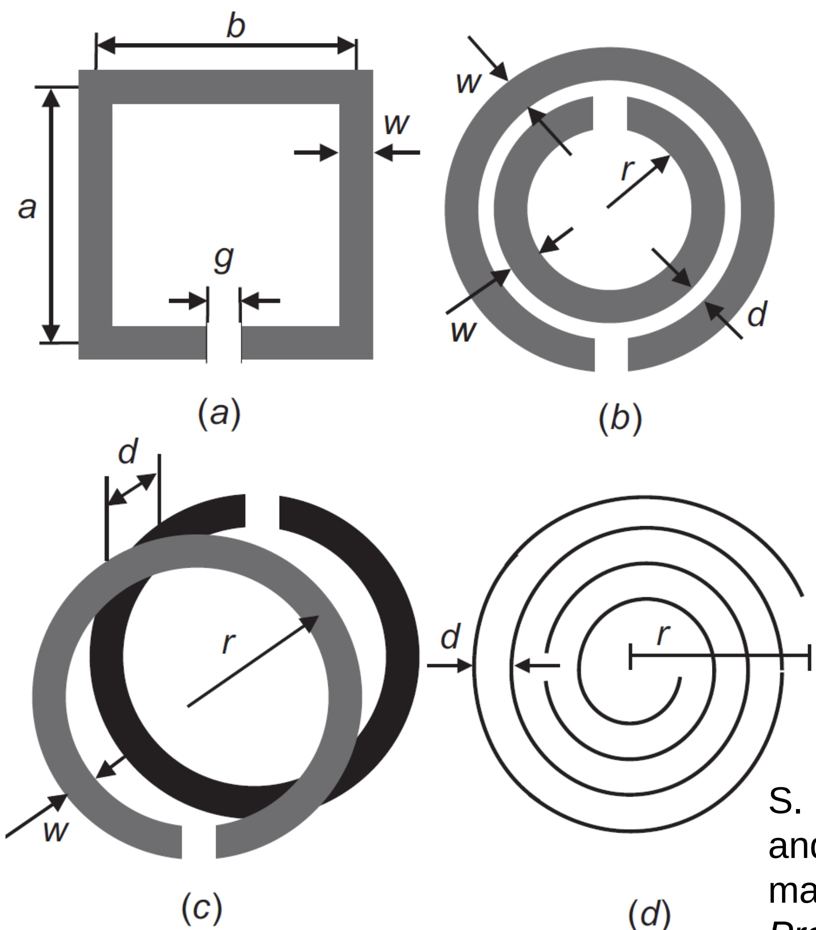
Negative permeability: Various geometries

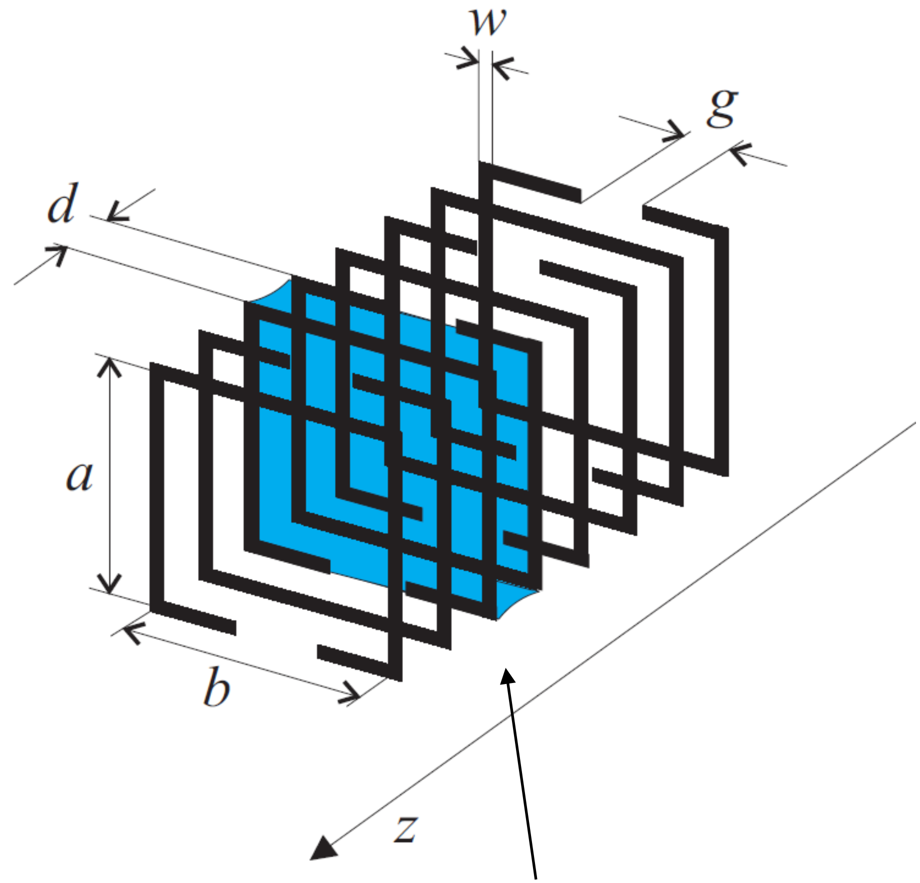




A.N. Lagarkov, et al., *Electromagnetics,* vol. 17, no. 3, pp. 213-237, 1997 (left);
J.B. Pendry, et al., *IEEE Trans. Microwave Theory Techn.,*
vol. 47, pp. 2075-2084, 1999 (right).

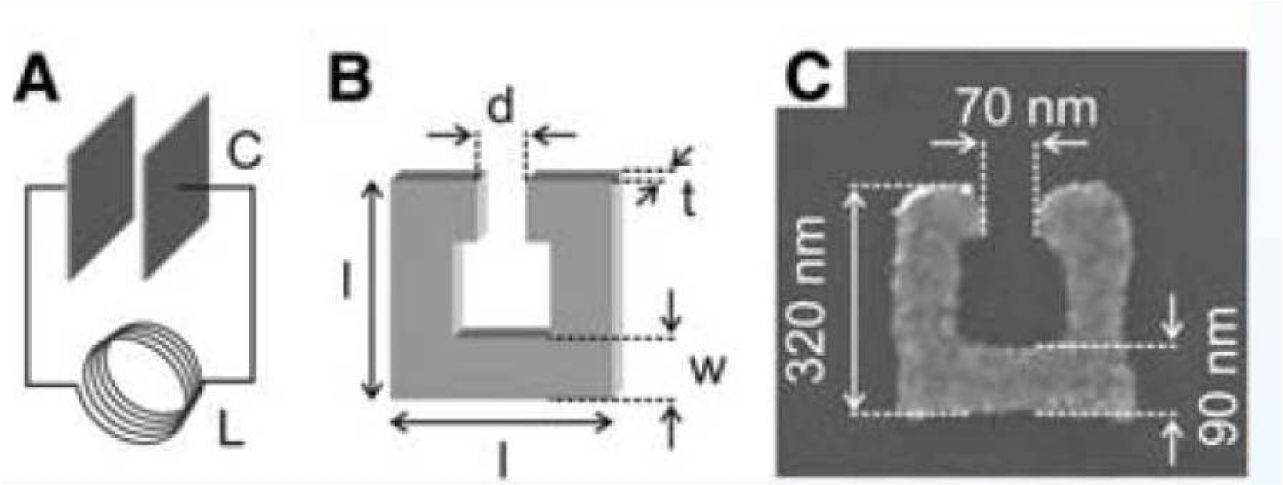
Artificial magnetics





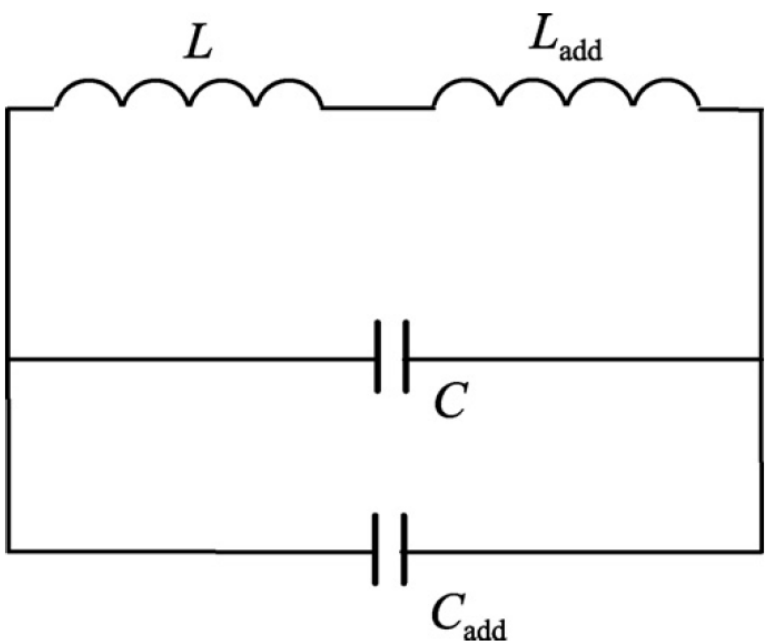
S. Maslovski, P. Ikonen, I. Kolmakov, S. Tretyakov, and M. Kaunisto, Artificial magnetic materials based on the new magnetic particle: Metasolenoid, in *Progress in Electromagnetics Research,* vol. 54, pp. 61-81, 2005.

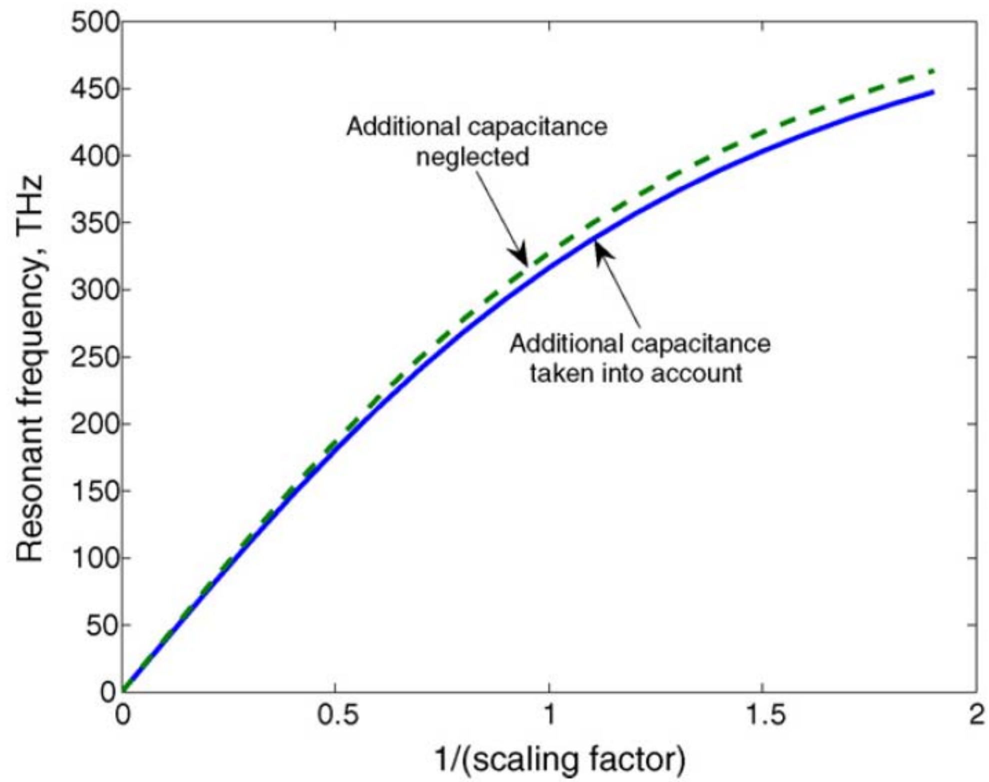
Going into the visible...
Miniaturization



S. Linden et al., Magnetic response of metamaterials at 100 Terahertz, *Science,* vol. 306, p. 1351, 2004.

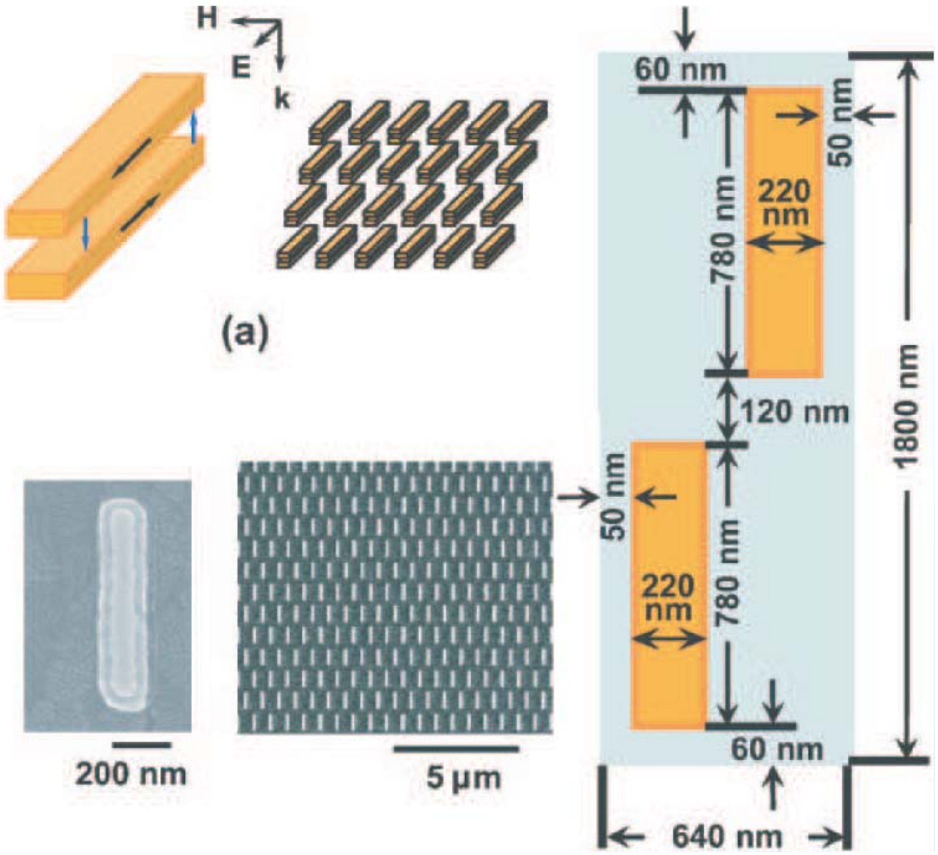
High-frequency saturation

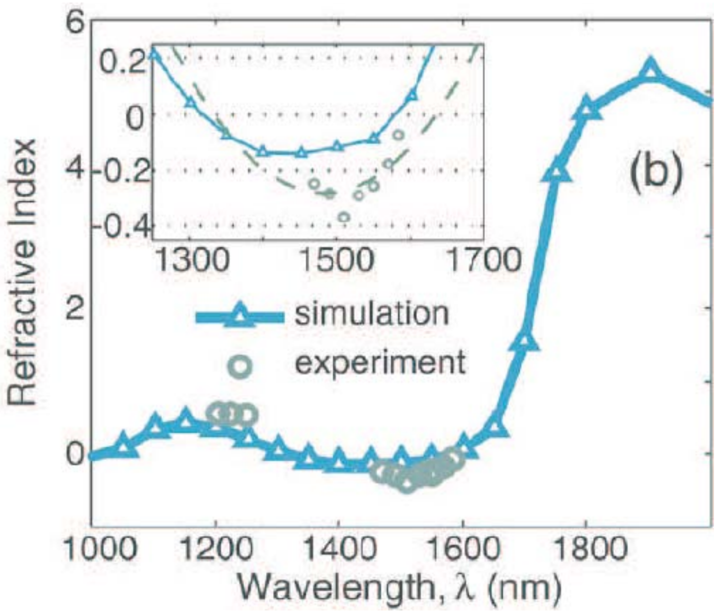




J. Zhou, T. Koschny, M. Kafesaki, E.N. Economou, J.B. Pendry, C.M. Soukoulis, Saturation of the magnetic response of splitring resonators at optical frequencies, Phys. Rev. Lett. 95 223902, 2005.
Pictures from: S. Tretyakov, On geometrical scaling of split-ring and double-bar resonators at optical frequencies, *Metamaterials,* vol. 1, no. 1, pp. 40–43, 2007.

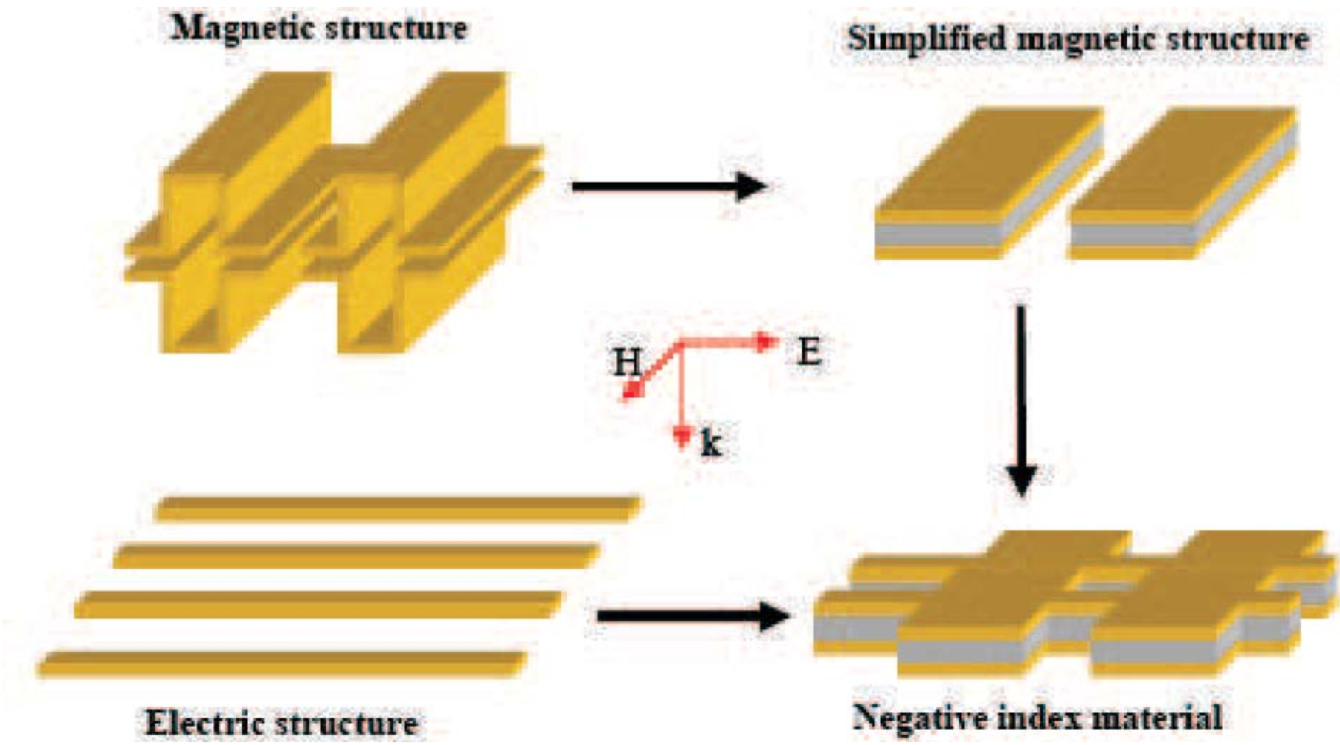
Or dual bars...





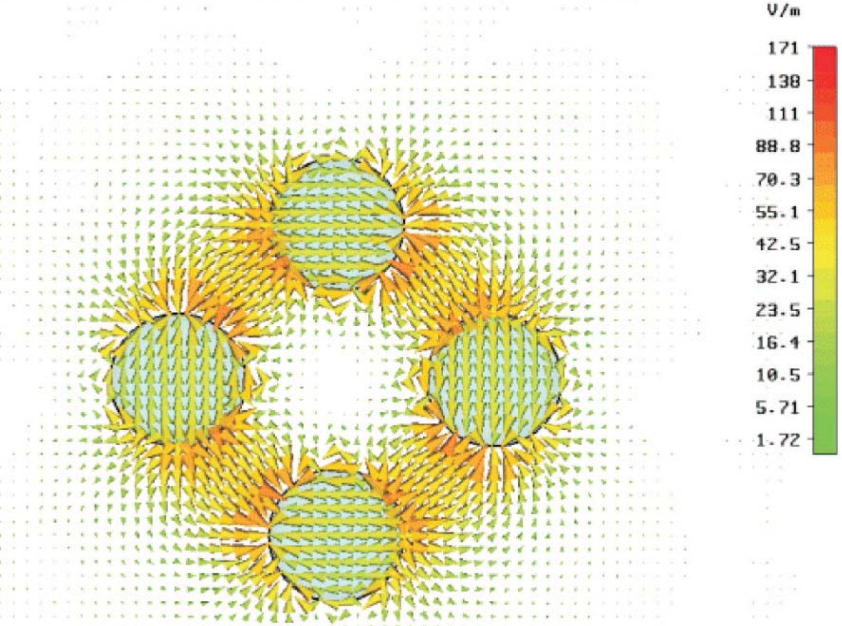
V. Shalaev et al., Negative index of refraction in optical metamaterials, *Optics Express,* vol. 30, p. 3356, 2005.

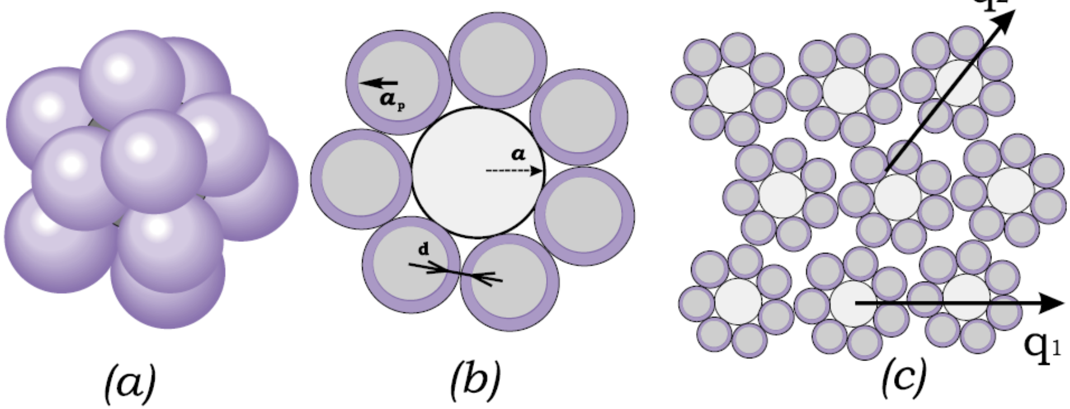
Or fish-nets



Shuang Zhang, Wenjun Fan, K.J. Malloy and S.R.J. Brueck,
Near-infrared double negative metamaterials, *Optics Express,* vol. 13, p. 4927, 2005.

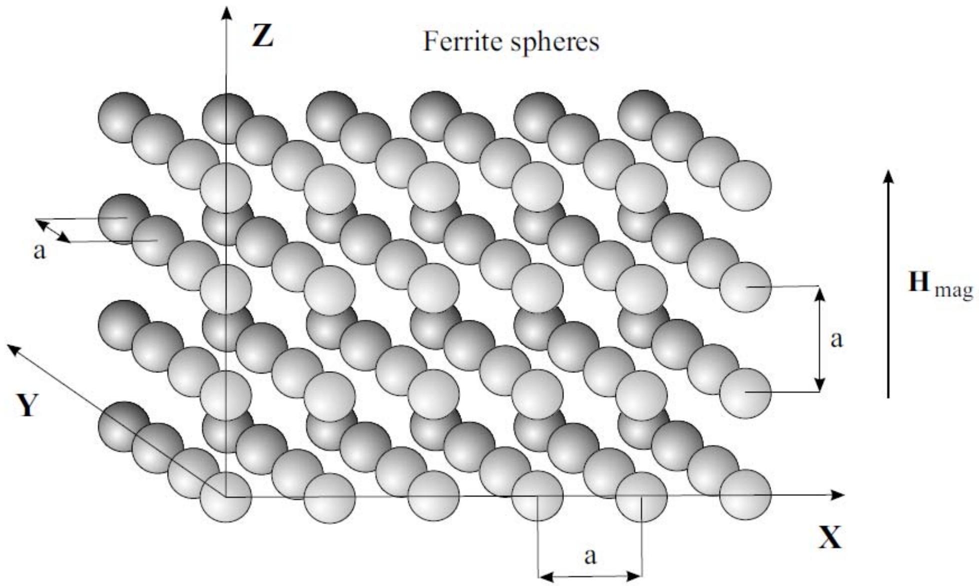
Or clusters of plasmonic nanoparticles

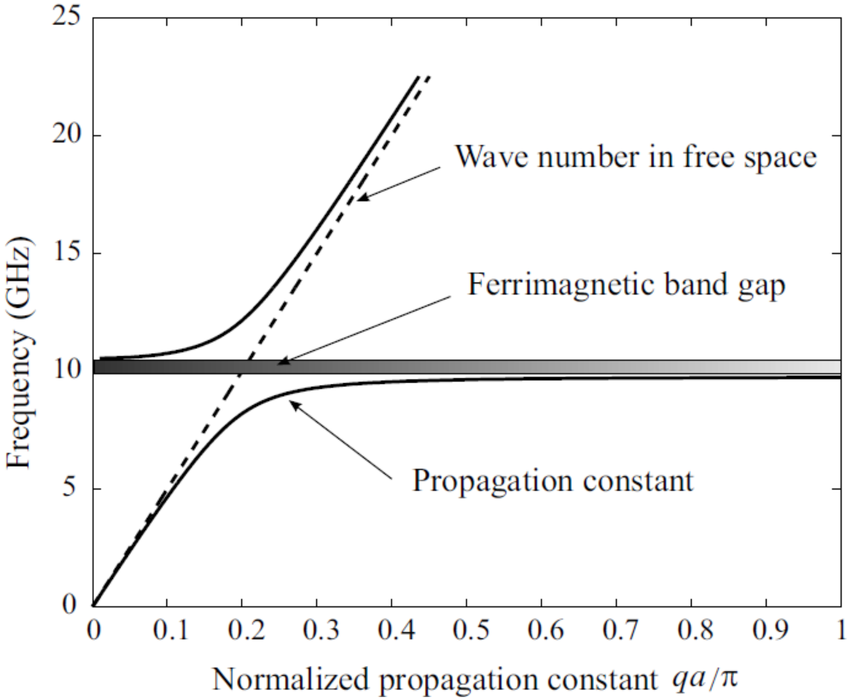




Left picture: A. Alù, A. Salandrino, and N. Engheta, *Opt. Express* **14**, 1557, 2006.
Right picture: C.R. Simovski and S.A. Tretyakov, *Phys. Rev. B*, vol. 79, p. 045111, 2009.

Magnetic EBGs





P.A. Belov, S.A. Tretyakov, A.J. Viitanen, Nonreciprocal microwave band-gap structures, *Physical Review E,* vol. 66, p. 016608, 2002.

Classes of linear materials

- **Reciprocal**
  - Magnetodielectrics
  - Chiral
  - Omega
  - ...
- **Nonreciprocal**
  - Ferrites and magnetized plasmas
  - Tellegen
  - Moving
  - ...

$$\mathbf{D} = \overline{\overline{\epsilon}} \cdot \mathbf{E} + \sqrt{\epsilon_0 \mu_0}\,(\overline{\overline{\chi}} - j\overline{\overline{\kappa}}) \cdot \mathbf{H}$$

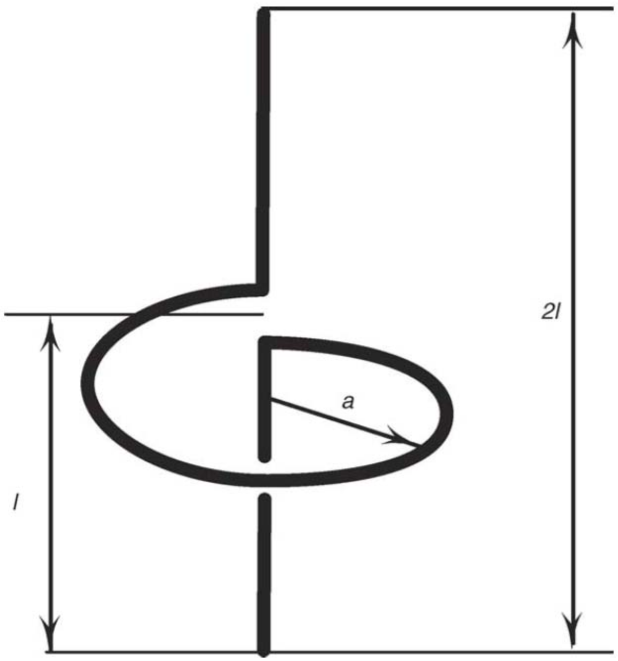
$$\mathbf{B} = \overline{\overline{\mu}} \cdot \mathbf{H} + \sqrt{\epsilon_0 \mu_0}\,(\overline{\overline{\chi}} + j\overline{\overline{\kappa}})^T \cdot \mathbf{E}$$

Chirality

Nonreciprocity

Artificial chiral media

$$\overline{\overline{\chi}} = 0, \qquad \mathrm{Trace}\{\overline{\overline{\kappa}}\} = \kappa \neq 0$$



Hierarchy of polarizabilities:

The "scaling factor" equals

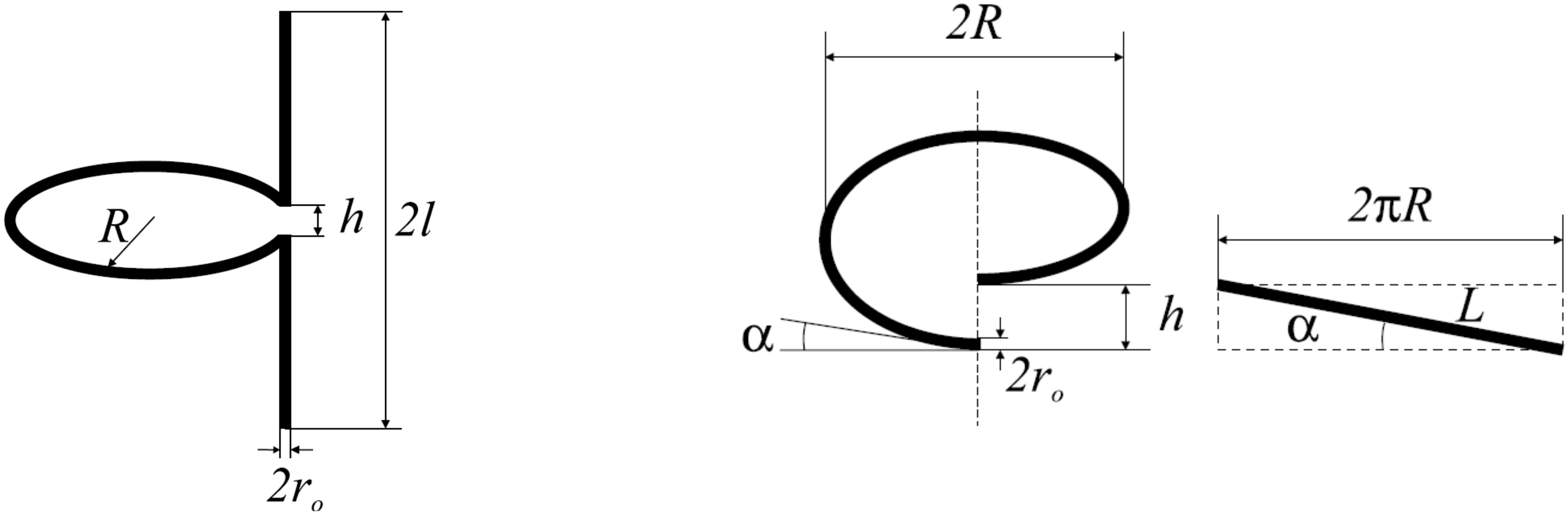
*k** loop area / arm length

Natural optical materials:
Scaling factor is very small

Metamaterials: it can be equal to 1

I.V. Lindell, A.H. Sihvola, S.A. Tretyakov, A.J. Viitanen, *Electromagnetic waves in chiral and bi-isotropic media,* Norwood, MA: Artech House, 1994.

”Optimal” spirals



N_c	1	2	3	4	5	6	7	8
α (degrees)	13.7	7.1	4.7	3.6	2.9	2.4	2.0	1.8

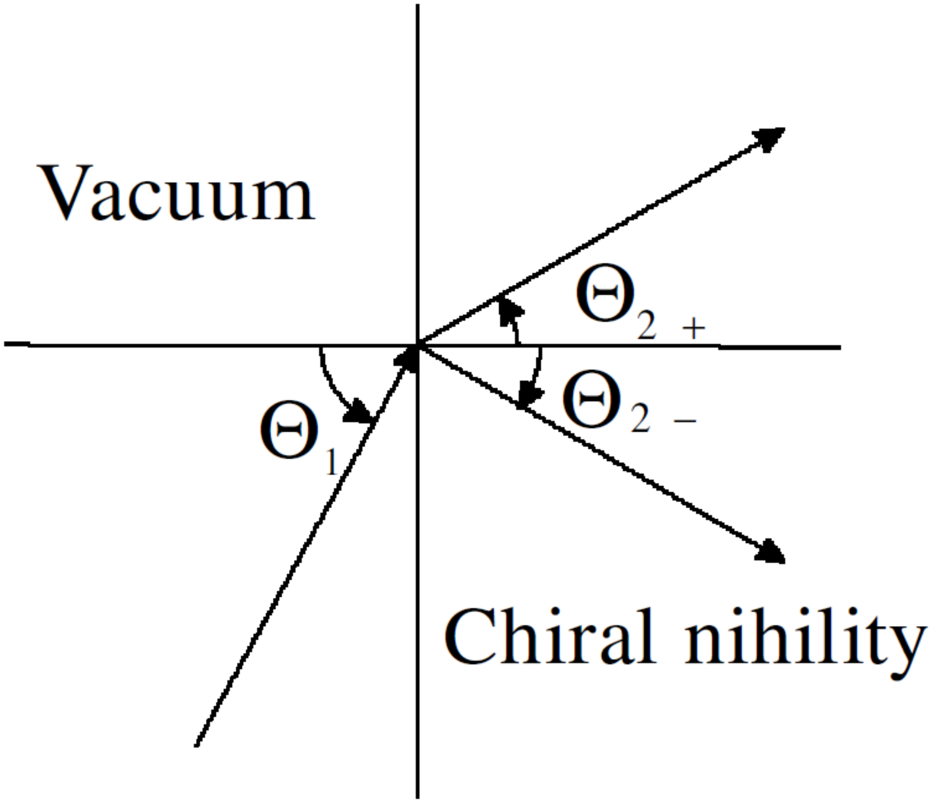
N_c = number of turns

Electric polarizability = magnetic polarizability = cross-polarizability

E. Saenz, I. Semchenko, S. Khakhomov, K. Guven, R. Gonzalo, E. Ozbay, S. Tretyakov, Modelling of spirals with equal dielectric, magnetic and chiral susceptibilities, *Electromagnetics,* vol. 28, pp. 476–493, 2008.

Chiral nihility

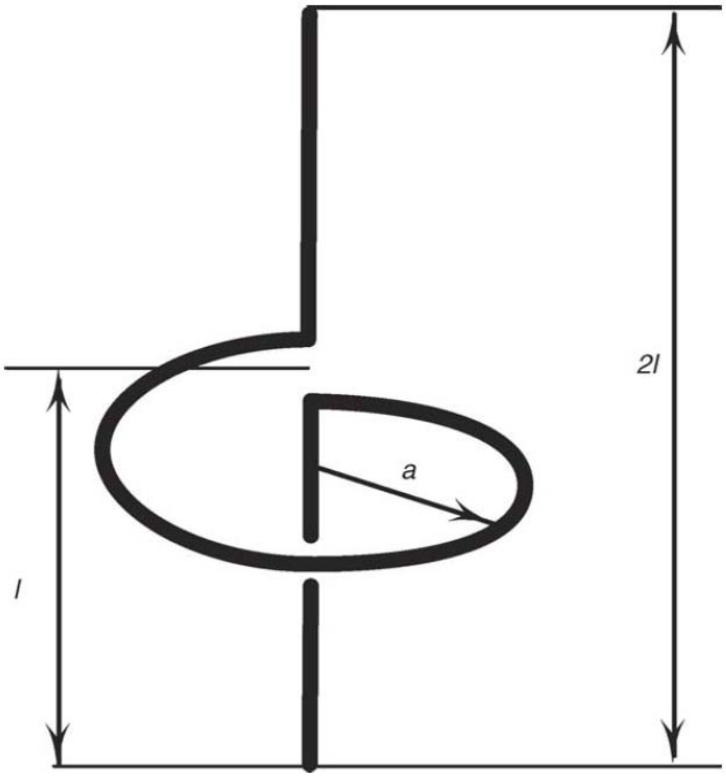
Permittivity = permeability = 0, chirality parameter nonzero

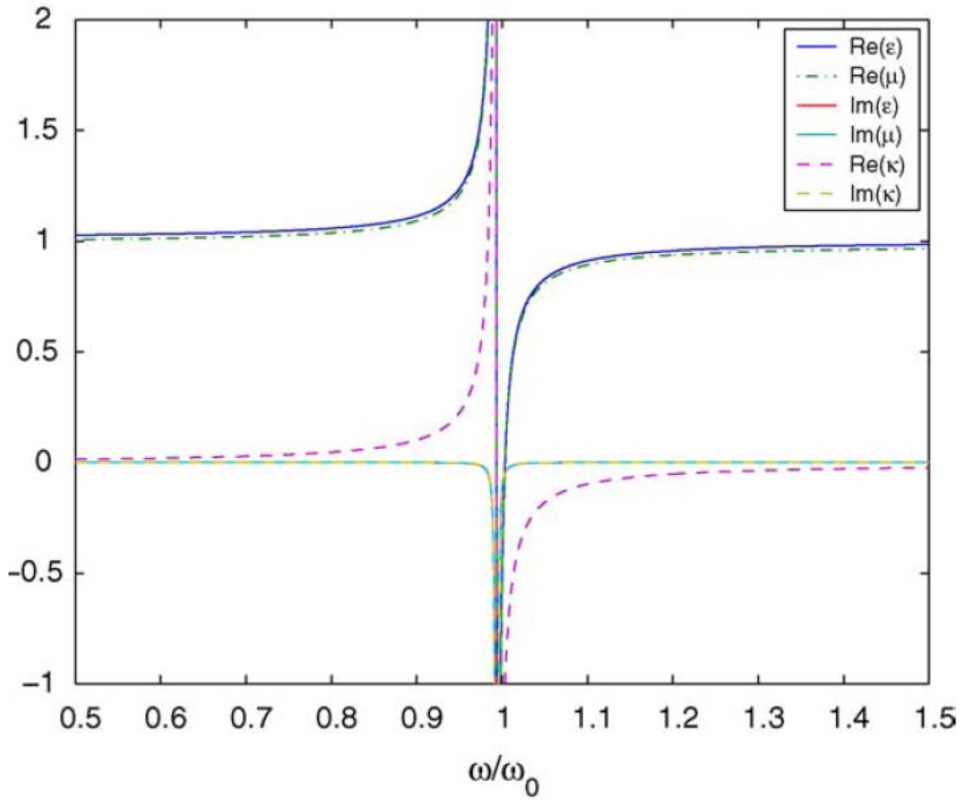


Negative refraction
Negative reflection
Standing-field spirals...

S. Tretyakov, I. Nefedov, A. Sihvola, S. Maslovski, C. Simovski,
Waves and energy in chiral nihility, *Journal of Electromagnetic Waves and Applications,*
vol. 17, no. 5, pp. 695-706, 2003.

Chiral nihility: design example





S. Tretyakov, A. Sihvola, L. Jylhä, *Photonics and Nanostructures - Fundamentals and Applications,* vol. 3, no. 2-3, pp. 107-115, 2005.

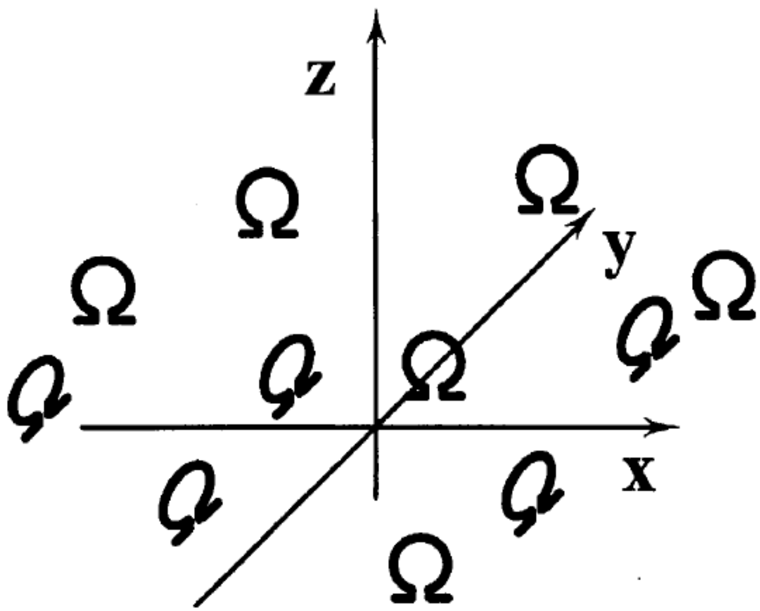
Artificial bi-anisotropic media (reciprocal)

1. Omega media

$$\overline{\overline{\chi}} = 0$$

$$\mathrm{Trace}\{\overline{\overline{\kappa}}\} = \kappa = 0$$

$$\overline{\overline{\kappa}} = -\overline{\overline{\kappa}}^T$$



A.N. Serdyukov, I.V. Semchenko, S.A. Tretyakov, A. Sihvola, *Electromagnetics of bi-anisotropic materials: Theory and applications,* Amsterdam: Gordon and Breach Science Publishers, 2001.

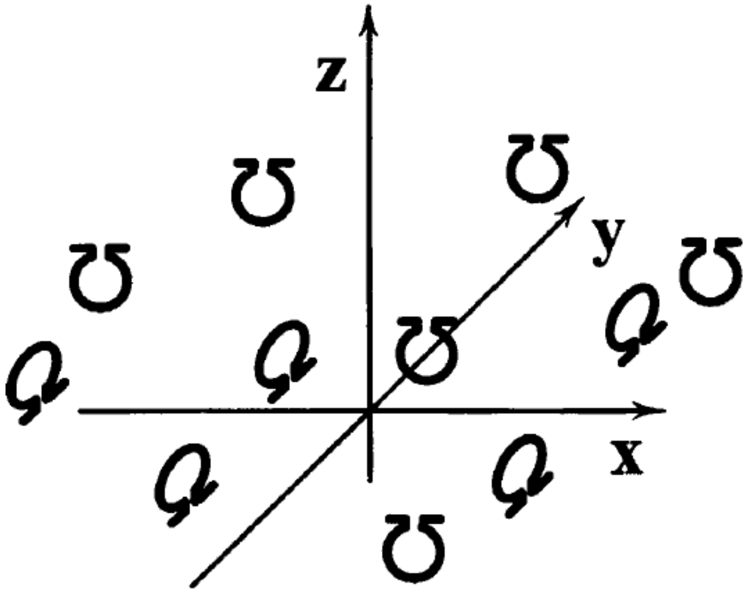
Artificial bi-anisotropic media (reciprocal)

2. Pseudochiral media

$$\overline{\overline{\chi}} = 0$$

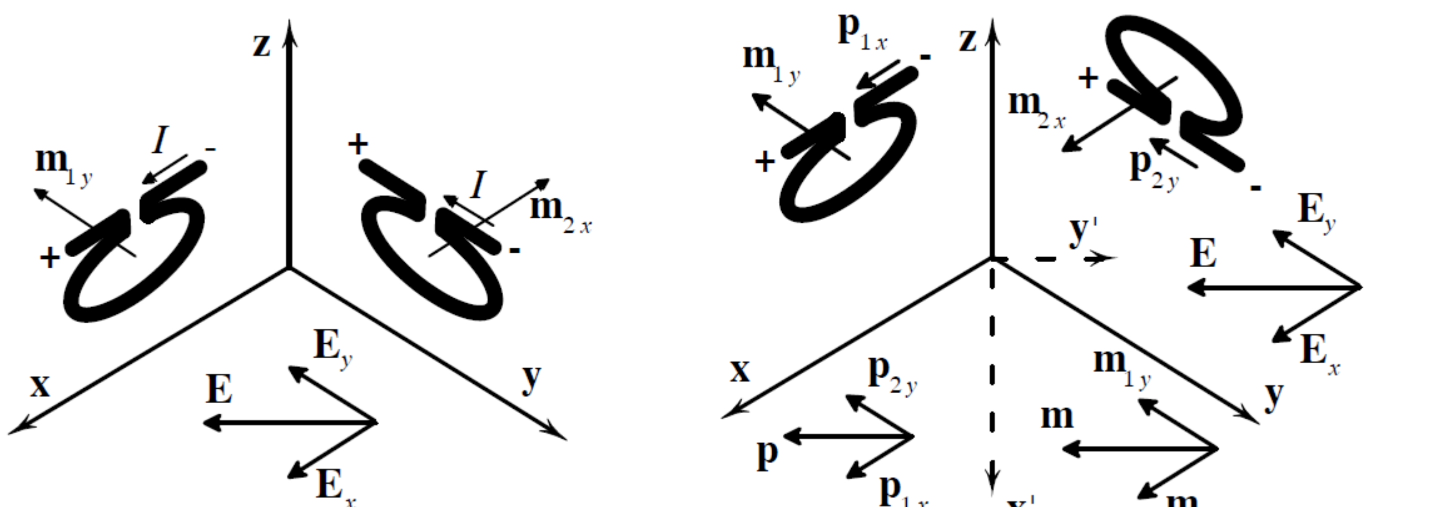
$$\text{Trace}\{\overline{\overline{\kappa}}\} = \kappa = 0$$

$$\overline{\overline{\kappa}} = \overline{\overline{\kappa}}^T$$



A.N. Serdyukov, I.V. Semchenko, S.A. Tretyakov, A. Sihvola, *Electromagnetics of bi-anisotropic materials: Theory and applications,* Amsterdam: Gordon and Breach Science Publishers, 2001.

Chiral effects in pseudochiral media



$$\mathbf{D} = \epsilon_0(\epsilon_t \overline{\overline{I}}_t + \epsilon_n \mathbf{z}_0\mathbf{z}_0)\cdot\mathbf{E} - j\sqrt{\epsilon_0\mu_0}K(\mathbf{x}_0'\mathbf{x}_0' - \mathbf{y}_0'\mathbf{y}_0')\cdot\mathbf{H}$$

$$\mathbf{B} = \mu_0(\mu_t \overline{\overline{I}}_t + \mu_n \mathbf{z}_0\mathbf{z}_0)\cdot\mathbf{H} + j\sqrt{\epsilon_0\mu_0}K(\mathbf{x}_0'\mathbf{x}_0' - \mathbf{y}_0'\mathbf{y}_0')\cdot\mathbf{E}$$

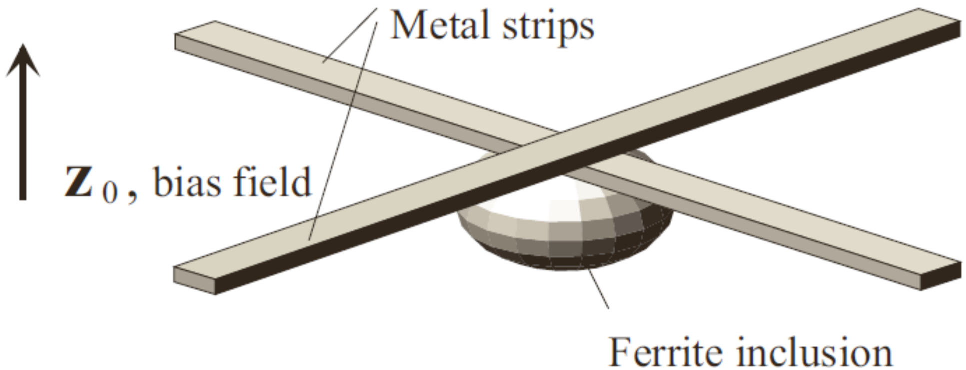
A.A. Sochava, C.R. Simovski, S.A. Tretyakov, Chiral effects and eigenwaves in bi-anisotropic omega structures, *Advances in Complex Electromagnetic Materials* (Ed. by A. Priou, A. Sihvola, S. Tretyakov, and A. Vinogradov), NATO ASI Series High Technology, vol. 28, Dordrecht/Boston/London: Kluwer Academic Publishers, pp. 85-102, 1997.

Artificial bi-anisotropic media (nonreciprocal)

1. Tellegen media

$$\mathrm{Trace}\{\overline{\overline{\chi}}\} = \chi \neq 0$$

Tellegen omega particle



Microwave experiment: S.A. Tretyakov, S.I. Maslovski, I.S. Nefedov, A.J. Viitanen, P.A. Belov, A. Sanmartin, Artificial Tellegen particle, *Electromagnetics,* vol. 23, no. 8, pp. 665-680, 2003.

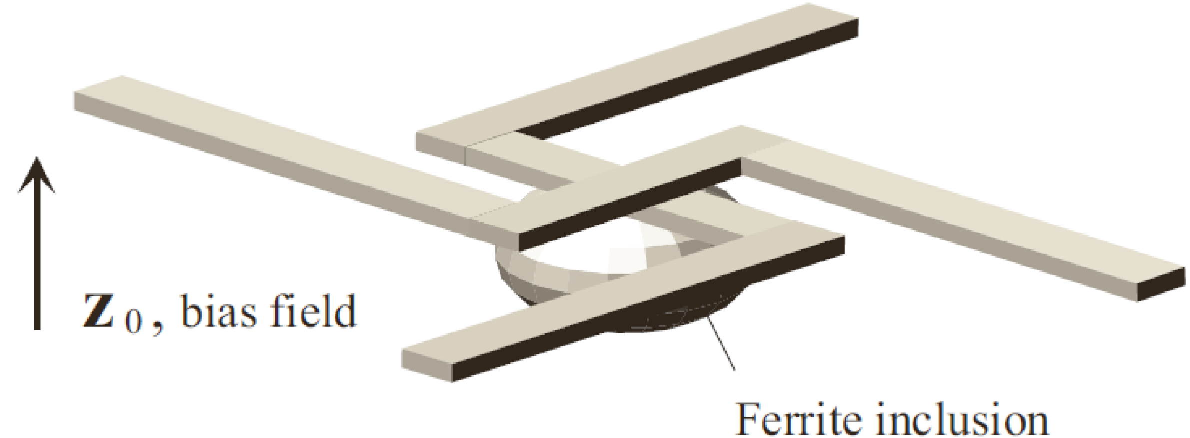
Artificial bi-anisotropic media (nonreciprocal)

2. ”Moving” media

$$\mathrm{Trace}\{\overline{\overline{\chi}}\} = \chi = 0$$

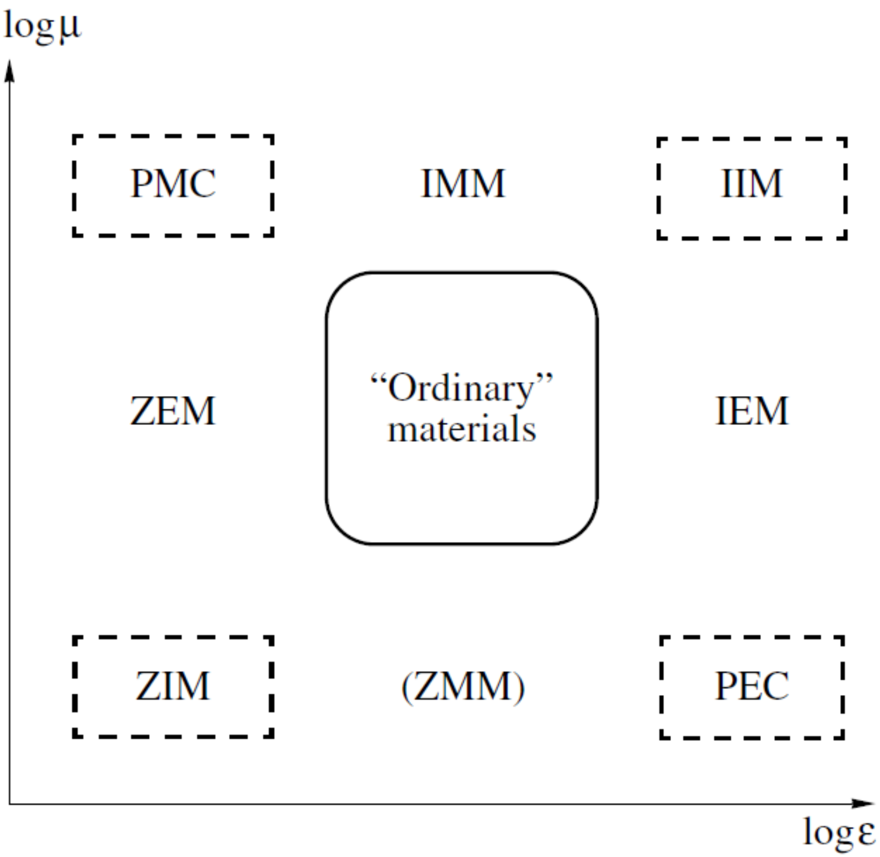
$$\overline{\overline{\chi}} = -\overline{\overline{\chi}}^T$$

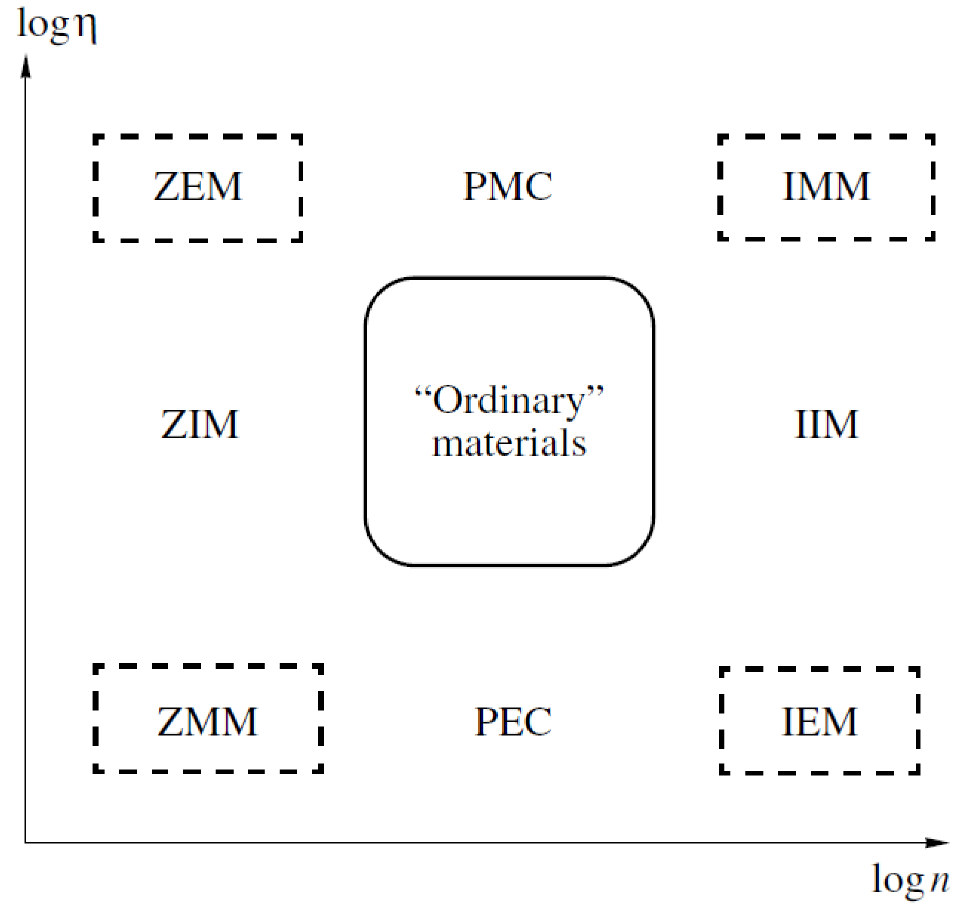
”Moving” chiral particle



S.A. Tretyakov, Nonreciprocal composite with the material relations of the transparent absorbing boundary, *Microwave and Optical Technology Letters,* vol. 19, no. 5, pp. 365-368, 1998.

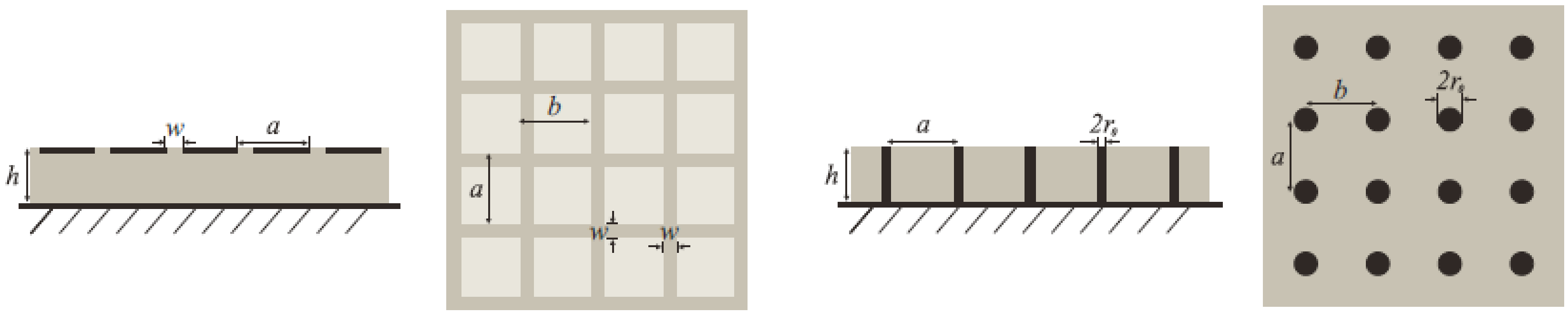
Towards infinities

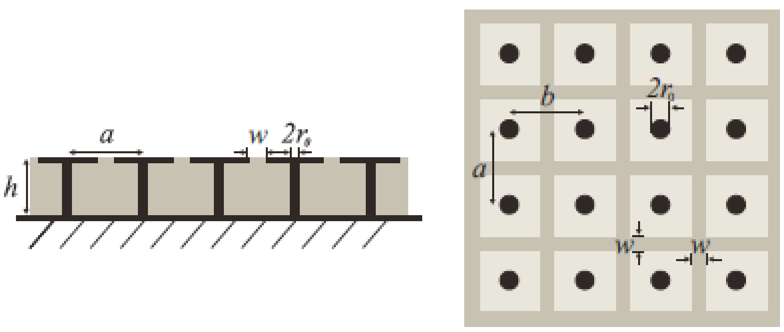




A. Sihvola, S. Tretyakov, and A. de Baas, Metamaterials with extreme material parameters, *Journal of Communications Technology and Electronics*, vol. 52, no. 9, pp. 986–990, 2007.

Reducing dimensions

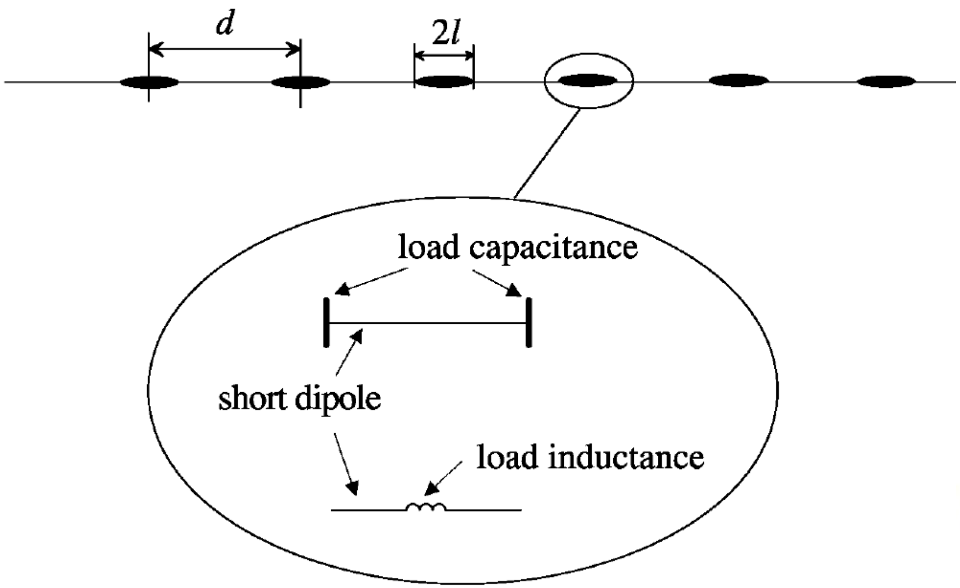


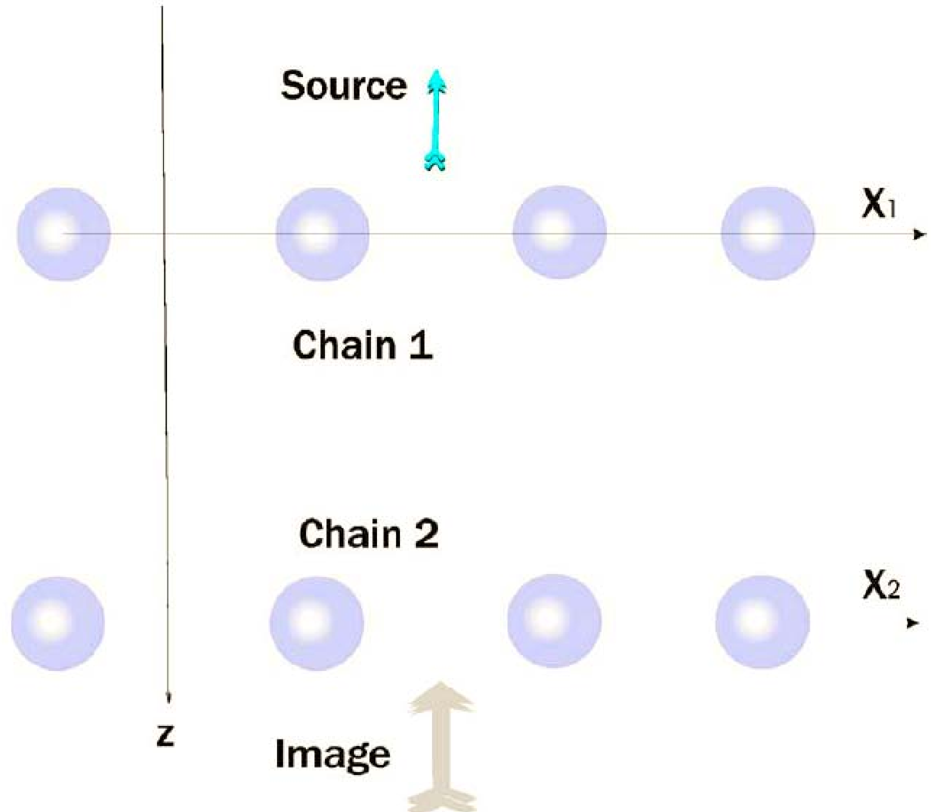


Artificial impedance surfaces

Picture from: O. Luukkonen and S. Tretyakov, Recent advancements in modeling of artificial impedance surfaces, Proc. of *3rd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (Metamaterials'2009),* pp. 5-7, London, UK, August 30- September 4, 2009.

Reducing further...





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Reducing even further...

But can we call one inclusion ”material”?