STRANGE AND UNCONVENTIONAL MATERIALS: HOW COMPLEX MUST THE ELECTROMAGNETIC DESCRIPTION BE ?

Ari Sihvola

Electromagnetics Laboratory, Helsinki University of Technology
P.O. Box 3000, FIN–02015 HUT, Finland.
e-mail: `ari.sihvola@hut.fi`

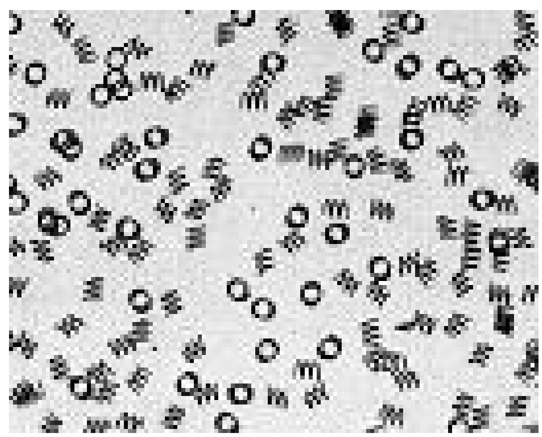
Abstract: This presentation deals with electromagnetic wave–material interaction from the point of view of qualitative changes in the material response as the structure of the material is complex in some sense. It is argued that much of such complexity in the level of metamaterial description can be understood from the platform of electromagnetic (even electrostatic) mixing rules and homogenisation principles.

1. INTRODUCTION

In electromagnetics—which connects to most of the commissions of the International Union of Radio Science, URSI, but with the main commission being B (Fields and Waves)—a very active field of study is the behaviour of complex materials in terms of how waves interact with them [1, 2, 3, 4]. To be sure, there are difficulties in trying to label such materials: how complicated should the behaviour be so that they deserve to be called "complex." In the loosest sense, very often so is done in connection with media displaying any deviation from the simple isotropic material response.

Let us, therefore, just list the following classes as examples of complex, exotic, strange, or unconventional materials:

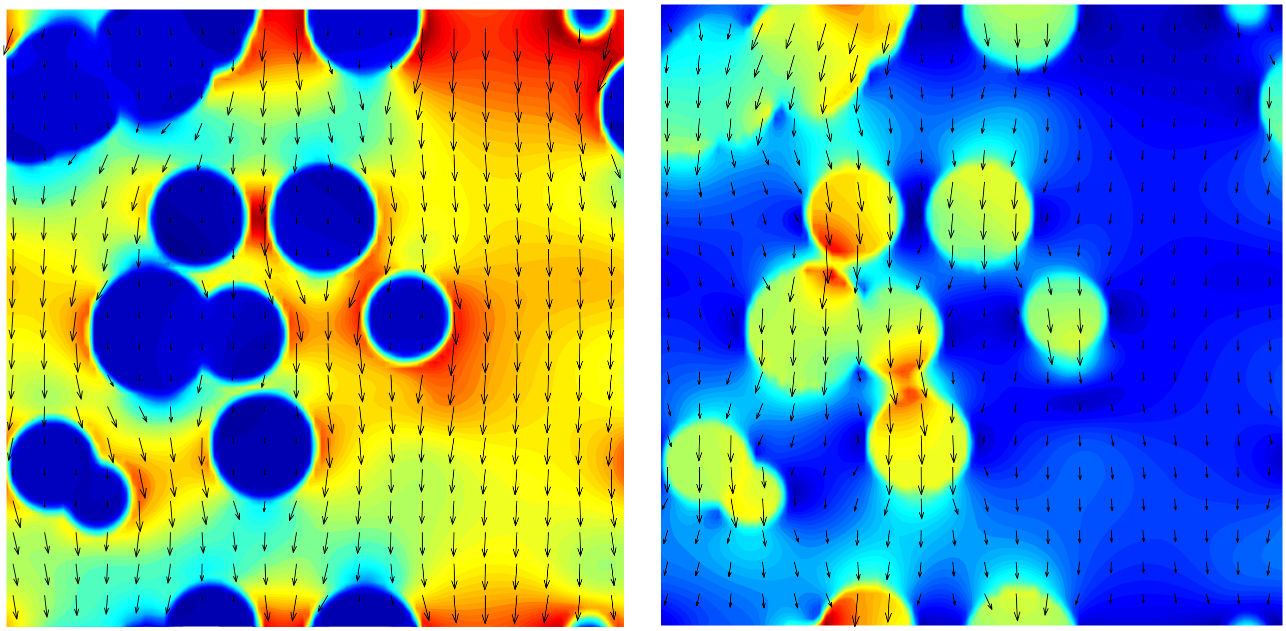
- magnetic and gyrotropic materials
- chiral, omega, magnetoelectric, and bian-isotropic materials
- Tellegen media and other non-reciprocal materials
- artificially enhanced non-linear materials
- photonic crystals, or PBG, EBG materials (photonic/electromagnetic band gap structures)
- materials with negative refractive index, with simultaneously $\epsilon_r < 0$ and $\mu_r < 0$; media capable of supporting backward waves
- two-dimensional materials, e.g., frequency selective surfaces
- smart materials and metamaterials



As an example of a complex material caused by simple geometrical pattern, here a sample of chiral material manufactured by the company Finnyards Ltd. Material Technology. Metal helices are randomly distributed (both in position and in orientation) in an epoxy matrix. The size of a single helix is around 1 mm. This sample shows its strongest chiral activity at around 8 GHz.

2. SPECIAL MATERIALS AS INHOMOGENEOUS OR RANDOM MEDIA

In a certain sense, common to all strange materials is the fact that the unexpected behaviour arises from inhomogeneities. Of course, a plain homogeneity responds to electromagnetic wave in an uninteresting manner. Certainly also, an arbitrarily random inhomogeneity may contribute to the macroscopic polarisability density just in an average way, creating no special new effects. But it is very often the case that a seemingly innocent inhomogeneity pattern in a material may be a cause for a qualitatively new type of macroscopic response. This is due to the intricate connectedness of electric and magnetic fields with the material geometry. *Ubi materia, ibi geometria*, according to Johannes Kepler's credo from 1601 [5]. One of the messages of this presentation will be that the emergent complexity in such "higher-level" materials can be understood in many cases very clearly with the use of classical mixing rules [6, 7, 8] and homogenisation principles.



An example of the numerical analysis of quasirandom structures from reference [9]: the electric flux in complementary two-phase materials. On the left, a Swiss cheese mixture (the background medium has lower permittivity than the spherical inclusions). On the right, a raisin pudding mixture (the background medium has higher permittivity than the spherical inclusions). The flux density, naturally, favors regions of higher permittivity.

3. REFERENCES

[1] Cf. the series chiral and bianisotropic conferences, most recent ones in Lisbon (September 2000) and Braunschweig (1998). Also in the "classical" electromagnetics meetings, several sessions on complex media are arranged.

[2] I.V. Lindell, A.H. Sihvola, S.A. Tretyakov, and A.J. Viitanen: *Electromagnetic Waves in Chiral and Bi-Isotropic Media*, Artech House, Boston and London, 1994.

[3] A. Serdykov, I. Semchenko, S. Tretyakov, and A. Sihvola: *Electromagnetics of Bi-Anisotropic Materials*, Gordon & Breach, 2001.

[4] J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart: Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Trans. Microwave Theory and Techniques*, Vol. 47, No. 11, pp. 2075-2084, November 1999.

[5] A. Sihvola: Ubi materia, ibi geometria. Available from `http://www.hut.fi/~asihvola/memos.html`

[6] A. Sihvola: *Electromagnetic Mixing Formulas and Applications*, IEE Publishing, Electromagnetic Wave Series, London, 1999.

[7] J.C. Maxwell Garnett: Colours in metal glasses and in metal films. *Transactions of the Royal Society* (London), Vol. CCIII, pp. 385-420, 1904.

[8] D.A.G. Bruggeman: Berechnung verschiedener physikalischen Konstanten von heterogenen Substanzen, I. Dielektrizitätskonstanten und Leitfähigkeiten der Mischkörper aus isotropen Substanzen. *Annalen der Physik*, Series 5, Vol. 24, p. 636-679, 1935.

[9] K. Kärkkäinen, A.H. Sihvola, and K.I. Nikoskinen: Analysis of a three-dimensional dielectric mixture with finite difference mathod, *IEEE Trans. Geoscience and Remote Sensing*, Vol. 39, No. 5, pp. 1013-1018, May 2001.