Homogenization of Metamaterial-loaded dielectric Substrates for Antenna Applications

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We present a novel approach to the homogenization of metamaterial-loaded dielectric substrates for patch antennas using FDTD as an electromagnetic solver and the T-matrix method formalism to consider multiple interactions between resonant inclusions inside a composite dielectric substrate. Our motivation comes from the need to reduce the complexity in modeling antenna substrates with inclusions that can be used to improve antenna efficiency, increase its bandwidth, and increase its directivity.

The homogenization is often viewed as a process of calculating the dependence of the effective propagation constant inside the medium on the incident wavevector for a single incident wave direction in the low-frequency limit. The objective is to obtain the effective material properties and simplify the analysis reducing the problem to the homogeneous bulk medium. Thus, the effective refractive index is defined as: $n_{eff}(\vec{k}) = \lim_{k \to 0}\left(\frac{ck}{\omega}\right)$ [A.A. Krokhin, E. Reyes, *Phys. Rev. Letters*, Vol. 93, no.2, July 2004, 023904]. This approach was shown to work for 1D, 2D, and 3D photonic crystals (PCs). In this paper, we show that the approach which uses the low-frequency approximation may not be appropriate for metamaterial structures with the wavelength-to-size ratio of 1:4-1:5 and for finite metamaterial structures encountered in loaded dielectric substrates for antenna applications. In addition, a solution to a 1-D metamaterial homogenization problem based on a full-wave numerical method to solve the wave interaction problem and the phase gradient to calculate the local value of the phase velocity in the metamaterial inside the waveguide was proposed recently [B-I. Popa and S.A.Cummer, *Phys. Rev. B*, vol. 72, 165102, 2005]. The formalism used by the method is not applicable to more complex geometrical configurations of metamaterials that are often encountered in composite substrates.

A homogenization procedure that accounts for the effects of electromagnetic interactions on the direction of energy flow and local effective phase velocity and is easily adaptable to the changes in .the substrate geometry, is, therefore, necessary. For infinite structures, there exists a variety of periodic boundary conditions that reduce the interaction problem to the Floquet mode analysis. For an arbitrary finite problem, we are employing a decomposition approach based on FDTD analysis of a single MTM cell scattering and T-matrix analysis of interaction between metamaterial cells. Similar analysis has been used to analyze scattering by buried objects in a lossy dispersive medium [Sahin, A., Miller, E.L., *IEEE Trans. on Ant. and Prop.*, Vol. 46, Issue 5, May 1998, pp. 672-678]. Wu et al. proposed a homogenization approach using T-matrix and analytical Mie theory for 2-D homogenization problem [Feng Wu and Keith W. Whites, *IEEE Ant. and Prop. Soc. Int. Symp.*, 2000, Vol. 1, 16-21, July 2000, pp. 372–375]. However, our procedure is different from Wu's approach since we are dealing with an antenna substrate problem and are using FDTD as an electromagnetic solver to compute single MTM cell scattering matrix. Our results will include the k-β diagrams of analyzed discrete metamaterials in comparison to their bulk counterparts. Numerical results for frequency-dependent antenna input impedances computed with the discrete metamaterial model and their radiation patterns. will be compared to the ones computed using the traditional homogenization procedure and the bulk dispersive medium model.