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# Electromagnetic Characterization of Metamaterials: Activities of the ECONAM Project

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**Abstract.** In this overview we discuss the challenges of effective media modeling of complex artificial electromagnetic materials (metamaterials) and present the main activities of the FP7 Coordination Support Action ECONAM, devoted to development, testing, and dissemination of methods and tools for electromagnetic characterisation and metrology of nanostructured composite materials.

**Keywords:** Metamaterial, permittivity, permeability, reflection, transmission, spatial dispersion.
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## INTRODUCTION

Conventionally, the electromagnetic properties of materials are described by their permittivity and permeability tensors. There are no means for the direct measurement of electromagnetic parameters, which are for this reason dependent on the model used for their extraction. Approaches to measurements of even these fundamental electromagnetic characteristics of materials vary dramatically for electromagnetic waves of different frequencies, e.g. radio waves and light, and require specialised measurement techniques. These difficulties are dramatically escalated in electromagnetic characterisation and metrology of nanostructured materials with complex geometries of unit cells and exotic electromagnetic response.

For example, a device can operate at the wavelength of 500-600 nm, the structural periodicity is 50-100 nm, and the particle sizes are of the order of 30-70 nm. Such structures can still be described in terms of effective parameters (permittivity and permeability) of an equivalent homogeneous medium. However, the conventional models based on quasi-static homogenisation procedures normally applied at the atomic level are not applicable here, and the resulting effective phenomenological parameters (like permittivity and permeability) often have quite different physical meaning as compared with conventional materials.

The ECONAM project (http://econam.metamorphose-vi.org/) is a Coordinating and Support Action funded by the European Commission within the FP7 Programme. The main project objective is to consolidate efforts and bring coordination in the European work towards development, testing, and dissemination of methods and tools for electromagnetic characterisation and metrology of nano-structured composite materials. The main novel characterisation approaches are focused on intrinsically interrelated developments and harmonisation of the material phenomenological models, standardisation of characteristic parameters and measurement techniques for evaluating the specified parameters. The coordinator of the Project is Prof. A. Sihvola, and its scientific coordinator is Prof. C. Simovski. The project started in May 2008, and its duration is 3 years. In this overview we will discuss the challenges of electromagnetic characterization of metamaterials and present the main activities of this project.

## EXPERT CONSULTATIVE GROUPS AND THEIR ACTIVITIES

The main activities of the ECONAM project are carried out by two expert consultative groups specializing on the following aspects of the problem: Characterization Theory and Modeling (chaired by F. Bilotti), and Measurement Techniques and Standards (chaired by A. Schuchinsky).

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## Characterization Theory and Modeling

The challenging objectives of this group are consultation and support of the research community and third parties on the theory and modelling of electromagnetic characterization of nanostructured materials.

During the first year of the project this group of experts produced several overview and recommendation documents available at the ECONAM web site (http://econam.metamorphose-vi.org/activities/expert-group-on-the-theory-and-modelling). The group started its activities by identifying the physical requirements for physically well defined effective material parameters. The following requirements have been identified. Physically sound (local) material parameters

* are independent of the spatial distribution of fields excited in the material sample,
* are independent of the geometrical size and shape of the sample,
* satisfy the causality requirement (Kramers-Kronig relations),
* satisfy the passivity requirement (II law of thermodynamics).

The first two requirements are difficult to satisfy for many nanostructures, mainly because the samples usually contain only a few (or even one) layers of inclusions or patterned surfaces across their thickness. This introduces limitations on the applicability area of the effective parameters and demands the use of alternative descriptions in terms of surface impedance or grid impedance. The last two basic physical requirements must be satisfied to ensure that the use of the effective medium description does not lead to nonphysical results.

Following literature analysis, the group has found that there is no unique and mandatory receipt how to define electromagnetic parameters of lattices beyond the purely static limit and reviewed the exiting approaches to defining such parameters and extracting them from measured or simulated response of metamaterial samples (usually thin slabs under plane-wave excitation).

The most common procedure is based on extraction of the effective parameters (permittivity and permeability) from reflection and transmission coefficients of a slab at the normal incidence. The Nicolson-Ross procedure [1] or its later modifications is commonly used. In the overview produced by the ECONAM group it is explained that this procedure gives so called Bloch material parameters, that is, the effective parameters which describe the fundamental Bloch wave in the corresponding infinite lattice. Unfortunately, for the most interesting metamaterial regime, where electric and magnetic resonances overlap, the permittivity and permeability extracted from S-parameters of a slab do not have the usual physical meaning of measures of polarization in the medium and show nonphysical behavior. In this case, description of a lattice in terms of its Bloch impedance and propagation constant of the fundamental Bloch mode appears to be preferable. Conditions under which the Nicolson-Ross retrieval gives physical results have been formulated.

Thus, it is clear that in the design and studies of metamaterials as artificial electromagnetic materials with unusual properties we very often deal with the situation when the effective parameters retrieved from the reflection/transmission measurements are not the usual (local) parameters, and they do not adequately describe the electric and magnetic polarization responses (e.g., [2]). Even in structures where near-field interactions between inclusions are negligible, the retrieved parameters are non-local beyond the quasi-static limit (the difference becomes significant for frequencies approaching the resonance band of the inclusions) [3]. The main reason of the difference between the retrieved and local electromagnetic is the nonzero phase shift of the wave per unit cell of the artificial material lattice. This leads to a not negligible Drude transition effect at the sample interfaces [4].

There exist other procedures for introducing and extracting effective parameters, but at this stage they are not enough well developed. For this reason, this expert group calls for a discussion of these issues. It is obvious that further efforts are needed to develop a set of characterization techniques for description of electromagnetic response of emerging complex composite materials with unusual electromagnetic properties.

## Measurement Techniques and Standards

This expert group has the aim to consult and support of the research community and third parties on the measurement techniques and standards in measurements. The members have made an overview of the state-of-the-art and the most promising measurement techniques for metamaterial characterization. Below we present a short summary of the report produced of this expert group (available at http://econam.metamorphose-vi.org/activities/expert-group-on-measurement-techniques). Most measurements of metamaterials consist of transmission and reflection, often followed by a transformation to retrieve the real and imaginary parts of permittivity and permeability (see the previous Section). Because the phase information can be more difficult to obtain than in S-parameter measurements in the microwave region, alternative schemes have been developed. Similarly, a wedge-shaped metamaterial in the microwave region can straightforwardly demonstrate negative refraction – which becomes more difficult in the near infrared and visible, with the need to obtain large area samples with several layers. For some experiments, simulations of the structures are essential for the ultimate goal of the retrieval of material parameters. The normalised S parameters retrieved from the simulations are used to extract epsilon and mu via the Fresnel equations (the Nicolson-Ross method, see the discussion above), often with simplifying assumptions. Techniques for retrieving the phase include the use of phase masks, angular resolved measurements, ellipsometry, where the ratio of TM-to-TE polarized light is plotted as a function of frequency for oblique incidence - and femto-second laser interferometry, where the group and phase velocities are obtained from interferograms.

The situation becomes quite a bit more complex if oblique incidence of light onto the metamaterial slab is considered. For usual optical materials, generally all optical quantities become tensors of rank three. Only very few experiments on metamaterials at optical frequencies have addressed oblique incidence of light [5,6]. These papers have just reported intensity transmittance and/or reflectance spectra for various angles with respect to the surface normal as well as for various different azimuth angles, but they have completely refrained from translating these measurements into effective "material" parameters. Theoretical publications addressing possible retrieval procedures are, however, available in the literature (e.g. [7,8]), but these studies are incomplete and not confirmed experimentally. On the other hand, only oblique incidence probing allows one to determine full set of components of material parameter tensors for anisotropic structures.

In addition to plane-wave characterization of nanostructures, there exists a number of other methods including near-field optical measurements, the optical Fourier spectroscopy, and the measurement of the optical transfer function form.

## Special Session at Metamaterials'2009

The ECONAM project participants have organized a special session at the 3rd International Congress on Advanced Electromagnetic Materials in Microwaves and Optics, London, UK, Aug 30th-Sept 4th, 2009. The following papers have been presented:

* Applicability of classical mixing rules: from positive to negative parameters (H. Wallén, H. Kettunen, and A. Sihvola)

* Weakly and strongly coupled optical metamaterials (C. Soukoulis, J. Zhou, M. Kafesaki, Th. Koschny)

* Characterization of plasmonic metamaterials using effective parameters (C. Fietz, D. Korobkin, B. Neuner, C. Wu, G. Shvets)

* On the locality of Drude transition layers for metamaterials (C. Simovski)

* On non-Maxwellian boundary conditions for metamaterial interface (A. Vinogradov, A. Merzlikin, S. Zouhdi).

Proceedings of the Congress are available from the Congress web site http://congress2009.metamorphose-vi.org/.

## CONCLUSIONS

At this stage, there are many different opinions on a number of issues related to electromagnetic characterization of complex composite media, and the participants of the ECONAM project believe that it is important that the research community works out a coherent view by wide discussions in the literature and on scientific meetings.

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