Aalto University
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Electromagnetic metamaterials: Past, present, and future

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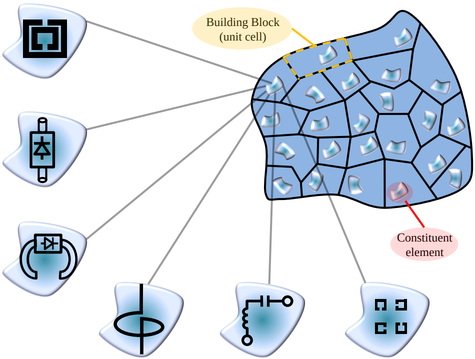
September 7, 2015

Metamaterial concept

Metamaterial is “an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties”



Picture by M. Lapine, modified by M. Albooyeh

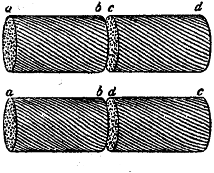
Outline

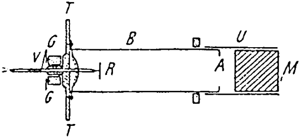
Metamaterial as "an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties"

Unit cells are electrically small: Effectively homogeneous media, characterized by permittivity, permeability,...

- Past: How old we are?
  - 15 years of metamaterials
  - 150 years of Maxwell's equations
- Present: What do we know today?
- Future: What next?

Artificial chiral materials: Imitating nature





Bose (India)

Lindman (Finland)

J.C. Bose, Proc. Royal Soc., vol. 63, pp. 146-152, 1898; K.F. Lindman, Öfversigt af Finska Vetenskaps-Societetens Förhandlingar, LVII, A, no. 3, 1914 (Annalen der Physik, 63, no. 4, 621-644, 1920).

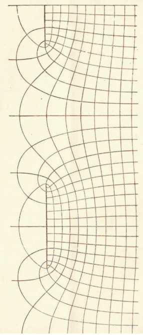
Probably the first metasurface: 1898

On the Reflection and Transmission of Electric Waves by a Metallic Grating.

By Prof. HORACE LAMB, F.R.S.

[*Extracted from the Proceedings of the London Mathematical Society, Vol. XXIX., Nos.* 644, 645.]

The main problem of this paper consists in the calculation of the disturbance produced in a train of electric waves by a plane grating composed of parallel, equal, and equidistant metallic strips. The treatment is approximate, and involves the assumption that the wave-length is large compared with the distance between the centres of consecutive strips; the application is, therefore, rather to Hertzian waves than to phenomena of ordinary Optics. The previous mathe-



In the above investigation, the coefficient of the primary wave has been taken to be unity. On the same scale, the coefficients of the reflected and transmitted waves are $-1+B_0$ and B_0, or

$$-\frac{1}{1+ikc} \quad \text{and} \quad \frac{ikc}{1+ikc},$$

respectively. Hence the *intensities* I, I' (say) of these waves, in

$$c = \frac{a}{\pi}\log\frac{a}{2\pi b}$$

$$c = \frac{a+b}{\pi}\log\sec\frac{\pi a}{2(a+b)}.$$

H. Lamb, On the reflection and transmission of electric waves by a metallic grating, Proc. London Math. Soc., vol. 29, ser. 1, 523-544, 1898.

Engineering properties of a metasurface: 1898

The intensities of the reflected and transmitted waves, in terms of that of the primary wave, are therefore

$$= \frac{1}{1+k^2c^2}, \quad I' = \frac{k^2c^2}{1+k^2c^2}. \qquad (95)$$

If the wave-length is at all large compared with c, kc is small, and the reflection is almost total. But, for any given wave-length (large compared with a), kc may be made as great as we please by sufficiently diminishing the radius b of the wires. In this way we can pass to the case of free transmission.

Artificial dielectrics

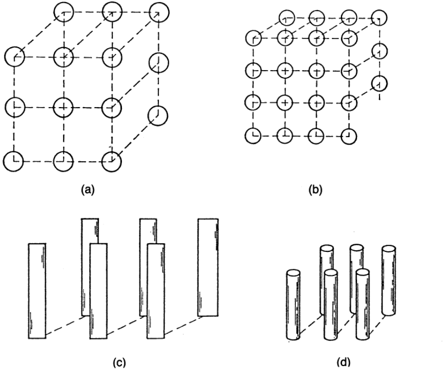
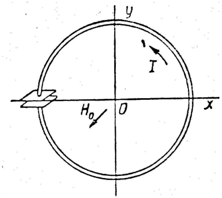


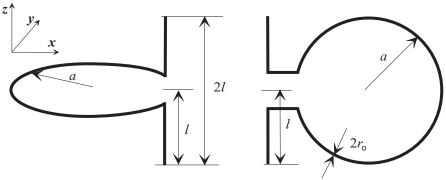
Fig. 12.1. Typical artificial dielectric structures. (a) Three-dimensional sphere medium. (b) Three-dimensional disk medium. (c) Two-dimensional strip medium. (d) Two-dimensional rod medium.

W.E. Kock, Metallic delay lenses, Bell Syst. Tech. J., vol. 27, 58-82, 1948; J. Brown, The design of metallic delay dielectrics, Proc. IRE (London), vol. 97, part III, 45-48, 1950.

Artificial magnetics: Split rings

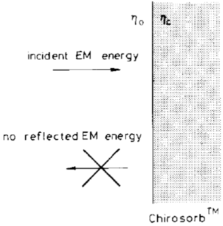


$$\chi_m^0 = \frac{\omega^2 \mu_0^2 C S^2}{1 - \omega^2 LC}$$



S.A. Schelkunoff and H.T. Friis, Antennas: Theory and Practice, New York: Wiley, 1952; D. Jaggard, N. Engheta, and many other authors, 1980–2000, S.A. Tretyakov, F. Mariotte, C.R. Simovski, T.G. Kharina, J.-P. Heliot, Analytical antenna model for chiral scatterers: Comparison with numerical and experimental data, IEEE Trans. Antennas Propag., vol. 44, no. 7, 1006-1014, 1996.

Exciting possibilities in absorber applications



V.K. Varadan, V.V. Varadan, and A. Lakhtakia, On the possibility of designing anti-reflection coating using chiral composites, J. Wave-Mater. Interact., vol. 2, 71-81, 1987; D. Jaggard and N. Engheta, Chirosorb as an invisible medium, Electronics Lett., vol. 25, no. 3, 173-174, 1989. Comment by J.C. Monzon, vol. 25, no. 16, p. 1060.

$$\mathbf{D} = \epsilon_\mathrm{P}\mathbf{E} - j\xi_c\mathbf{B},\ \mathbf{H} = \frac{1}{\mu_\mathrm{P}}\mathbf{B} - j\xi_c\mathbf{E} \Rightarrow \eta = \sqrt{\frac{\mu_\mathrm{P}}{\epsilon_\mathrm{P} + \mu_\mathrm{P}\xi_c^2}}$$

$$\mathbf{D} = \epsilon\mathbf{E} - j\kappa\mathbf{H},\ \mathbf{B} = \mu\mathbf{H} + j\kappa\mathbf{E} \Rightarrow \eta = \sqrt{\frac{\mu}{\epsilon}}$$

Research in chiral and bianisotropic media: Complex media electromagnetics

- **Bianisotropics 2000**, 8th International Conference on Electromagnetics of Complex Media, 27-29 September 2000, Technical University of Lisbon, Portugal
- **Bianisotropics'98**, 7th International Conference on Complex Media, 3-6 June 1998, Technical University of Braunschweig, Germany
- **Bianisotropics'97** - International Conference and Workshop on Electromagnetics of Complex Media, 5-7 June 1997, The University of Glasgow, Great Britain

- **Chiral'96** - NATO Advanced Research Workshop, July 1996, St. Petersburg - Moscow, Russia.
- **Chiral'95** - International Conference on the Electromagnetic Effects of Chirality and its Applications, October 1995, The Pennsylvania State University, USA.
- **Chiral'94** - 3rd International Workshop on Chiral, Bi-isotropic and Bi-anisotropic Media, May 1994, Perigueux, France
- **Bianisotropics'93** - Seminar on Electrodynamics of Chiral and Bianisotropic Media, October 1993, Gomel, Belarus.
- **Bi-isotropics'93** - Workshop on Novel Microwave Materials, February 1993, Helsinki University of Technology, Finland.

The role of chirality in absorbers

Microscopic view

$$\mathbf{p} = \alpha_{\rm ee}\mathbf{E} + \alpha_{\rm em}\mathbf{H}, \qquad \mathbf{m} = \alpha_{\rm mm}\mathbf{H} + \alpha_{\rm me}\mathbf{E}$$

$$\epsilon = \epsilon_{\rm host} + \frac{1}{D}\left(N\alpha_{\rm ee} - N^2\frac{\Delta}{3\mu_{\rm host}}\right), \quad \mu = \mu_{\rm host} + \frac{1}{D}\left(N\alpha_{\rm mm} - N^2\frac{\Delta}{3\epsilon_{\rm host}}\right)$$

$$D = 1 - N\frac{\alpha_{\rm ee}}{3\epsilon_{\rm host}} - N\frac{\alpha_{\rm mm}}{3\mu_{\rm host}} + N^2\frac{\Delta}{9\epsilon_{\rm host}\mu_{\rm host}}$$

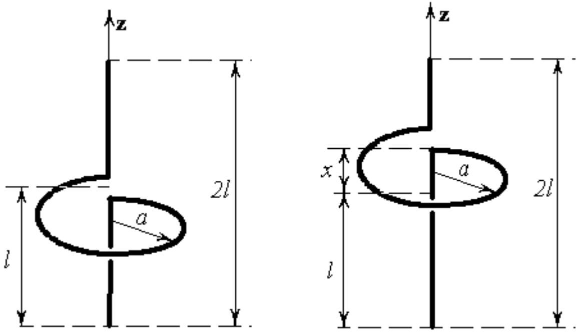
$$\Delta = \alpha_{\rm ee}\alpha_{\rm mm} - \alpha_{\rm em}\alpha_{\rm me}$$

But, most commonly

$$\alpha_{\rm ee}\alpha_{\rm mm} = \alpha_{\rm em}\alpha_{\rm me}, \qquad \Rightarrow \qquad \Delta = 0!$$

S.A. Tretyakov, A.A. Sochava, C.R. Simovski, Influence of chiral shapes of individual inclusions on the absorption in chiral composite coatings, Electromagnetics, vol. 16, no. 2, pp. 113-127, 1996.

Chiral shapes

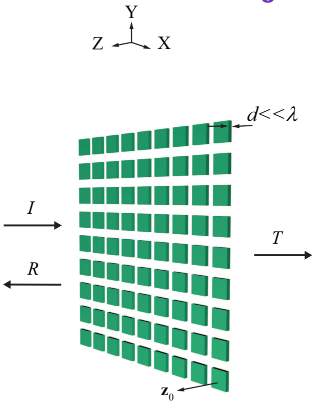


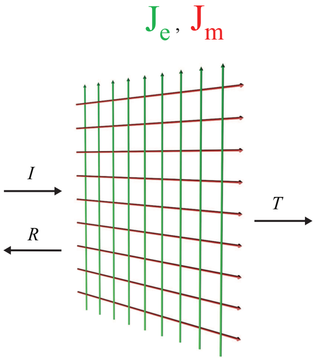
$$\Delta = \alpha_{ee}\alpha_{mm} - \alpha_{em}\alpha_{me} = 0 \qquad \Delta = \alpha_{ee}\alpha_{mm} - \alpha_{em}\alpha_{me} \neq 0$$

S.A. Tretyakov, A.A. Sochava, C.R. Simovski, Influence of chiral shapes of individual inclusions on the absorption in chiral composite coatings, Electromagnetics, vol. 16, no. 2, pp. 113-127, 1996.

Metasurface absorbers

Engineered electric and magnetic current sheets





$$J_e = \frac{j\omega \mathbf{p}}{S}, \qquad J_m = \frac{j\omega \mathbf{m}}{S}$$

Here S is the unit-cell area.

Absorbers: Zero reflected and transmitted fields

T. Niemi, A. Karilainen, and S. Tretyakov, Synthesis of polarization transformers, IEEE Trans. Antennas Propagation, vol. 61, no. 6, pp. 3102-3111, 2013.

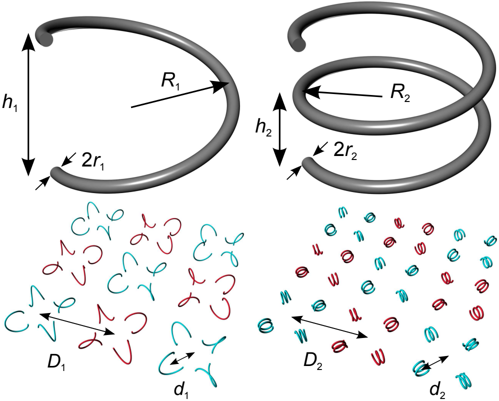
$$\mathbf{E}_{\rm ref} = -\frac{j\omega}{2S}\left(\eta_0\widehat{\alpha}_{\rm ee} \pm 2j\widehat{\Omega} - \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}\right)\mathbf{E}_{\rm inc}$$

$$\mathbf{E}_{\rm tr} = \left[1 - \frac{j\omega}{2S}\left(\eta_0\widehat{\alpha}_{\rm ee} + \frac{1}{\eta_0}\widehat{\alpha}_{\rm mm}\right)\right]\mathbf{E}_{\rm inc} \mp \frac{\omega}{S}\widehat{\kappa}\,\mathbf{z}_0 \times \mathbf{E}_{\rm inc}$$

Magnetic response ($\alpha_{\rm mm}$) controls matching; omega coupling (Ω) controls asymmetry in reflections from two sides; chirality (κ) controls polarization transformation in transmission.

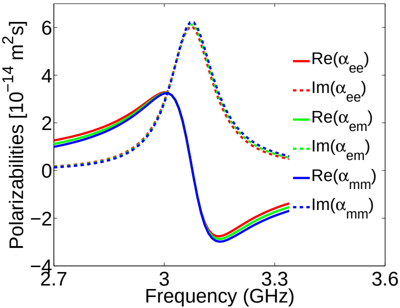
For full absorption the chirality parameter $\widehat{\kappa}$ must be zero!

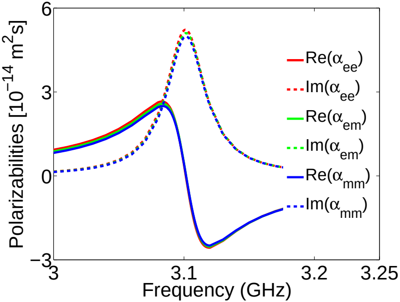
Chirality in modern absorbers



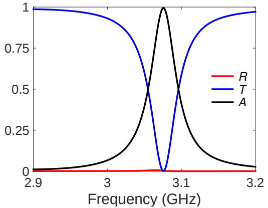
V.S. Asadchy, I.A. Faniayeu, Y. Radi, S.A. Khakhomov, I.V. Semchenko, and S.A. Tretyakov, Broadband reflectionless metasheets: Frequency-selective transmission and perfect absorption, Phys. Rev. X, vol. 5, p. 031005, 2015.

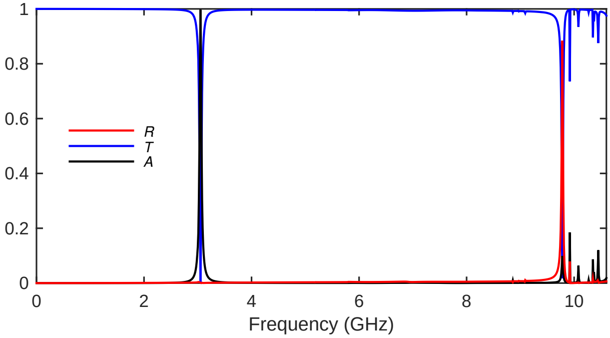
Polarizabilities of spirals can be balanced



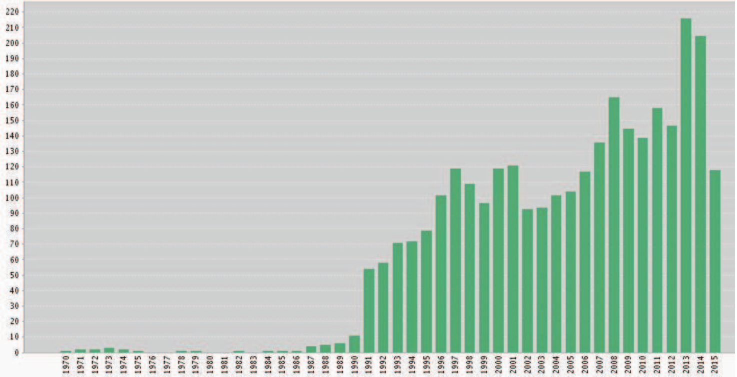


Frequency response





Papers on “chirality” AND “electromagnetic”

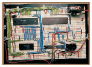


Sharp raise around 1990 (“invisible material”)

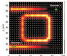
Somewhat down around 2000 (chirality and bianisotropy is well understood)

Up again? 2013-14

Modular approach in electronics and *metatronics*

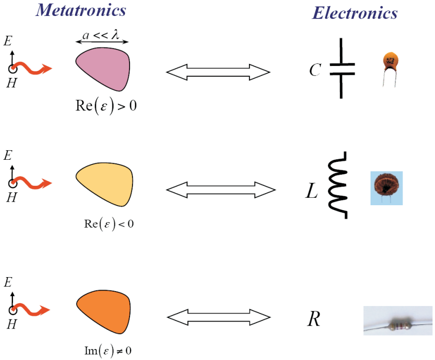


Electronics $\boldsymbol{J} = \sigma_e \boldsymbol{E}$



From: D. Prather's group

Photonics $\boldsymbol{D} = \varepsilon \boldsymbol{E}$



Pictures by N. Engheta.

N. Engheta, Circuits with Light at Nanoscales: Optical Nanocircuits Inspired by Metamaterials, Science, vol. 317, p. 1698, 2007.

Modular approach in metamaterials: *Materiatronics*

General (linear) electromagnetic material:

$$\mathbf{D} = \overline{\overline{\epsilon}} \cdot \mathbf{E} + \overline{\overline{a}} \cdot \mathbf{H}$$

$$\mathbf{B} = \overline{\overline{\mu}} \cdot \mathbf{H} + \overline{\overline{b}} \cdot \mathbf{E}$$

General (linear) meta-atom:

$$\mathbf{p} = \overline{\overline{\alpha}}_{\rm ee} \cdot \mathbf{E} + \overline{\overline{\alpha}}_{\rm em} \cdot \mathbf{H}$$

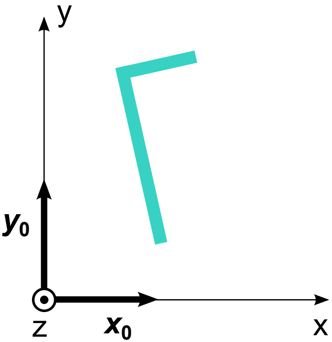
$$\mathbf{m} = \overline{\overline{\alpha}}_{\rm mm} \cdot \mathbf{H} + \overline{\overline{\alpha}}_{\rm me} \cdot \mathbf{E}$$

What are the basic *modules* from which any meta-atom and any medium can be built?

A.A. Sochava, C.R. Simovski, S.A. Tretyakov, Chiral effects and eigenwaves in bi-anisotropic omega structures, Advances in Complex Electromagnetic Materials, NATO ASI Series High Technology, vol. 28, Kluwer Academic Publishers, pp. 85-102, 1997.

Basic building blocks: fundamental meta-atoms?

Let us consider some arbitrary reciprocal particle:



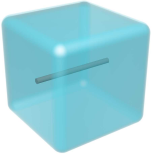
$$\mathbf{p} = \overline{\overline{\alpha}}_{\rm ee}\cdot\mathbf{E}+\overline{\overline{\alpha}}_{\rm em}\cdot\mathbf{H} = \left(\alpha_{\rm ee}^{xx}\mathbf{x}_0\mathbf{x}_0 + \alpha_{\rm ee}^{yy}\mathbf{y}_0\mathbf{y}_0\right)\cdot\mathbf{E}+\left(\alpha_{\rm em}^{xz}\mathbf{x}_0 + \alpha_{\rm em}^{yz}\mathbf{y}_0\right)\mathbf{z}_0\cdot\mathbf{H}$$

$$\mathbf{m} = \overline{\overline{\alpha}}_{\rm mm}\cdot\mathbf{H}+\overline{\overline{\alpha}}_{\rm me}\cdot\mathbf{E} = \alpha_{\rm mm}^{zz}\mathbf{z}_0\mathbf{z}_0\cdot\mathbf{H} + \mathbf{z}_0\left(\alpha_{\rm me}^{zx}\mathbf{x}_0 + \alpha_{\rm me}^{zy}\mathbf{y}_0\right)\cdot\mathbf{E}$$

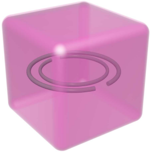
Reciprocity: $\overline{\overline{\alpha}}_{\rm me} = -\overline{\overline{\alpha}}_{\rm em}^{T}$

Electric and magnetic meta-atoms

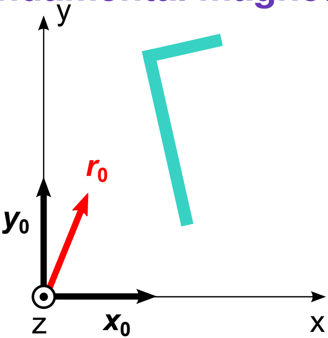
1. Electric dipole (e.g., a small resonant antenna)



2. Magnetic dipole (e.g., a split ring)



Fundamental magnetoelectric meta-atoms?



$$\overline{\overline{\alpha}}_{\rm em} = \left(\alpha_{\rm em}^{xz}\mathbf{x}_0 + \alpha_{\rm em}^{yz}\mathbf{y}_0\right)\mathbf{z}_0 = K\mathbf{r}_0\mathbf{z}_0$$

$$K = \sqrt{(\alpha_{\rm em}^{xz})^2 + (\alpha_{\rm em}^{yz})^2}, \quad \mathbf{r}_0 = \frac{1}{K}\left(\alpha_{\rm em}^{xz}\mathbf{x}_0 + \alpha_{\rm em}^{yz}\mathbf{y}_0\right)$$

$\mathrm{tr}\left(\overline{\overline{\alpha}}_{\rm em}\right) = 0,$ because $\mathbf{r}_0 \cdot \mathbf{z}_0 = 0$

Splitting into symmetric and anti-symmetric parts, we have

$$\overline{\overline{\alpha}}_{\rm em} = \overline{\overline{\alpha}}_{\rm em}^{\rm S} + \overline{\overline{\alpha}}_{\rm em}^{\rm A}$$

where

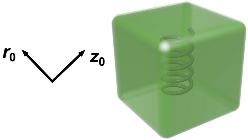
$$\overline{\overline{\alpha}}_{\rm em}^{\rm S} = \frac{K}{2}\left(\mathbf{r}_0\mathbf{z}_0 + \mathbf{z}_0\mathbf{r}_0\right), \qquad \overline{\overline{\alpha}}_{\rm em}^{\rm A} = \frac{K}{2}\left(\mathbf{r}_0\mathbf{z}_0 - \mathbf{z}_0\mathbf{r}_0\right)$$

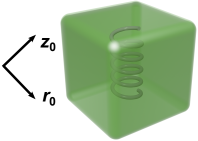
We need spirals

We can write the symmetric part of $\overline{\overline{\alpha}}_{\rm em}$ in the diagonal form:

$$\overline{\overline{\alpha}}_{\rm em}^{S} = \frac{K}{2}\left(\mathbf{v}_0\mathbf{v}_0 - \mathbf{w}_0\mathbf{w}_0\right) \quad \text{where } \mathbf{v}_0 = \frac{\sqrt{K}}{2}(\mathbf{r}_0+\mathbf{z}_0),\ \mathbf{w}_0 = \frac{\sqrt{K}}{2}(\mathbf{z}_0-\mathbf{r}_0)$$

Small spirals (right- and left-handed)





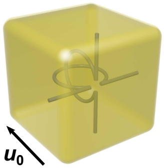
And the last element is. . .

What particle topology corresponds to $\overline{\overline{\alpha}}_{\rm em}^{\rm A} = \frac{K}{2}\left(\mathbf{r}_0\mathbf{z}_0 - \mathbf{z}_0\mathbf{r}_0\right)$?

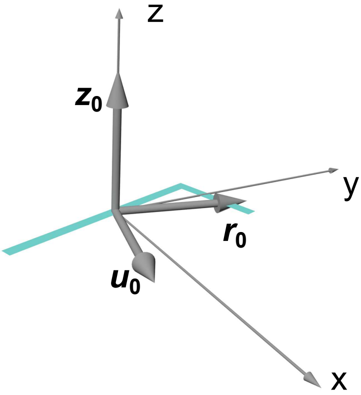
$$\mathbf{r}_0\mathbf{z}_0 - \mathbf{z}_0\mathbf{r}_0 = -\mathbf{u}_0 \times \left(\mathbf{r}_0\mathbf{r}_0 + \mathbf{z}_0\mathbf{z}_0\right) = -\mathbf{u}_0 \times \overline{\overline{I}}$$

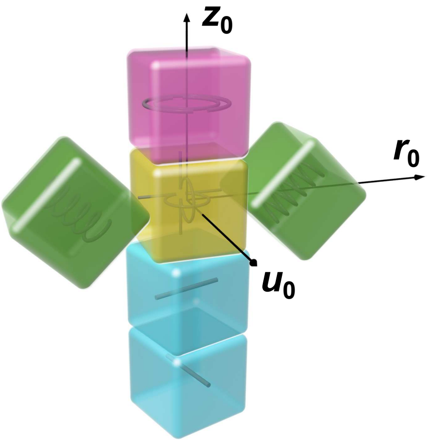
operator of 90° rotation around $-\mathbf{u}_0$.

Uniaxial omega particle: a “hat”



Our example Γ-particle decomposed into fundamental building blocks





Our Γ-particle is a *pseudochiral omega particle*

$\kappa = \mathrm{tr}\left(\overline{\overline{\alpha}}_{\mathrm{em}}\right)$: chirality parameter

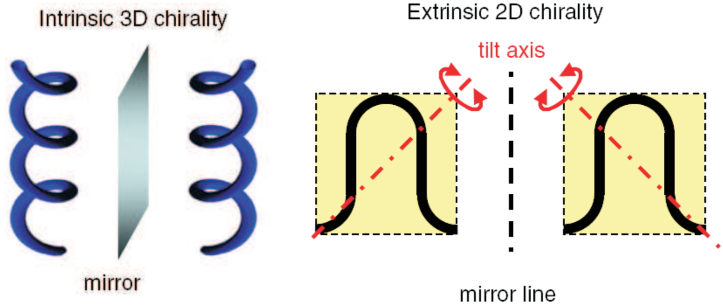
$\overline{\overline{N}} = \overline{\overline{\alpha}}_{\mathrm{em}}^{\mathrm{S}}$ (trace-free): pseudochirality parameter

$\overline{\overline{J}} = \overline{\overline{\alpha}}_{\mathrm{em}}^{\mathrm{A}}$: omega parameter

Coupling parameters	Class
$\kappa \neq 0,\ \overline{\overline{N}} = 0,\ \overline{\overline{J}} = 0$	Isotropic chiral medium
$\kappa \neq 0,\ \overline{\overline{N}} \neq 0,\ \overline{\overline{J}} = 0$	Anisotropic chiral medium
$\kappa = 0,\ \overline{\overline{N}} \neq 0,\ \overline{\overline{J}} = 0$	Pseudochiral medium
$\kappa = 0,\ \overline{\overline{N}} = 0,\ \overline{\overline{J}} \neq 0$	Omega medium
$\kappa \neq 0,\ \overline{\overline{N}} = 0,\ \overline{\overline{J}} \neq 0$	Chiral omega medium
$\kappa = 0,\ \overline{\overline{N}} \neq 0,\ \overline{\overline{J}} \neq 0$	Pseudochiral omega medium
$\kappa \neq 0,\ \overline{\overline{N}} \neq 0,\ \overline{\overline{J}} \neq 0$	General reciprocal bi-anisotropic medium

S.A. Tretyakov, A.H. Sihvola, A.A. Sochava, C.R. Simovski, Magnetoelectric interactions in bi-anisotropic media, J. of Electromagnetic Waves and Applications, vol. 12, no. 4, pp. 481-497, 1998.

About terminology



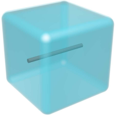
E. Plum, V.A. Fedotov, and N.I. Zheludev, Extrinsic electromagnetic chirality in metamaterials, J. Opt. A: Pure Appl. Opt., vol. 11, 074009, 2009.

Intrinsic chirality = chirality

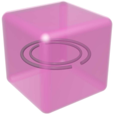
Extrinsic chirality = pseudochirality

We can realize any reciprocal bianisotropic response combining only

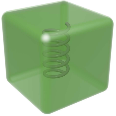
1. Electric dipoles (e.g., small resonant particles)



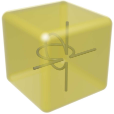
2. Magnetic dipoles (e.g., a split ring)



3. Uniaxial chiral particles (e.g., spirals)



4. Uniaxial omega particles (e.g., “hats”)



Fifth element?

Second-order spatial dispersion is more than artificial magnetism!

E.g. for isotropic media we have

$$\mathbf{D} = \epsilon_{\mathrm{P}}\mathbf{E} - j\xi_c\mathbf{B} + \beta\nabla\nabla\cdot\mathbf{E} + \gamma\nabla\times(\nabla\times\mathbf{E}), \qquad \mathbf{H} = \frac{1}{\mu_0}\mathbf{B} - j\xi_c\mathbf{E}$$

equivalent to

$$\mathbf{D} = \epsilon_{\mathrm{P}}\mathbf{E} - j\xi_c\mathbf{B} + \beta\nabla\nabla\cdot\mathbf{E}, \qquad \mathbf{H} = \frac{1}{\mu_{\mathrm{P}}}\mathbf{B} - j\xi_c\mathbf{E}, \qquad \mu_{\mathrm{P}} = \frac{\mu_0}{1-\omega^2\mu_0\gamma}$$

Thus, we still need to be able to realize

$$\mathbf{p} = \alpha_5\nabla\nabla\cdot\mathbf{E}$$

What can be this basic particle providing α_5?

Old, but largely unexplored area

жидкие кристаллы). При учете пространственной дисперсии в изотропной, негиротропной среде $\varepsilon_{ij}(\omega, \mathbf{k}) = (\delta_{ij} - k_i k_j/k^2)\,\varepsilon^{tr}(\omega, k) + (k_i k_j/k^2)\,\varepsilon^{l}(\omega, k)$, причем $\varepsilon^{tr}(\omega, 0) = \varepsilon^{l}(\omega, 0) = \varepsilon(\omega)$ (подробнее см. ниже). Отметим, что тен-

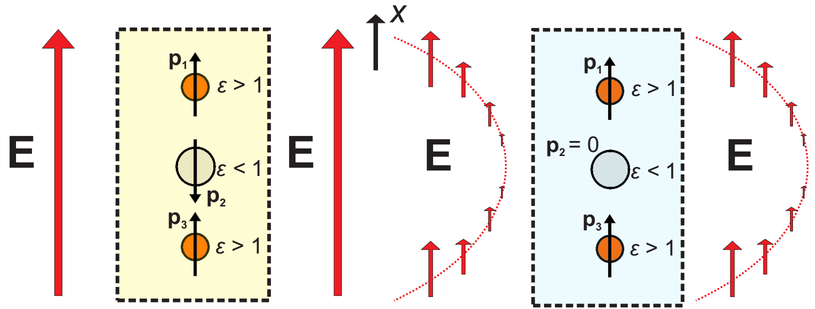
тропной среде: выделенное направление создается волновым вектором. Если среда не только изотропна, но обладает также и центром инверсии, тензор ε_{ik} может быть составлен только из компонент вектора $\mathbf{k}$ и единичного тензора δ_{ik} (при отсутствии центра симметрии может стать возможным также и член с единичным антисимметричным тензором e_{ikl}; см. § 104). Общий вид такого тензора можно записать как

$$\varepsilon_{ik}(\omega, \mathbf{k}) = \varepsilon_t(\omega, k)\left(\delta_{ik} - \frac{k_i k_k}{k^2}\right) + \varepsilon_l(\omega, k)\frac{k_i k_k}{k^2}, \qquad (103{,}12)$$

где ε_t и ε_l зависят только от абсолютной величины волнового вектора (и от ω). Если напряженность $\mathbf{E}$ направлена по волно-

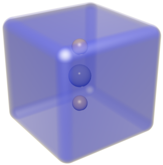
V.M. Agranovich, V.L. Ginzburg, Crystal optics with allowance for spatial dispersion; exciton theory, part I, Sov. Physics Uspekhi, vol. 5, 323-346, 1962. L.D. Landau and E.M. Lifshitz, Electrodynamics of Continuous Media, 2nd edition, Pergamon Press, 1984.

One possible topology for the *fifth element*



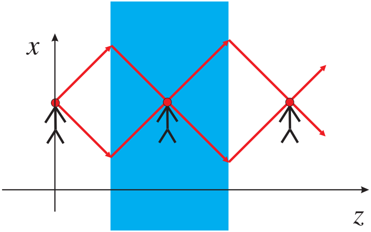
$\mathbf{p}_{\text{total}} = 0$

$p_{\text{total}} = \alpha_5 \bullet \partial^2 E_x / \partial x^2$

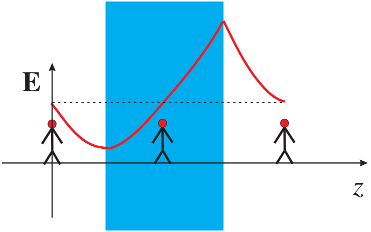
Fifth element: 

Exciting possibilities offered by media with negative material parameters

A slab with $\epsilon_r = \mu_r = -1$ is a perfect lens



V. Veselago, 1967 (propagating waves)



J. Pendry, 2000 (all modes)

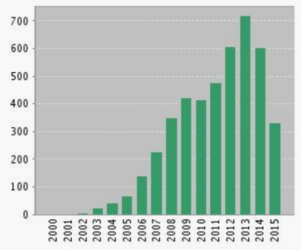
J. Pendry, Negative refraction makes a perfect lens, Phys. Rev. Lett., vol. 85, 3966-3969, 2000.

“Metamaterial” term appears around the year 2000

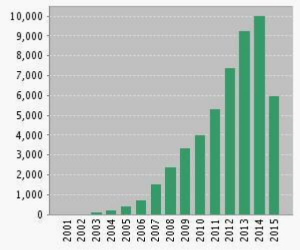
Composite medium with simultaneously negative permeability and permittivity By: Smith, DR; Padilla, WJ; Vier, DC; et al. PHYSICAL REVIEW LETTERS Volume: 84 Issue: 18 Pages: 4184-4187 Published: MAY 1 2000

Direct calculation of permeability and permittivity for a left-handed metamaterial By: Smith, DR; Vier, DC; Kroll, N; et al. APPLIED PHYSICS LETTERS Volume: 77 Issue: 14 Pages: 2246-2248 Published: OCT 2 2000

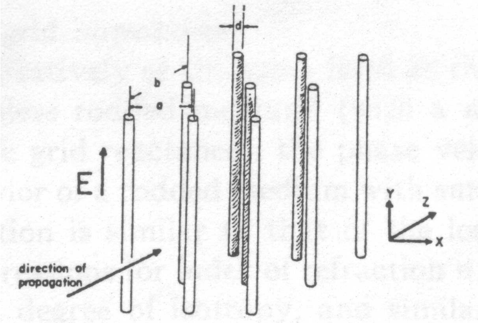
Published Items in Each Year



Citations in Each Year



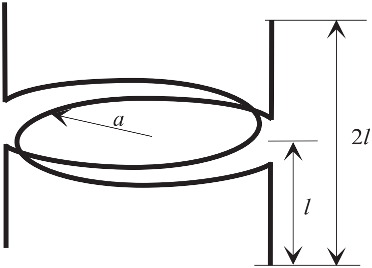
Negative permittivity: Wire medium

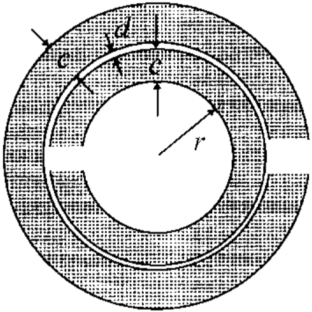


$$\epsilon_p = \epsilon_0 \left(1 - \frac{\omega_p{}^2}{\nu^2 + \omega^2} + j \frac{\omega_p{}^2 \nu / \omega}{\nu^2 + \omega^2} \right)$$

J. Brown, Artificial dielectrics having refractive indices less than unity, Proc. IEE, vol. 100, part 4, 51-62, 1953; W. Rotman, Plasma simulations by artificial dielectrics and parallel plate media, IRE Trans. Antennas Propag., 81-96, Jan. 1962.

Negative permeability: SRR

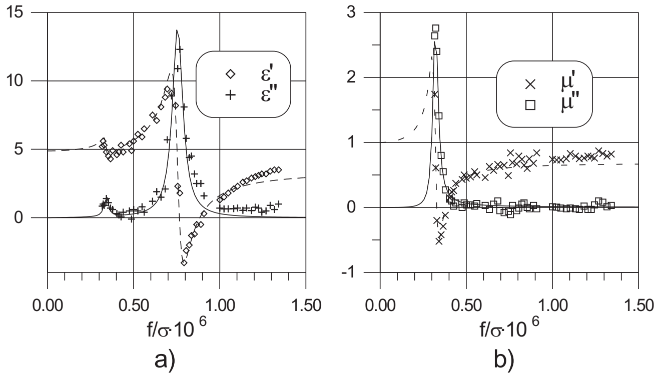




A.N. Lagarkov, et al., *Electromagnetics,* vol. 17, no. 3, pp. 213-237, 1997 (left);

J.B. Pendry, et al., *IEEE Trans. Microwave Theory Techn.*, vol. 47, pp. 2075-2084, 1999 (right).

$\mu < 0$, first(?) experiment



A.N. Lagarkov, V.N. Semenenko, V.A. Chistyaev, D.E. Ryabov, S.A. Tretyakov, C.R. Simovski, Resonance properties of bi-helix media at microwaves, *Electromagnetics,* vol. 17, no. 3, pp. 213-237, 1997.

Both ϵ and μ negative

R.A. Shelby, D.R. Smith, and S. Schultz, Experimental verification of a negative index of refraction, Science, vol. 292, pp. 77-79, 2001. The highest number of citations (Web of Science: over 4000).

First *metamaterial* as a medium with properties not found in nature: Wire medium

More than just negative permittivity:

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

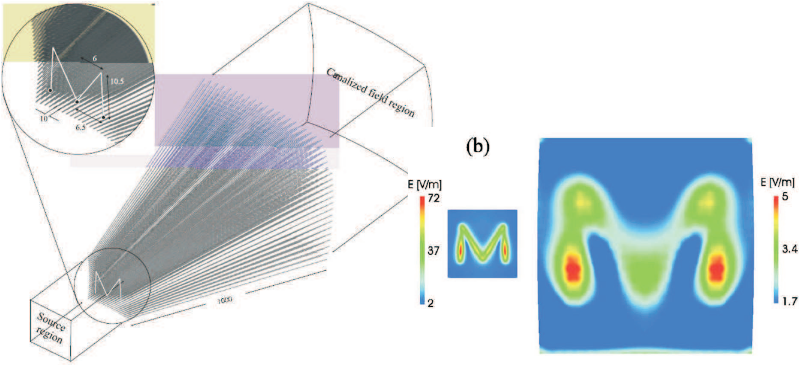
In space-time domain:

$$\mathbf{D}(x,y,z,t) = \epsilon_0 \mathbf{E}(x,y,z,t) + \frac{\epsilon_0 k_p^2 c}{4} \mathbf{z}_0 \int_{-\infty}^{t} \int_{z-c(t-t')}^{z+c(t-t')} E_z(x,y,z',t')\, dz'\, dt'$$

P.A. Belov, R. Marques, S.I. Maslovski, I.S. Nefedov, M. Silveirinha, C.R. Simovski, and S. A. Tretyakov, Strong spatial dispersion in wire media in the very large wavelength limit, *Phys. Rev. B,* vol. 67, 113103, 2003.

Canalization of waves in wire media

Enlarging superlens



P. Ikonen, C. Simovski, S. Tretyakov, P. Belov, and Y. Hao, Magnification of subwavelength field distributions at microwave frequencies using a wire medium slab operating in the canalization regime, Applied Phys. Lett., vol. 91, 104102, 2007.

Strong spatial dispersion in metasurfaces

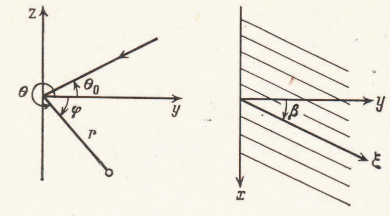


Рис. 1. Система координат: θ_0 – угол падения волны; r, θ – координаты точки наблюдения; $\varphi=2\pi-\theta$

1. *Постановка задачи.* Пусть сетка образована параллельными проводами радиусом a, расположенными в плоскости $z=0$ при $y>0$ под углом β к оси y (рис. 1). Расстояние между проводами – b. Вторичное поле $\mathbf{E}$ при $a\ll b\ll\lambda$ удовлетворяет усредненному граничному условию [6] (зависимость от времени имеет вид $e^{-i\omega t}$):

$$(1)\qquad E_\xi^i+E_\xi=-i\rho\frac{\alpha}{2}\left(j_\xi+\frac{1}{k^2}\operatorname{grad}_\xi\operatorname{div}\mathbf{j}\right),\quad z=0,\quad y>0,$$

где $\alpha=(2b/\lambda)\ln(b/2\pi a)$, $\mathbf{j}=j\boldsymbol{\xi}_0$ – усредненная плотность тока,

V.A. Rozov, S.A. Tretyakov, Diffraction of plane electromagnetic waves by a semi-infinite grid made of parallel conductors arranged at an angle to the grid’s edge, Radioeng. and Electronic Phys., vol. 29, no. 5, pp. 37-47, 1984. M.I. Kontorovich, On screening effect of closed meshes, Zhurnal Techn. Fiziki, vol. 9, 2195-2210, 1939.

Strong spatial dispersion in 2D and 3D compared

2D metasurface (1939–1962):

$$E_x = j\eta_0 \frac{d}{\lambda} \ln \frac{d}{2\pi r_0} \left(1 + \frac{1}{k^2} \frac{\partial^2}{\partial x^2}\right) J_x$$

3D metamaterial (2003):

$$\epsilon_x = \epsilon_0 \left(1 - \frac{k_p^2}{k^2 - k_x^2}\right)$$

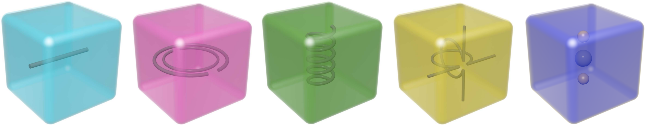
Using $\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} = \epsilon \mathbf{E}$, we get

$$E_x = -\frac{k^2}{\epsilon_0 k_p^2} \left(1 + \frac{1}{k^2} \frac{\partial^2}{\partial x^2}\right) P_x$$

Where we are now?

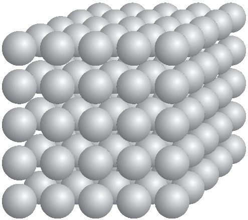
We have

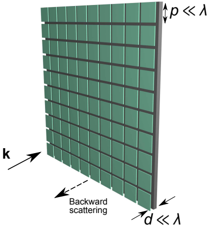
- Artificial dielectrics, magnetics, chiral media. . . (“imitations of nature”)
- Some artificial materials with properties not found in nature (negative refractive index, strong spatial dispersion, hyperbolic dispersion, . . .)
- *Materiatronics* concept (all possible effects up to the second-order spatial dispersion terms)



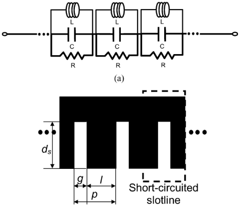
What next?

Exploring all dimensions


3D



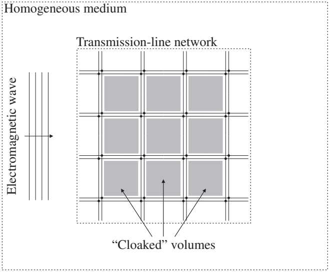
2D

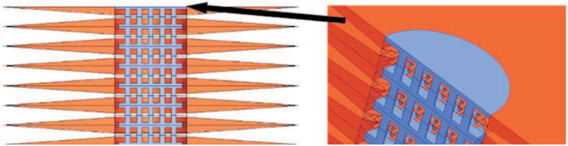


1D

Amr M.E. Safwat, S.A. Tretyakov, A.V. Räisänen, High-impedance wire, IEEE Antennas and Wireless Propagat. Lett., vol. 6, pp. 631-634, 2007.

Fourth dimension: Transmission-line cloak

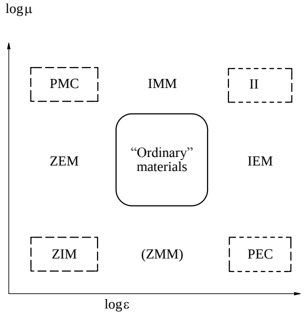




P. Alitalo, O. Luukkonen, L. Jylhä, J. Venermo, and S.A. Tretyakov, Transmission-line networks cloaking objects from electromagnetic fields, IEEE Trans. Antennas Propagation, vol. 56, no. 2, pp. 416-424, 2008.

Exploring the whole parameter space: probing extreme values

		ε	μ	n	η
PEC	perfect electric conductor	large	small	undefined	very small
PMC	perfect magnetic conductor	small	large	undefined	very large
ZIM	zero-index material	small	small	very small	undefined
IIM	infinite-index material	large	large	very large	undefined
ZEM ENZ	zero-electric material	very small	undefined	small	large
ZMM MNZ	zero-magnetic material	undefined	very small	small	small
IEM	infinite-electric material	very large	undefined	large	small
IMM	infinite-magnetic material	undefined	very large	large	large



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.

Exploring extreme responses of materials

For example, the propagation constants of RCP and LCP waves in chiral materials are different:

$$k_\pm = k_0(n \pm \kappa)$$

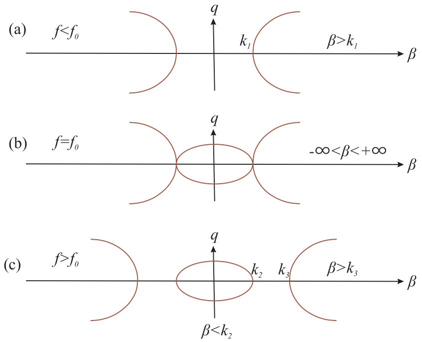
In *chiral nihility* materials, where $n \approx 0$, the difference is maximized: $k_\pm = \pm k_0 \kappa$.

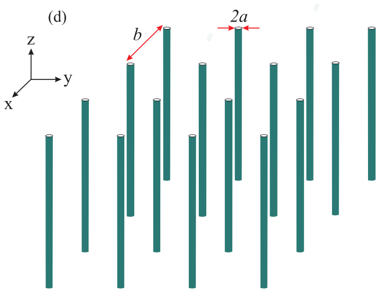
S. Tretyakov, I. Nefedov, A. Sihvola, S. Maslovski, C. Simovski, Waves and energy in chiral nihility, Journal of Electromagnetic Waves and Applications, vol. 17, no. 5, pp. 695-706, 2003.

In composites of *optimal* spirals $n - \kappa = 1$ and waves of one of the eigenpolarizations propagate as in free space (inclusions are invisible).

I.V. Semchenko, S.A. Khakhomov, and S.A. Tretyakov, Chiral metamaterial with unit negative refraction index, European Physical Journal-Appl. Phys., vol. 46, 32607, 2009.

Exploring universal properties of artificial materials



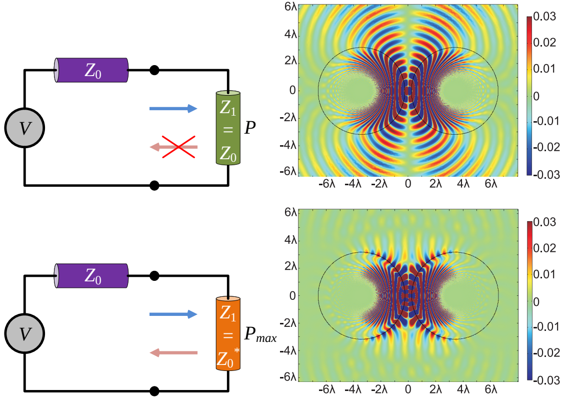


M.S. Mirmoosa, S.Yu. Kosulnikov and C.R. Simovski, Unbounded spatial spectrum of propagating waves in a polaritonic wire medium, Phys. Rev. B 92, 075139, 2015.

Poster session I, poster 69.

Targeting ultimate performance

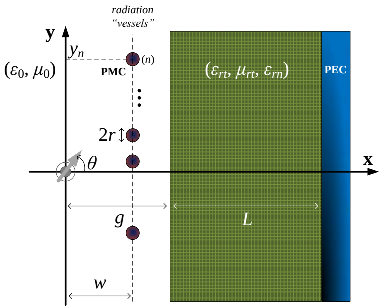
Metamaterial which is infinitely more black than the ideally black body

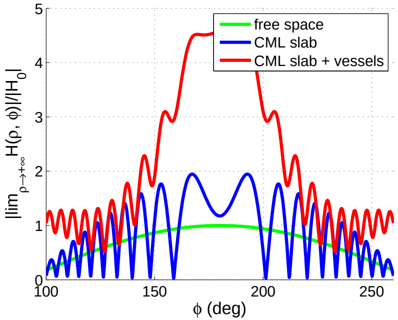


C.A. Valagiannopoulos, J. Vehmas, C.R. Simovski, S.A. Tretyakov, S.I. Maslovski, Electromagnetic energy sink, arxiv.org/abs/1507.00974, 2015.

Session “Metamaterials absorbers and thermal metamaterials”, Wednesday, 16.15.

Going over fundamental limits





Passive planar reflectors can increase the radiated field more than 2 times (work in progress, C. Valagiannopoulos et al.)

Power spectral density of thermal radiation into far zone can be arbitrary high.

S. I. Maslovski, C. R. Simovski, S. A. Tretyakov, Overcoming black body radiation limit in free space: metamaterial "thermal black hole", arXiv:1412.4625, 2014.

About the name

Metamaterial is "an arrangement of artificial structural elements, designed to achieve advantageous and unusual electromagnetic properties".

- Artificial electromagnetic materials
- Complex (electromagnetic) media (materials)
- Metamaterials

Many confusions may arise, e.g.
"Metamaterials or left-handed media were first introduced by Veselago [1] and rediscovered with proposals for implementation by Pendry [2]. . . "

"Metamaterial Revolution: The New Science of Making Anything Disappear. . . "

Conclusions

- Artificial electromagnetic materials (metamaterials) and metasurfaces have been studied since at least the year 1898: we are at least 117 years old
- There is still lots of work on developing and applying ***materia****tronics*
  - Optimal (application-driven) designs
  - Extreme-performance metamaterials
  - Active and parametric structures, including non-Foster
  - Full exploration of spatial dispersion (mesoscopic regimes)
  - Going into quantum regime
  - . . .