PROJECT III.5: PHOTONIC CRYSTALS AND METAMORPHIC MATERIALS

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Objectives

To design, optimize and fabricate photonic crystals and frequency-agile metamaterials (metamorphic materials) to be used as electromagnetically active filters and substrates/superstrates for novel embedded antenna architectures and other systems (filters, waveguides and resonators) operating in the microwave/mm-wave region, for applications in novel RF transceivers.

MAIN RESULTS IN 2009

Theory and Design of Metamorphic Materials

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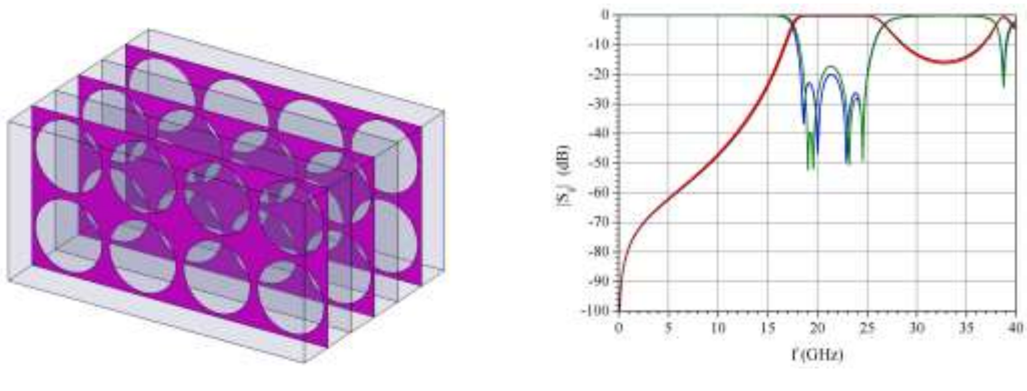
Composite electromagnetic media have long been the subject of interest for a variety of theoretical and practical reasons and in a variety of physical realizations as amorphous mixtures, ordered media, frequency-selective surfaces, photonic crystals etc. A wide range of interesting physical phenomena is revealed in several of these realizations, most importantly frequency-modulated reflection and transmission.

In this work we present the newly defined metamorphic materials which are artificial metallo-dielectric structures composed of passive elements and switches, that exhibit bulk electromagnetic transitions among a set of dinstinct electromagnetic states, each characterized by a specific range of values of the reflected electromagnetic field. According to the interconnect topologies of the metallic inclusions, a metamorphic material behaves, at a single frequency, as an electric conductor, a passive or active magnetic conductor, an absorber or an amplifier. Further, we have developed a completely analytical theory of scattering for these materials as well as a method of extraction of their effective permittivity and permeability at all frequencies, based on a resonant inverse-scattering theory. Detailed evaluations are given of the complex dispersive wave impedance, refractive index, permittivity and permeability functions for each metamorphic state of a specific 3-state metamorphic material and specific design rules are also derived. It is found that, as a rule, the electric and magnetic wall states are related to resonant permittivity and permeability values, respectively. Finally, it is shown that negative resonant values of the imaginary part of the resulting effective permittivities or permeabilities are consistent with energy conservation for passive electromagnetic media, despite contrary claims that exist in previous literature.

Among the many structures we have analyzed, we present the characterization of the metamorphic material when the switch topology makes it a photonic crystal composed of stacked conducting screens containing arrays of holes, scaled at microwave/mm-wave frequencies, shown in Fig. 1a in 3 monolayers.



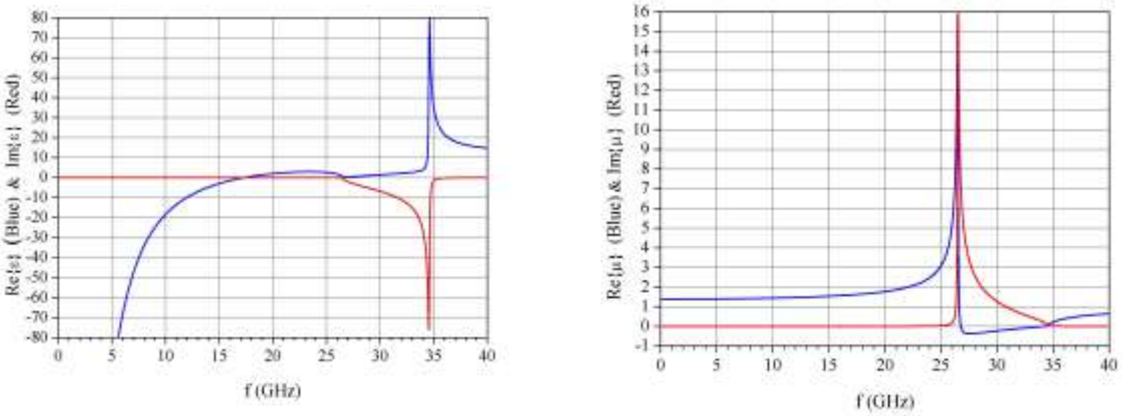
(a) (b)

Fig. 1 *a) Three stacked monolayers of metallic screens having a tetragonal lattice of large holes, immersed in a dielectric matrix. b) Reflection (Blue-Numerical/Green-Analytical) and Transmission (Red-Numerical /Brown-Analytical).*

In Fig. 1b we compare the corresponding S-matrices derived computationally through HFSS and analytically through our analytical approach. The agreement is excellent at quite high frequencies, past the plasma frequency (17 GHz) and including the multi-resonance regime.

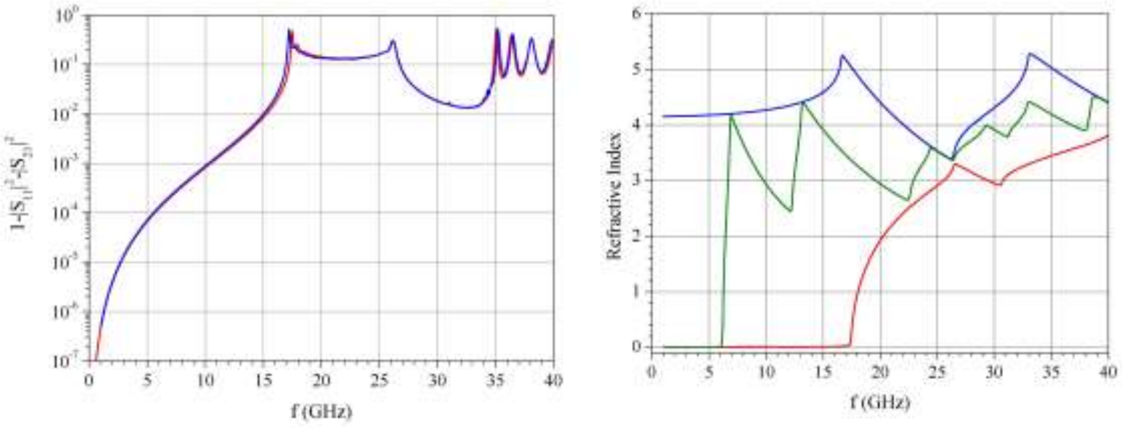
In Fig. 2a, b we present the extracted relative complex permittivity and permeability. The medium behaves as a metal up to 17 GHz, where it reaches the (artificial) plasma frequency. Thereafter it behaves as a dielectric, up to 25 GHz, and at even higher frequencies it develops very high resonant magnetization, including negative real part of the permeability, and negative imaginary part of the permittivity at select frequencies.

Contrary to the traditional view, this last property does not make the material active, provided the effective response functions are multiplexed in frequency in the way shown in Fig. 2. Indeed, we show in Fig. 3a the total power loss of a 10-monolayer metamaterial slab. The red curve is obtained analytically with input the effective functions of Fig.2, while the blue curve is a direct HFSS numerical simulation. The two results are in excellent agreement and show a positive-definite loss throughout the frequency range. Fig. 3b shows the material metamorphism of the (real part of the) refractive index as a function of frequency, for 3 switch states interconnecting the metal inclusions. This electronically adjustable dispersion reflects a corresponding reconfigurable functionality of metamorphic materials suitable for a variety of filtering applications.



(a) (b)

Fig. 2 *a) Extracted complex effective permittivity for the hole medium. b) Extracted complex effective permeability.*



(a) (b)

Fig. 3 *a) Power loss for a 10-monolayer hole medium slab. b) Dispersive refractive index for 3 metamorphic states.*

PROJECT OUTPUT IN 2009

Chapters in books

1. “Theory and Design of Metamorphic Materials”, C. Kyriazidou, H. Contopanagos and N. Alexopoulos, Chapter 20 in Metamaterials Handbook, Vol. I Theory and Phenomena of Metamaterials, Part III, pp. 20.1-20.18, Filippo Capolino (Editor) CRC Press, Taylor & Francis, Boca Raton, FL. (Oct. 2009), 1736 pages.

Patents

1. “Unconditionally stable filter”, U.S. Patent 7,555,278, H. Contopanagos, S. Kyriazidou, J. Rael and R. Rofougaran, 30 June 2009