Design of Artifical Metmaterials with Desired Multi-physical Properties Using Topology Optimization

Gullu Kiziltas
Sabanci University, Orhanli, Tuzla, 34956, Istanbul, Turkey

Over the last decade, numerous studies have shown that artificial composites and metamaterials display superior electromagnetic response that can be attained by combining different materials subject to desired metrics. However, the perfect material combination is unique and extremely difficult to determine without formal synthesis schemes. Existing "conventional" metamaterials are still based on analytical or experimental studies, i.e. a formal design approach to predict the exact spatial combination of material constituents from scratch does not exist. In this paper, we develop a versatile approach to design the microstructure of 3D materials with prescribed multi-physical electromagnetic material tensors. The proposed framework is based on a robust material model and a generalized inverse synthesis tool relying on topology optimization. The former is derived using homogenization theory and asymptotic expansion applied to Maxwell's equations. It is capable of characterizing the effects of anisotropy and loss within materials that are formed with periodic unit cells of arbitrary geometries and multi-phases much smaller than the wavelength. Towards that goal, earlier developed synthesis framework [Y. El-Kahlout and G. Kiziltas, PIER,115, 343-380, 2011] that is capable of realizing predefined material constitutive parameters (such as desired permittivity or permeability) via designing the microstructure of artificial electromagnetic substrates will be updated to target spectrally dispersive materials with multi-physical electromagnetic properties. The goal is to develop a formal design framework suitable for realizing the 'unconventional' microstructure of 3D metamaterials that are inherently spectrally dispersive and display the desired electromagnetic permittivity and permeability at the same time. The current design framework is suitable for designing the periodic microstructure of desired anisotropic artificial magneto-dielectrics from available isotropic material phases by integrating Finite Elements (FE) based analysis tool (using COMSOL MULTIPHYSICS-PDE Coefficient Module) with optimization tools. After homogenizing Maxwell's Equations (MEQ) in order to estimate the effective spectral multi-physical material parameters of the periodic composite, the material model is combined with earlier multi-physical models applied to mechanical multi-physical properties such as Poisson's ratio and Young's modulus. Then, the FE analysis tool is used to evaluate intermediate fields at the 'micro-scale' level of the periodic unit cell that is integrated with the homogenized MEQ's in order to calculate both 'macro-scale' effective constitutive parameters of the overall bulk periodic structure. Consequently, the proposed framework allows topology design capabilities of microstructures with desired frequency dependent multi-physical material properties in three dimensions. This inverse synthesis capability is demonstrated on left handed metamaterials with negative effective permittivity and permeability. Initial design results show that the creation of a new class of 3D artificial material to custom design is indeed possible pointing towards the possibility to synthesize alternative metamaterial microstructures with possibly additional physical properties such as metamaterials with desired thermal and mechanical behavior. If successful, when combined with advanced manufacturing schemes, these capabilities will allow the automatic generation of totally novel yet unthinkable material designs that will lead to a new paradigm in electromagnetic multi-disciplinary material design.