# Session 0A1a
# New Results and Prospective Co-operative Research Directions on Metamaterials: the Metamorphose Network

# Modeling Isotropic DNG Media for Microwave Applications

**I. Vendik**, **O. Vendik**, **M. S. Gashinova**, **I. Kolmakov**, **and M. Odit**
St. Petersburg Electrotechnical University, Russia

**L. Jylhä**, **S. Maslovski**, **and S. Tretyakov**
Helsinki University of Technology, Finland

**O. Ouchetto and S. Zouhdi**
Laboratoire de Génie Electrique de Paris LGEP-Supélec, France

In this review presentation we will discuss various possibilities to realize isotropic artificial backward-wave materials. Different structures and models are suggested and discussed.

1) A composite medium consisting of two sublattices of dielectric spherical particles of high permittivity and different radii embedded in a dielectric matrix of smaller permittivity are considered. It has been shown [1] that such a composite medium reveals properties of an isotropic double negative media (DNG) in the frequency range where resonance oscillations of $H_{111}$ mode in smaller spheres and $E_{111}$ mode in larger spheres are excited simultaneously. The $E_{111}$ resonance and the $H_{111}$ resonance give rise to the magnetic dipole momentum and the electric dipole momentum, correspondingly. Averaging the magnetic momentum and the electric momentum over the cells belonging to the appropriate spherical particles reveals the negative permeability and the permittivity.

2) An improved mixing rule [2] for the effective permittivity and permeability of a composite material consisting of two sets of resonant dielectric spheres in a homogeneous background is presented. The equations are validated using the Mie theory and numerical simulations. The effect of a statistical distribution of sphere sizes on the increasing of losses in the operating frequency band is discussed and some examples are shown.

3) A new technique [3] is presented for the accurate computation of the effective constitutive parameters of lattices containing particles with complicated shape. This technique is based on the periodic unfolding method. The method is based on the decomposition of the fields in a main part without micro-oscillations, and a remainder part taking them into account. The idea of this decomposition is inspired by the method of Finite Element approximations. Verification data is presented for lattices of dielectric cubes obtained with the Maxwell-Garnett method. Corrector results are also studied as a function of frequency.

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# Optical Properties of Nanostructured Metamaterials

**I. Romero**[1], **S. Riikonen**[1], **and F. J. G. de Abajo**[1,2]

[1]Donostia International Physics Center, Spain
[2]Centro Mixto CSIC-UPV/EHU, Spain

The optical properties of different metamaterials composed of metallic nanoparticles are investigated from a theoretical point of view. We consider materials composed of layers of periodically disposed particles and analyze the anisotropic dielectric function of these systems as a function of frequency and layer spacing. The dielectric function is obtained by solving Maxwell's equations using a layer-KKR method and by comparing the reflectance of planar surfaces of such materials with Frenel's equations for different angles of incidence and polarizations of the incoming light. We will also discuss the role that the shape of the particles have in the dielectric function, comparing materialas composed of spherical and ellipsoidal particles.

# Losses in the PEMC Boundary

**I. V. Lindell and A. H. Sihvola**
Helsinki University of Technology, Finland

PEMC (Perfect Electromagnetic Conductor) was recently introduced as an ideal boundary material [1]. It is characterized by one real parameter, the PEMC admittance $M$, whose special values $M = 0$ and $1/M = 0$ correspond to the respective PMC and PEC cases. Realization of a PEMC boundary in terms of a lossless gyrotropic slab has also been recently suggested [2]. For real $M$, PEMC boundary is lossless while the realization would always have some loss.

In the present study extension of ideal PEMC boundary to one with small losses is given. It is shown that it is not enough to give the admittance parameter $M$ a complex value $M_r + jM_i$ but an additional conductance parameter $G$ must be introduced as well so that a lossy version of PEMC must involve three real parameters satisfying the inequality $G > |M_i|$.

As a simple example, reflection of a linearly polarized plane wave from a slightly lossy PEMC surface is studied showing how the pure polarization rotation caused by the ideal PEMC is added by a (small) decrease of the amplitude and a (small) change to elliptic polarization. Also, an analysis of a Fabry-Perot type of resonator made of two PEMC planes with losses is described.

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# Microwave Applications of Left/Right-handed Transmission Lines

**I. Vendik**[1], **O. Vendik**[1], **D. Kholodnyak**[1], **S. Zubko**[1], **I. Kolmakov**[1]
**I. Kolmakova**[1], **E. Serebryakova**[1], **I. Nefedov**[2], **S. Tretyakov**[2]
**F. Martín**[3], **J. Bonache**[3], **J. García-García**[3], **and I. Gil**[3]

[1]St.-Petersburg Electrotechnical University, Russia
[2]Helsinki University of Technology, Finland
[3]Universitat Autònoma de Barcelona, Spain

Numerous investigations have been undertaken in the area of metamaterials exhibiting negative refractive index. Such artificial materials are also known as Veselago media or left-handed materials. Recently a transmission line (TL) approach to realization of metamaterials was introduced [1–3]. Concept of right-handed (RH) and its dual left-handed (LH) transmission lines was used for a description of artificial transmission lines. In this review paper we will present some recent developments in this field.

A possibility to design a phase shifter with reduced frequency dispersion using combined sections of LH TL and RH TL was analyzed [4]. It was shown that there is no improvement in the phase shifter bandwidth due to combining positive and negative transmission line sections, except replacing devices with large positive phase shifts by devices with an equivalent small negative phase shift. Reduction of frequency dispersion can be attained using artificial transmission-line sections with positive anomalous dispersion.

An attractive feature of LH and RH lines is that the dispersion characteristics of both lines have a negative-going slope and the frequency dependencies of the slope for these lines are in a close agreement over a wide frequency range. That makes possible a design of a wide-band digital phase shifter based on switchable LH and RH TL channels. A theoretical approach was suggested and applied to i) digital phase shifters based on switchable LH and RH TL channels using p-i-n diodes and ii) digital phase shifters based on tuneable composite RLH-TL using ferroelectric varactors [5]. Results of simulation and experimental investigations of one-bit and multi-bit phase shifters are presented.

Another interesting application of CRLH-TL concerns microwave filters. Specifically, by alternating LH and RH TL sections implemented by means of split rings resonators (SRR) or complementary split rings resonators (CSRR), it is possible to synthesise narrow band pass filters [6] and diplexers [7] with high frequency selectivity and small dimensions. This is achieved thanks to the resonant nature of the artificial TL sections employed, to the small electrical size of the resonators, and to the presence of transmission zeros, which can be tailored to achieve the required characteristics.

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# Mode Coupling at the Periodic Boundary of Metamaterial

**G. Granet**[1], **A. Poyedinchuk**[2], **and N. Yashina**[2]

[1]Universite Blaise Pascal, France
[2]IRE NAS of Ukraine, Ukraine

Mathematical modeling of electromagnetic waves interaction with periodic boundary of metamaterial is based, as a rule, on the traditional approach, that is the solution to boundary value problems of diffraction theory. The solution to relevant spectral problems for eigen oscillations (eigen frequency is a spectral parameter) or/and eigen waves (propagating constant is a spectral parameter) presents the essential complementation to this approach. The successful association of these two ways of consideration of boundary value problem provides the possibility to treat the physical regularities and peculiarities of the resonant wave scattering by metamaterial on qualitatively new level and to get deeper understanding of complicated phenomena.

In this presentation the spectral problems for eigen waves and mode (natural oscillations) of the wavy periodic boundaries of the media with negative permittivity or/and permeability are considered. The C-method serves as efficient tool for the solution of boundary value and spectral problems of electromagnetic wave diffraction by periodic boundary of metamaterials.

The numerical algorithms and corresponding codes have been constructed and implemented for computation of complex frequencies of eigen modes (oscillations) and propagation constants of surface waves.

The study of regularities and peculiarities in the spectral characteristics (eigen complex frequencies, propagation constants of eigen modes and waves, corresponding electromagnetic field patterns, etc.) behavior with geometrical and electromagnetic parameters of periodic boundary varying have been carried out within rather wide range of parameters.

Special attention has been focused on the study of the phenomenon of eigen modes (oscillations) and eigen waves coupling.

On the base of the theory of critical points (Morse's critical points) of analytical functions of several variables the mathematical model of the inter mode coupling phenomenon, arising on the wavy periodic boundary of material with single or/and double negative parameters has been developed.