Topology Optimization of Dielectric Substrates for Filters and Antennas Using SIMP

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Summary

In this paper a novel design procedure based on the integration of full wave Finite Element Analysis (FEA) and a topology design method employing Sequential Linear Programming (SLP) is introduced. The employed design method is the Solid Isotropic Material with Penalization (SIMP) technique formulated as a general non-linear optimization problem. SLP is used to solve the optimization problem with the sensitivity analysis based on the adjoint variable method for complex variables. A key aspect of the proposed design method is the integration of optimization tools with a fast simulator based on the finite element-boundary integral (FE-BI) method. The capability of the design method is demonstrated by two design examples. First, we developed a metamaterial substrate with arbitrary material composition and subject to a pre-specified antenna bandwidth enhancement. The design is verified and its performance is evaluated via measurements and simulation. As a second example, the material distribution for a Thermo-Photovoltaic (TPV) filter subject to pre-specified bandwidth and compactness criteria is designed. Results show that the proposed design method is capable of designing full three-dimensional volumetric material textures and printed conductor topologies for filters and patch antennas with enhanced performance.

1 INTRODUCTION

Evidence in literature demonstrates that use of artificial composite materials provides for a greater potential in designing new electromagnetic/RF devices [1–3]. However, existing studies dealing with design optimization for RF applications focused to a large extent on size or shape design only [4–7]. So far, material and topology optimization has not been pursued primarily due to the challenges associated with the fabrication of inhomogeneous materials and the limited access to versatile and efficient analysis tools. There are very few examples in the literature on topology optimization of electrical devices and these have dealt with problem specific, restricted or semi-analytic tools for magneto-static applications [8,9]. Here, our goal is to develop a general design method that draws from a broader class of design solutions as compared to conventional design methods and is capable of achieving topology and material designs for “new” electromagnetic devices with much higher performance.
In this paper, a topology optimization method based on the Solid Isotropic Material with Penalization Method (SIMP) is extended to develop full three-dimensional material topology designs for electromagnetic devices. The design problem is formulated in a non-linear optimization framework and is integrated with a fast full wave Finite Element-Boundary Integral (FE-BI) simulator. Solution of the optimization problem is obtained via the Sequential Linear Programming (SLP) with a sensitivity analysis based on the adjoint variable method for complex variables. This sensitivity analysis is specifically derived for the antenna’s input impedance and filter’s transmission coefficient and integrated into the simulator.

The capability of the proposed design method is demonstrated by two design examples. One example refers to the dielectric material topology of a patch antenna subject to pre-specified bandwidth and miniaturization criteria. The optimized design is post-processed via adaptive image filtering and is transformed into a two-material composite for manufacturability. The final substrate is manufactured using Thermoplastic Green Machining as a composite of Low Temperature Co-firing Ceramic (LTCC) filled with stycast polymer. In the second example, the dielectric substrate topology is designed for a spectral filter with bandpass behavior. Results from both miniaturized antenna and spectral filter case studies demonstrate the capability of the proposed method of designing full three-dimensional volumetric material textures for EM applications with enhanced performance.

2 BACKGROUND

This section provides an overview of the main milestones in electromagnetic (EM) design optimization. In the second part of the section, we present some background on topology optimization in structural mechanics and how it applies to EM. At the end of the section, we give some examples of topology optimization studies with the understanding that topology optimization refers only to the optimum material distribution approach.

2.1 Overview of Design Synthesis (Optimal Design) in EM History

The topic of optimal design in electromagnetics has a long history [10]. In other fields of engineering, the history of optimal design is even longer, dating back to Lagrange [11] and will be reviewed shortly in Section 2.2 in the context of structural topology optimization. Optimization theory in structural mechanics has had a history of 45 years. However, modern optimization theory as pertains to electromagnetics came much later. Among the pioneering works is that of Marrocco and Pironneau [12] who developed an optimum design of a magnet using lagrangian finite elements for modeling. Considering more general inverse problems in EM, it is appropriate to quote the fundamental contribution by Hadamard [13] who classified the optimization problem into two classes: well-posed and ill-posed classes.

As is well known, the solution of inverse problems is done iteratively. Historically, these iterations were carried out by cut and try operations taking months for each iteration or test. As a result, the design process relied on experience and intuition and was impractical. Today, modern optimization theory offers a great variety of automated techniques [14] for solving inverse problems in EM. These can be generally categorized in deterministic and stochastic techniques. Deterministic techniques (e.g. Simplex, Rosenbrock, gradient, quasi-Newton, Newton-Raphson, Sequential Quadratic Programming, Lagrangian Multipliers) seek the minimum point based on the information given by the negative of the gradient (sensitivity) of the objective function. Challenges in their implementation are the requirement to evaluate the gradient of the objective function and issues relating to the algorithm convergence. In contrast, gradient based techniques are mathematically well-behaved and do not involve heuristics. Hence, they are regarded as more attractive for most practical real world applications.