



Wave–material interaction in radio science through the history of URSI

Ari Sihvola⁽¹⁾

(1) Aalto University, School of Electrical Engineering, Box 15500, 00076 Aalto, FINLAND

Abstract

Radio science is the study of radio waves. The behavior of radio waves, as electromagnetic waves, is governed by Maxwell equations. In the real world, waves interact with material bodies and structures, and therefore the study of wave–material interaction connects to the fundamental interests of URSI. This presentation discusses the research on the interaction of radio waves with materials from the 19th century throughout the century-old history of URSI. The emphasis is on the electromagnetic characterization of complex media and metamaterials. Particular attention is given to the process in which the homogenization of a microscopic sample of medium leads to a macroscopic description which requires new and qualitatively different properties from those appearing in the microscopic scale.

1 Introduction

Maxwell's laws of electromagnetics appear in a fascinating simple quadruple of equations, in particular in free space where they (aside from sources) only contain two field quantities (the electric field \mathbf{E} and the magnetic displacement \mathbf{B}). When the fields have connection to polarizable matter, induced currents are generated, but the formal appearance of Maxwell equations can be preserved by introducing two response fields, the electric displacement vector \mathbf{D} and the magnetic field vector \mathbf{H} . Depending of the character of matter, these response vectors are particular functions of the primary electric and magnetic fields.

Electromagnetic and optical characterization of matter has a long history that goes back to pre-URSI times into the 19th century with works by people like O. Mossotti, R. Clausius, L.V. Lorenz, and H.A. Lorentz, leading to important results on the connection of a collection of particles and their effective structural parameters. And it is worth to pay attention to the fact that also media which affect wave propagation in a peculiar way has a long history with the studies on electromagnetics of chiral (handed) materials by Jagadish Chandra Bose in 1890's and Karl Ferdinand Lindman in 1910's [1]. Since radio waves are in the core of URSI interests, also this interaction with matter has a central role in the business of URSI. It is safe to say that during the 100 years of the existence of our Union, wave interaction with materials has received an ever increasing role in the scientific activities on radio science, visible both in the General As-

semblies and in particular the Commission B conferences (which by the present time go under the name *Symposia on Electromagnetic Theory*) [2].

This is partly due to the strongly growing interest during the past decades towards complex man-made materials, functional and tailored structures, and metamaterials in general. This trend is not only happening within radio science and electromagnetics but also in optics, acoustics, and thermal and elastomechanical materials sciences. And like in other fields, also in radio science, a large number of conference series and scientific journal have emerged during this century that focus on metamaterials and complex media, some of them having already a respectable history [3].

In terms of the present Commission structure of URSI, the studies of wave interaction with materials falls to a great extent in Commission B (Field and Waves), although these issues are also encountered and studied in Commissions F, G, and H which deal with waves in earthly and geophysical environments. From the historical perspective, the interaction of waves with complex matter has been of interest, in particular in connection with the waves in magnetized plasma in the Earth's ionosphere. This was highlighted already at the time of the 60th birthday celebrations of our International Union of Radio Science, by the Honorary President of URSI, Professor Walter Dieminger, in the Anniversary Colloquium in 1979 [4].

2 The variety of electromagnetic response in complex matter

In simple non-magnetic materials, the constitutive relations between the electrical and magnetic fields and displacements is written

$$\mathbf{D} = \epsilon\mathbf{E}, \quad \mathbf{B} = \mu_0\mathbf{H} \quad (1)$$

through the material permittivity ϵ and the free-space permeability μ_0 .

Such description with a simple permittivity ϵ of the medium, although quite a useful simplification in many cases, however applies only in limited circumstances. Natural and artificial materials cannot be described by a "dielectric constant". The relation between the responses and

the exciting fields is rather a functional

$$\begin{pmatrix} \mathbf{D} \\ \mathbf{B} \end{pmatrix} = \mathcal{F} \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} \quad (2)$$

Here the operator \mathcal{F} is assumed very general, in other words the constitutive relations may take different functional forms, describing various physical mechanisms. Such effects appear in

- lossy media, leading to complex values of the material parameters
- magnetic media, for which the permeability μ is no longer that of free space μ_0
- anisotropic media for which the response vector does not, in general, align with the excitation vector, leading often to birefringence (double refraction)
- non-reciprocal media, caused by, for instance, external constant magnetic field, sometimes called gyrotropic media
- chiral (parity-breaking) media for which there is (reciprocal) magnetoelectric coupling, leading to optical activity
- generally bianisotropic media, combining magnetoelectric coupling and anisotropy [5]
- dispersive media, for which the response parameter depends on frequency (temporal dispersion, corresponding to a medium having memory) and/or depends on wavevector (spatial dispersion, for which the medium response is not spatially local)
- media with varying dimensionality: tridimensionally voluminal, planar two-dimensional structures (metasurfaces, metaboundaries), one-dimensional metalines, or even media characterized by a fractal dimension
- photonic crystals (electromagnetic band gap structures) are often treated as complex media for their strong spatial dispersion, in other words the wave experiences different refractive index depending on the propagation angle
- non-linear media for which the response of the medium to a sum of two excitations is not necessarily the same as the sum of the responses of the excitations separately
- media whose internal composition allows cross-coupling between different physical processes besides electromagnetic ones (having thermoelectric or piezoelectric couplings, for example); for such media the description in Equation (2) needs to have a third row, like in *tri-isotropic media* [6]

3 Levels of material description in electromagnetics

If a medium with a given permittivity were absolutely homogeneous down to the most microscopic level, its macroscopic response would show the same dielectric behavior as

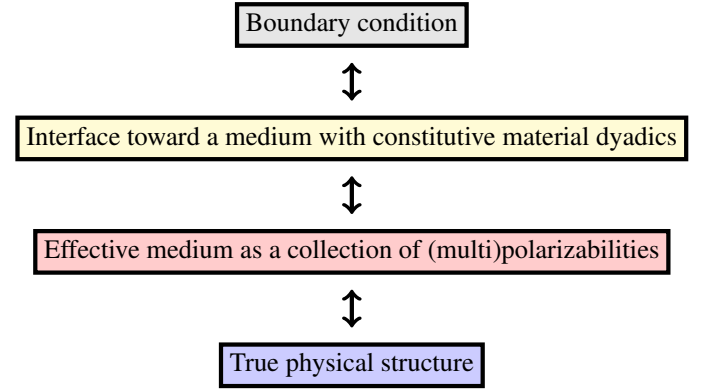


Figure 1. Electromagnetic description of heterogeneous matter with different scales of materialization. (Modified from [8], with permission.)

this only building-block material. However, media which may appear uniform and homogeneous when looked at a coarse scale, always consist of small-detail structure which becomes visible when it is observed with higher resolution. This structure, when homogenized, may lead to the need of new type of response parameters on a larger scale. For example, a laminar microstructure consisting of dielectrically isotropic layers leads to anisotropic macroscopic permittivity (the permittivity depends on the direction of the excitation field, and is no longer a scalar but needs to be expressed as a dyadic). Therefore one can say that on the higher level, new properties appear. Anisotropy is one example of such *emergent* phenomenon. Chirality is another. Structural colors of butterfly wings are still another beautiful manifestation of such emergence, and in the design of metamaterials, many further examples have been generated [7].

The process of homogenizing a microstructure and moving between the levels in the characterization of materials can be understood as illustrated in Figure 1. The true inhomogeneities (polarizable particles) of a material medium in the bottom layer are modeled by electric and magnetic dipoles and multipoles that interact with their neighbors. A lot of details are lost, and the effects of the primary particles are simplified into multipoles. At the next level, the homogenization is performed by taking into account the interaction between adjacent multipoles by proper mixing principles, leading to effective constitutive parameters (scalars, dyadics, tensors; which can be anisotropic, magnetoelectric, dispersive, depending on the degree of complexity of the microstructure).

The uppermost level in Figure 1 is needed in case of metasurfaces and boundaries. Boundary conditions [9] are idealized concepts with which electromagnetic problems involving material structures can be mathematically efficiently modeled when the interfaces have strong material contrasts, like in connection of PEC and PMC (perfect electric/magnetic conductor) bodies. The materialization of

such boundaries requires analysis of the response of potential materials to physically realize such effective boundaries. This process is contained in the arrows between the two uppermost blocks in the figure.

4 Conclusion

All samples of materials, both natural and man-made, display fascinating inhomogeneities when observed into their microscopic landscape. The structure, be it regular, amorphous, or random, can have an enormous amount of geometrical degrees of freedom. Electromagnetic fields penetrate into every microscopic structural detail within the medium. The effective behavior after homogenization, in the macroscale, may be radically different from the dielectric response of the separate component materials that form the mixture, and this can lead to any of the complex responses enumerated above in Section 2.

The process described in Figure 1 considers only a single step in going upwards (or downwards) in the scales of matter. It is important to bear in mind that there is a long "way" from our everyday life scale (of meters) down to the atomic levels (of ångströms). This fact has been concisely distilled by R.P. Feynman into his famous slogan from 1959: "There's plenty of room at the bottom" [10].

Hence this homogenization process, from lower level to upper, may need to be performed repetitively: the output of a lower-level homogenization serves as input material parameters to the new homogenization at a scale with larger spatial characteristics. These properties are already emergent, and again they will be transferred to the next "generation". Generation as a metaphor is in my opinion very suitable in this connection due to the fact that like children, the homogenized-level quantities inherit the "genes" from their more fundamental level but the inheritance does not lead to averaging; like children, they are something qualitatively different from their parents [11].

References

- [1] I. V. Lindell, A. H. Sihvola, S. A. Tretyakov, A. J. Viitanen, *Electromagnetic waves in chiral and bi-isotropic media*, 332 pp., Boston and London: Artech House, 1994.
- [2] T. B. A. Senior, "The Commission B Electromagnetic Theory Symposia," *IEEE Antennas and Propagation Magazine*, **35**, 6, pp. 26–28, December 1993.
- [3] A. Sihvola, I. Semchenko, S. Khakhomov, "View on the history of electromagnetics of metamaterials: Evolution of the congress series of complex media," *Photonics and Nanostructures — Fundamentals and Applications*, **12**, 4, pp. 279–283, 2014, doi: 10.1016/j.photonics.2014.03.004.
- [4] W. Dieminger, "60 years of research on the propagation of radio waves in the ionosphere," in *URSI 1919–1979 — Proceedings of the 60th Anniversary Colloquium* (C. M. Minnis, editor), pp. 19–29, Union Radio-Scientifique Internationale, Brussels, 1979.
- [5] J. A. Kong, "Wave propagation in moving anisotropic media" (Thesis for the degree of Doctor of Philosophy), Electrical Engineering, Syracuse University, 1968.
- [6] A. Sihvola, "Polarizability of a tri-isotropic sphere," *Physical Review E*, **64**, 046609 1–4, 2001.
- [7] A. Sihvola, "Electromagnetic emergence in metamaterials," in *Advances in Electromagnetics of Complex Media and Metamaterials* (S. Zouhdi, A. Sihvola, M. Arsalane, editors), NATO Science Series: II: Mathematics, Physics, and Chemistry, **89**, pp. 1-17, Kluwer Academic Publishers, Dordrecht, 2003.
- [8] B. Kong, P. Ylä-Oijala, A. Sihvola, "Electromagnetic scattering analysis of SHDB objects using surface integral equation method," *Photonics*, **7**(4), 134, December 2020, doi: 10.3390/photonics7040134.
- [9] I. V. Lindell, A. Sihvola, *Boundary Conditions in Electromagnetics*, IEEE Press, Wiley, Hoboken, NJ, USA, 258 pages, 2020.
- [10] R. P. Feynman, "There's plenty of room at the bottom – An invitation to enter a new field of physics" *Engineering and Science magazine*, **XXIII**, 5, February 1960.
- [11] A. Sihvola, "Metamaterials: a personal view," *Radioengineering*, (invited paper), **18**, 2, Part I: Special Issue on Artificial EM Materials and Metamaterials, pp. 90-94, June 2009.