Design Optimization of Artificial Magneto-dielectrics for RF Applications

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Abstract

In this paper we will propose a design framework based on the integration of FE-BI based analysis tools with optimization techniques suitable for RF device design made of artificial magneto-dielectrics. For design optimization of artificial magneto-dielectrics via topology optimization, the Sequential Linear Programming and an exact sensitivity analysis based on the solution of the adjoint problem is proposed. The proposed framework can be adopted for artificial material microstructure design following a two step procedure: Parametric design optimization of effective material properties combined with inverse topology optimization. Results of the parametric optimization show that the proposed integration possibly solved with evolutionary optimization techniques is possible if appropriate speed-up techniques are adopted. An alternative for speeding up the proposed large scale design optimization problem based on approximate frequency based response functions is also presented.

1. Introduction

Engineered materials, such as new composites, electromagnetic bandgap and periodic structures [1] have attracted considerable interest in recent years due to their remarkable and unique electromagnetic behavior. As a result, an extensive literature on the theory and application of artificially modified materials exists. Already photonic crystals have been utilized in RF applications due to their extraordinary propagation characteristics [2], [3]. More recently, computations using double-negative materials [4], [5] and photonic crystals [6] illustrate that extraordinary gain can be achieved when small dipoles are placed inside other exotic materials that exhibit resonance at specific frequencies. Of importance is that recent investigations of material loading demonstrate that substantial improvements in antenna performance can be attained by loading bulk materials such as ferrites or by simply grading the material subject to specific design objectives [7]. Ceramics with multitone materials have also been used for miniaturization [8] and pliable polymers [9] possibly with ceramics or ferrite power loading offer new possibilities in three dimensional (3D)/volumetric antenna design and multilayer printed structures, including 3D electronics. However, despite their novel behavior, issues abound as relates to their practical realization and lack of formal design framework. As the variety of examples in the literature shows, perfect combination of materials is unique and extremely difficult to determine without optimization. To address this issue, in this paper we develop a design framework integrating FE-BI [10] based analysis tools with optimization techniques suitable for designing RF devices made of artificial magneto-dielectrics. Previous optimization studies on metamaterials indicate that properly designed dielectrics or a combination of different materials can lead to designs which have greater bandwidth and small size [10], [11]. Nevertheless, the focus has been on dielectric composites with two or more constituent ceramic mixtures. Here, our goal is to propose a framework suitable to optimize the metamaterial profile fully, possibly with dielectric shades combined with magnetic materials to improve antenna performance such as miniaturization, bandwidth and efficiency. The need for design, preferably design optimization is pertinent to the competing physics of these metrics. Instead of the more traditional approaches of optimizing the shape or geometry of the antenna via reactive loading, parasitic coupling and etching, here we integrate parametric design and inverse topology optimization methods, known as SIMP with robust FE-BI methods to design the magneto-dielectric substrate. When compared with more conventional optimization, where the topology of the device is assumed a priori and remains fixed, topology optimization offers much more degrees of freedom and allows the exploration of 3D artificial magneto-dielectric composites. Consequently, it is reasonable to expect that resulting designs have novel configurations with much higher performance. Critical to the design process is the integration of parameteric design with topology optimization based on sensitivity analysis developed for both the dielectric permittivity and magnetic permeability and the use of fast and general analysis tools. The proposed novel design approach effectively combines FEA with optimization techniques and allows for full flexibility in geometry and material specifications across three dimensions for possible antenna and filter applications. This by definition is a large-scale multi-physics inverse topology optimization problem. The proposed framework is flexible enough to be solved via evolutionary optimization techniques if appropriate speed-up techniques are adopted. An alternative solution for speeding up is discussed here. It is based on approximate frequency based response functions.

2. Design Optimization Framework

In any automated optimum design, the goal is to identify in some automatic process the device structure subject to some prescribed performance. The proposed design optimization framework is demonstrated in Fig. 1.

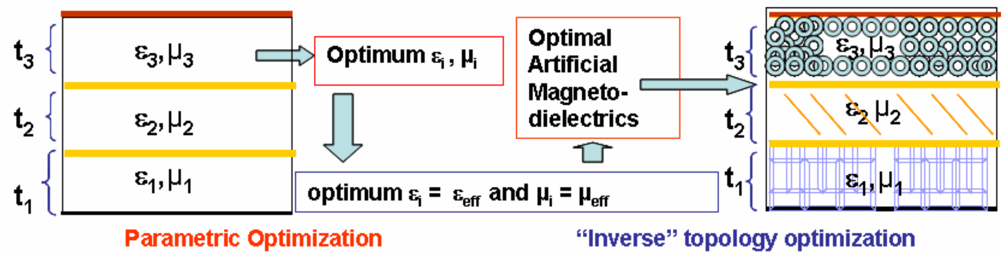

Figure 1: Proposed design optimization framework

Among existing design methods are size, shape and topology optimization. The proposed framework consists of parametric optimization followed by inverse topology optimization. Simply stated, design via topology optimization implies the determination of the best arrangement given a limited volume of available (electromagnetic) material within a spatial domain subject to delivering optimal (electromagnetic) performance of the concept design. The inverse process systematically and iteratively eliminates and re-distributes material throughout the domain to obtain a concept structure matching desired effective material properties, ε_{eff} and μ_{eff} obtained in the first step. The topology design method proposed here is based on the Density Method also known as the Solid Isotropic Material with Penalization (SIMP) method. The essence of SIMP is to assume some explicit relationship between the so-called normalized density ρ and the actual material property, here the dielectric permittivity $\varepsilon=\varepsilon_0\varepsilon_r$ and permeability $\mu=\mu_0\,\mu_r$. A suitable interpolation would be:

$$\rho = (\varepsilon_{\text{int}} - \varepsilon_{air})/(\varepsilon_{orig} - \varepsilon_{air})^{1/n} \qquad\qquad \rho = (\mu_{\text{int}} - \mu_{air})/(\mu_{orig} - \mu_{air})^{1/n} \tag{1}$$

where *int* and *orig* refer to the intermediate and available original (relative) dielectric permittivities of the solid, respectively. The power 1/n is an empirical penalization power smaller than 1/2 for convergence purposes. The goal is to arrive at the optimum distribution of material (densities) delivering the effective material properties obtained in the first step via parametric optimization subject to specific performance merits of a device. For this purpose, the design volume is divided into design cells/finite elements to introduce a full volumetric design space. The material property of each design cell is controlled simultaneously in each iteration step and updated by following a mathematical algorithm to reach a final design. From this viewpoint, a device is represented by material properties at every point in space via a single density variable. The design problem is easily recognized as a general non-linear optimization problem with usually several thousand variables/FEs, which makes the use of gradient-based optimization techniques a must for the solution of the optimization process. Sequential Linear Programming (SLP) method employing the DSPLP package in the SLATEC library [10] is chosen here. Updates of the design variables are pursued thru the adjoint variable method [10], which is a gradient determination method and permits full interface with the FE-BI electromagnetic solver. The proposed framework by definition is a large-scale multi-physics inverse topology optimization problem [12] followed after a parametric optimization cycle. A design example is presented in the next section

3. Magneto-Dielectric Design via Parametric Optimization

In this section we introduce a parametric design optimization study for magneto-dielectrics substrates. The goal is to determine optimal values of the permittivity and permeability of each magneto-dielectric layer supporting a probe fed patch antenna subject to high bandwidth and size constraints. These optimal values will serve as objective metrics to be attained subsequently via inverse homogenization as discussed above. The ultimate goal is to determine the microstructure of each layer subject to effective material properties. Chosen microstrip patch antenna consists of 3 magneto-dielectric layers. The allowable permittivity and permeability range is between 1 and 25. The objective function is chosen as $f(x) = \min[\max(|s_{11}|_i)]$ where $i = 1,...,N_{freq}$ and x is the design vector.

The antenna is analyzed via full wave FE-BI tools to compute return loss (s11) values. The optimization scheme choosen here is Sequential Quadratic Programming. Bandwith performance improvement is aimed by changing the material properties of the dielectric layers. Their optimum composition will be found subsequently via inverse topology optimization. From this point of view, the magneto-dielectric layers here can be seen as an effective material. The optimization of their properties gives us the best bandwitdh performance subject to chosen optimization model via a SQP algorithm and the full wave analysis tool. Initial design refers to a homogeneous dielectric substrate with $\varepsilon = 3$ and $\mu = 3$. Operating frequency range is 0.5 GHz - 3 GHz sampled with 0.1 GHz. Geometric details and optimization results are shown in Fig. 2. Convergence was reached in about 35 iterations. The initial design structure doesn't have a resonance between our working frequency range. However, the optimal design achieved a bandwidth at -5dB with an initally unmatched resonance in the desired frequency range. With the improvement attained with only 6 design variables and a pre-chosen antenna geometry, the results clearly demonstrate the effect of artificial magneto-dielectric substates on the bandwidth of the microstrip patch antenna. A design search considering the conducting patch as well, i.e. the integration of the conductivity of each layer should allow for much wider bandwidth. It is also noted that the chosen objective function is not favoring matched performance but rather just bandwidth. A more suitable objective function could be employed to aim for well matched behavior. The next step is to feed the resulting ε and μ (ε_1=8, μ_1=2.45, ε_2 =5.8, μ_2 =15.9, ε_3 12.5, μ_3 =2.6) into the inverse topology optimization scheme to explore the layer microstructure.

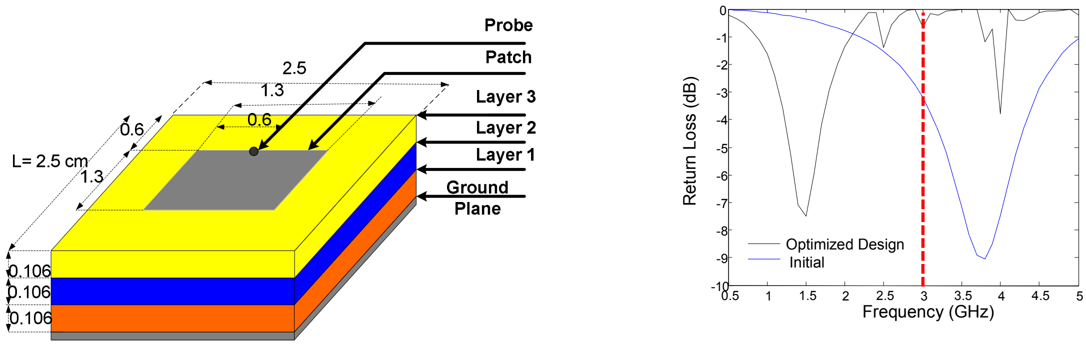

Figure 2: Antenna geometry (left) and corresponding parametric bandwidth design results (right)

To arrive at global optimal design solutions for a two-step large scale design optimization problem subject to performance metrics calculated at sampled frequency points, heuristic search routines need to be employed. The proposed framework is flexible enough to be solved via evolutionary optimization techniques to address this issue, if appropriate speed-up techniques are adopted. One alternative is based on approximating frequency based response functions via Bayesian trained rational functions and is discussed in the next section.

4. Speed-Up Framework for Fast Reanalysis

Bayesian trained [13] rational functions proves to have a powerful yet simple approximation capability based on statistics and just a single controlling parameter, *coef*. Here, we focus on sampling with lower number of frequency points (11 vs. 101) and investigate the possibility of predicting the cost function reliably by interpolation using second order rational quadratic functions, 'quad-quad'. To ensure continuity of successive intervals for highly oscillatory response, first and zeroth order derivative continuities are imposed at interval end points. Coefficients of the quad-quad (Equation 2) satisfying these conditions are solved analytically.

$$y = \frac{\beta_1 + \beta_2 x + \beta_3 x^2}{1 + \beta_4 x + \beta_5 x^2} \quad (2)$$

Additional constraints comprise restricting the denominator from attaining roots inside the interval of interest to create poles in the return loss response. Solving for β's it is observed that *coef* values suiting all intervals do not exist and also depend greatly on the BC's. Hence, to predict the optimum *coef* in the interval, the use of Bayesian classifier seems to be appropriate. Knowing optimum *coef*s of the training set, Bayesian classifier will recognize the probabilistic nature of the training set and assign values and classes to the test sets accordingly. The efficiency and reliability of the quad-quad is assessed by comparing it with 2 fitting schemes: 1) Linear interpolation with exact same sampled frequency and 2) linear interpolation with the same number of data points. The latter requires twice as many number of function calls, equivalent to the quad-quad interpolation time due to additional calls for each point's finite difference calculation. All three interpolations are compared in Fig.3 for a selected group of 11 different artificial magneto-dielectric designs. 550 intervals obtained for all designs were used to train the Bayesian classifier and predict the optimum *coef* of the fitted curves. The error measure corresponds to the bandwidth.The difference between bandwidths is summed up over the entire frequency range to calculate the overall error. Results show that quad-quad predicts an error decrease by 27.6% and 55.9% with respect to double and single sampled linear fitting, respectively, a result motivating further work and use of quad-quad based curve fitting in proposed large scale optimization framework.

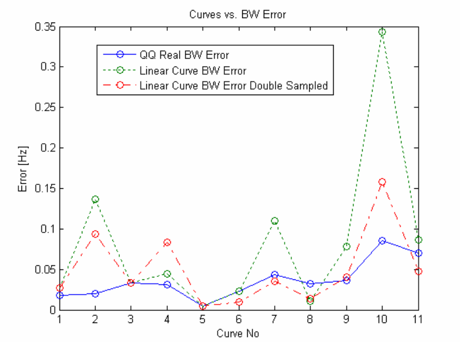

Figure 3: Bandwidth error vs. design number

5. Conclusion

The prorosed design optimization framework is suitable for the design of volumetric magneto-dielectrics from scratch and will give infinite possibilities for the design of advanced composite RF and millimeter wave systems including high performance, 3D integrated and vertically packaged circuitry. An in-depth analysis of the proposed interpolation's efficiency and reliability and its integration to the proposed inverse design framework will follow its use in designing material topologies with desired multi-physics properties via global optimization routines for miniaturized novel antennas.

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