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Review of Artificial Dielectrics Containing Small Scale Inclusions

Invited Paper

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ABSTRACT: This paper reviews some of the latest advances in the field of artificial dielectrics. The dielectric properties (permittivity and losses) can be designed and synthesized by placing small scale inclusions in a host medium. This work will create many new opportunities for antenna designers and will also lead to applications in transformation optics. This paper highlights the progress made in understanding the analytical, practical and measurement aspects of this work.

INTRODUCTION

Heterogeneous mixtures can be produced by embedding inclusions of equal or varying sizes, whose bulk materials can have different physical and electromagnetic (EM) properties within a host media [1–12]. This work can be thought of as a subset of metamaterials where the global properties are dependent on both the periodic structure and the physical properties. However, the aim is not to create frequency selective surfaces [13], artificial magnetic conductors [14] or double negative materials [15] but to control the dielectric properties.

Lord Rayleigh considered artificial dielectrics in the late 19th century [1]. This was remarkable for occurring less than 30 years after James Clerk Maxwell developed his theories about electromagnetic waves. These inclusions are typically in the nano or micro-scale size or can be micro-sized clusters of nanoparticles. The inclusions can be dielectric [2], [11], [16] or metallic/conducting [6], [7], [10], [17], [18]. Different lattice arrangements of these particles within the homogenous media are also possible. The typical arrangement is the simple cubic (SC) lattice in which the inclusions are equi-distant from each other in all three dimensions (axes). Other cubic lattice arrangements include face-centred cubic (FCC), body-centred cubic (BCC).

The level of interest in this work has recently increased as simulation tools can now handle the large computational requirements in terms of memory and computation time. In parallel with this, our understanding of materials and material processing has allowed us to consider more complex manufacturing methods. In particular, the recent and imminent advances in nanotechnology will allow the fabrication of very complex structures that could not previously be imagined. As consumers and industry demand ever smaller gadgets with increasing levels of wireless communication – it is vital that EM engineers exploit the material properties to maximize the advantages. A new emerging application is transformation optics where the local permittivity is graded to benefit radome and lensing applications [19], [20].

ANALYTICAL THEORY

Lewin [2] developed analytic theory for the effective permittivity, ε_{eff}, of small scale inclusions in a host medium. The polarisability interaction of the inclusions was calculated from first principles using spheres periodically embedded in infinite half space. The ε_{eff} is related to the permittivity of the host, the permittivity of the inclusion and the volume ratio, p, – see [2]. The spheres must be small ($<1/10\ \lambda$) so as to not directly interact with the incident wave. If the inclusions are very small, then the permittivity of the inclusion is not equal to its bulk value and the mathematics governing the effective permittivity of the mixture become more complex. A parallel set of equations exist for the magnetic permeability.

Other authors have developed similar equations for heterogeneous mixtures [6], [10–12], [16] . These formulas were compared and analyzed in [21]. Although, the equations visually look different – they can be re-arranged to be numerically analogous and give similar values. Note, that certain equations do not include the host permittivity terms and hence are only valid for inclusions in air [21].

SIMULATIONS OF HETEROGENEOUS STRUCTURES

The canonical equations can be compared with EM simulations. The simulation process works by applying an EM plane wave to the heterogeneous medium and then extracting the scattering (S-) parameters (S11 and S21) [22]. An inversion algorithm is applied to these S-parameters values to obtain the effective permittivity, permeability and losses [17]. The simulated results, despite having finite thickness, showed good agreement with the analytical equations [22]. Metallic inclusion produce larger effective permittivities than dielectric inclusions. The simulation methodology allows non-spherical shapes to be considered. The effective permittivity is strongly related the volume density, therefore, higher values can be obtained with cubic inclusions where the host permittivity was increased by up to 20 times [23]. More complex shapes may lead to different effective parameters with smaller volume ratios.

FABRICATION AND MEASUREMENTS OF HETEROGENEOUS STRUCTURES

It is not straight forward to produce structures of interest as they require a reasonably high volume ratio of inclusions (>10-20%) to substantially increase the ε_{eff}. They also need to have a reasonable area of a few centimetres as well as a height of greater than 0.5mm to allow reliable RF measurements. Experiments and simulations have confirmed that the effective permittivity will change if the inclusions are not exactly aligned. And if the inclusions are added randomly to the host material, then the volume fraction must be below the percolation threshold. However, it is envisioned that small positional inaccuracies can be tolerated. The dielectric properties of the mixtures can be measured using waveguides [22] or resonators [23]. Great care must be taken with dielectric measurements as the small metallic inclusions can capacitively couple with resonators. Hinojosa et al. used a coplanar waveguide to measure thin dielectric properties over a broad frequency range [27].

Other papers in this area include [24–31]. Krupka et al. investigated silver-gelatine metal-dielectric composites [24]. A wide range of permittivity values were achieved ($4 < \varepsilon_{eff} < 170$) by varying the silver content. However, high loss tangent values ($0.06 < \tan\delta < 0.25$) were also present and the loss tangent was found to be proportional to the real part of the permittivity. Micro and nano-sized silicon oxide particles were placed inside a host medium in [28]. It was found that the permittivity could be altered by changing the volume ratio. The maximum value of the loss tangent occurred at different frequencies with different volume ratios which suggests that the materials could be designed to have reduced losses for certain applications. Cobalt nanoparticles were placed inside a silicon oxide film; the effective RF conductivity increased with the volume content and was substantially different from the DC conductivity [30].

SUBSTRATES FOR MICROSTRIP PATCH ANTENNAS

Another potential application of artificial dielectrics is the design of bespoke substrates for antennas. If antenna engineers could choose their own permittivity values, then it would allow an extra degree of freedom in the antenna design process. It may also be possible to make the antennas and substrates in one integrated additive process which will be advantageous compared to slow and environmentally unfriendly etching processes to remove the unwanted copper. Furthermore, the electric fields are not uniformly distributed under the antenna and therefore it is advantageous to vary the local permittivity within the substrate and mapping the values to the electric fields – this can be potentially achieved by varying the volume density of small scale inclusions. Locating a high permittivity where the electric fields are small has been shown to increase the bandwidth [32–36]. Patch antenna substrates with small scale inclusions have been considered [22], [37]. The results demonstrated that reasonably efficiencies can be obtained that are equivalent to low loss substrates. If the inclusions were not cubes but flattened cuboids, then the analysis becomes more complicated as there is an element of anisotropy in the material.

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