Non-metallic metamaterials: modelling, design, and fabrication tolerances analysis

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Metamaterials are artificial materials, consisting of sub-wavelength building blocks, which can show anomalous and exotic electromagnetic responses. Metal-based metamaterials, as the first experimentally implemented metamaterials, have achieved significant progress in theory, fabrication, and characterization over a broad frequency range from microwave to visible. To alleviate the drawbacks of metal-based metamaterials, such as conductive loss and anisotropy, non-metallic metamaterials have been proposed and developed rapidly in the last decade. This thesis focuses on the analytical modeling and fabrication-tolerance analysis of non-metallic metamaterials consisting of an array of magnetodielectric spheres. Here, the term “magnetodielectric” refers, generally, to materials with relative permittivity and permeability both much greater than one, or to purely dielectric/magnetic materials.

The first half of this thesis presents the exact (within the dipole scattering approximation) dispersion equations of traveling waves supported by three-dimensional (3D) periodic arrays of two different magnetodielectric spheres arbitrarily arranged on a simple tetragonal lattice. To improve the calculation efficiency, fast converging expressions and their double summation form are derived for slowly converging summations in the dispersion equations. The presented theory has been tested by comparing its dispersion diagrams with corresponding ones in previous literature, and with those calculated by MIT Photonic-Bands (MPB). The dispersion diagrams of seven different arrangements of the spheres are analyzed for three combination of sphere types: 1) dielectric spheres with equal permittivity but different radius, 2) dielectric spheres with equal radius but different permittivity and 3) one set of spheres is purely dielectric while the other set is magnetic. Compared with results reported in previous literature, analysis of these possible arrangements of the spheres shows similar narrow DNG bandwidths for spheres combinations 1) and 2), and wider DNG bandwidths for spheres combination 3). Based on this theory, this thesis also develops a clear design procedure for double negative (DNG) metamaterials consisting of 3D periodic arrays of two different magnetodielectric spheres arranged on a simple tetragonal lattice. This procedure can give a design with widest possible DNG bandwidth and prescribed effective constitutive parameters at the operating frequency.

Effects of parameter variations on negative effective constitutive parameters of non-metallic metamaterials are analyzed in the second half of this thesis. These effects are evaluated in terms of the variability in effective constitutive parameters around the double negative (DNG) or single negative (SNG) region for given geometric and material parameters and their variations. Based on the Clausius-Mossotti expressions for the effective (bulk) constitutive parameters of non-metallic metamaterials, analytical expressions of variability of effective constitutive parameters depending on geometric and material parameters variations are developed using total differential. In practice, these expressions can be used to estimate the performance of a non-metallic metamaterial with given parameter variations that might exist due to fabrication tolerances. Based on these expressions, effects of parameter variations on effective constitutive parameters are analyzed for three types of metamaterials: a) 3D cubic array of identical magnetodielectric spheres; b) 3D cubic array of two different dielectric spheres with equal radius but different permittivity; c) 3D cubic array of two different dielectric spheres with equal permittivity but different radius. Results show that varying the following parameters impacts negative effective constitutive parameters in the following order from most to least: 1) radius of spheres; 2) constitutive parameters of spheres providing negative effective permittivity and/or permeability; 3) lattice constant of the array and the constitutive parameters of the array medium. For three particular case studies, results show that the DNG behavior may be extinguished if there are 0.78%, 0.0164%, and 0.0158% variations in all parameters of metamaterials a), b), and c), respectively. A complete set of analytical expressions for derivatives of Mie scattering coefficients are also obtained in order to calculate the total differential of variabilities of effective constitutive parameters of non-metallic metamaterials.