Design of 'lossy' metamaterials using inverse topology optimization

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Unusual properties of metamaterials offer enormous potential for advanced applications in the mm-wave, THz and optical frequency ranges. Anisotropic ferrites, chiral materials, photonic bandgap, left-handed and non-reciprocal media are well known paradigms. As the variety of examples in the literature shows, the perfect combination of materials is unique and extremely difficult to determine without a formal approach. Existing "conventional" metamaterials are 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. To address these issues, this paper aims to develop a formal design framework suitable for realizing the 'unconventional' microstructure of metamaterials that are inherently spectrally dispersive. 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 via designing the microstructure of artificial electromagnetic substrates will be updated to incorporate spectral dispersion. 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 an optimization technique (using MATLAB-Genetic Algorithm and Direct Search toolbox). Simulation of the periodic structure is an extremely challenging task because meshing at micro-level (much smaller than the periodic cell dimension) that spans over the entire bulk structure turning the computational problem into a very intensive one. Therefore, homogenizing Maxwell's Equations (MEQ) in order to estimate the effective spectral material parameters of the composite made of a periodic microstructure is the initial task of the framework. The FE analysis tool is used to evaluate intermediate fields (to be postprocessed as a part of the homogenization process) at the 'micro-scale' level of the periodic unit cell that is integrated with the homogenized MEQ's in order to calculate the 'macro-scale' effective constitutive parameters of the overall bulk periodic structure that is spectral in nature. Consequently, the proposed framework based on the solution of homogenized MEQ's via the micro-macro approach allows topology design capabilities of microstructures with desired frequency dependent material properties. This capability is demonstrated on a comparison with known spectral behavior of a metamaterial in literature. Then, the developed material model is employed to solve a two step inverse design problem. First, metamaterials with desired novel reflection response will be designed to determine their 'effective' spectral material properties via parametric multi-objective optimization scheme. Next step will be to synthesize the microstructure of the effective material property obtained earlier. Initial design results show that the creation of a new class of artificial material to custom design is indeed possible pointing towards the possibility to synthesize alternative metamaterial microstructures with low loss from 'scratch' overcoming the loss issue known of existing metamaterials. Realization of these non-intuitive metamaterial designs based on methods such as self-assembly, direct printing and novel sintering schemes will also be discussed. If successful, these capabilities will allow the automatic generation of totally novel yet unthinkable material designs that will lead to a new paradigm in electromagnetic material design.