Miniature Antenna Designs on Metamaterial Substrates

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Abstract: In this paper a novel design procedure based on the integration of full wave FEA and a topology design method employing SLP for the optimization is introduced. The employed design method is the Solid Isotropic Material with Penalization (SIMP) technique formulated as a general non-linear optimization problem. Sequential Linear Programming (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 method. As an example, the application of the SIMP design method is extended to develop metamaterial substrates with any arbitrary composition subject to antenna bandwidth enhancements.

Keywords: Topology Optimization, Material Design, Patch Antenna, Maximum Bandwidth, Miniaturization

Introduction

Recent advances in fast and rigorous full wave simulators and the concurrent availability of inexpensive manufacturing techniques for intricate shape and composite materials provides the opportunity to revolutionize traditional design optimization processes to topology and material optimization. Topology/ material optimization [*] draws from a broader class of design solutions as compared to conventional design methods based on size and shape optimization [*]. Hence topology optimization methods are capable of achieving designs with much higher performance. So far, very few examples exist in the literature on topology optimization of specific electrical devices [*]. In this paper, the Solid Isotropic Material with Penalization Method (SIMP) [*] is integrated with fast hybrid finite-element boundary integral (FE-BI) simulations to develop full three-dimensional antenna designs addressing these limitations.

It is well known that high-contrast substrates (metamaterials), although suitable for miniaturization lead to smaller bandwidth [*]. To overcome this limitation, a design method (extending the SIMP technique) is proposed to develop a miniature patch antenna with pre-specified bandwidth performance. The design method incorporates a general non-linear optimization formulation based on well-defined optimization algorithms such as Sequential Linear Programming (SLP) [*] and employs a simple continuous function to relate the actual material property to the introduced "density" variable. As part of the solution technique the adjoint sensitivity method [*] is employed to update the design variable in the sensitivity analysis. This permits full interface with the FE-BI electromagnetic solver and enhances the program efficiency.

The organization of the paper is as follows. First, the design procedure is introduced. This section starts with a discussion on the SIMP method and continues with the definition of the optimization model and its solution procedure. To demonstrate the capability of the proposed method, 3D material design example for a miniaturized patch antenna is presented. The presented design exhibits 250% bandwidth improvement for a fixed size patch antenna on a high contrast metamaterial substrate having a dielectric constant of ε_r =100.

Design Procedure

Analysis Method

The proposed design optimization method is based on the integration of the optimization tool with a hybrid finite-element boundary integral simulator [*]. Application of hybrid methods to infinite periodic structures provides full 3-D modeling flexibility and allows for designing arbitrary geometrical and material details. By virtue of the finite-element method, the simulator is suitable for complex structures such as those involving inhomogeneous dielectrics, resistive patches, conducting patches and blocks, feed probes, impedance loads, etc. This makes the simulator an ideal candidate for generalized, yet efficient optimization loops. Accurate results have already been obtained for scattering and radiation by cavities, slots, multilayer patch antennas and frequency selective surfaces, demonstrating the method's capability [7].

Design Method

The design method used here is the Density/Solid Isotropic Material with Penalization (SIMP) method, a topology optimization method. Topology optimization methods are general design methods used to obtain simultaneously the best geometric and topological configuration in terms of geometry, physical dimensions, connectivity of boundaries and material implants. SIMP has been accepted as a potential automated design tool for almost 20 years in the mechanical engineering area because of its simplicity and efficiency.

The essence of SIMP is that it basically assumes some explicit relationships between the so-called normalized density ρ and the actual material property, here the dielectric permittivity $\varepsilon = \varepsilon_0 \varepsilon_r$. The approach has the advantage that a material property is interpolated/graded using a smooth continuous function, which only depends on the material density and almost all possible topologies can be designed within the resolution of the finite element discretization. A suitable interpolation of the dielectric permittivity would be:

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

where ε_{int} and ε_{orig} are 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. An important aspect is that this parameterization allows for the formulation of the problem in a general non-linear optimization framework, which will be discussed in the next section. The goal is to arrive at the optimum distribution of material (densities) such that a specific performance merit of a device is optimized subject to certain design constraints. 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.

Optimization Model

For our design problem, the specific goal is to determine the substrate material distribution under a square patch antenna subject to pre-specified bandwidth and miniaturization requirements. An appropriate model for the corresponding topology optimization problem employing the SIMP method would be to find the design variables ρ that minimize the cost function:

$$f(\rho) = \min\left[\max(|s_{11}|_j) \right] \quad j = 1,...N_{freq} \tag{2}$$

Subject to a material volume constraint:

$$\sum_{i=1}^{NFE} \rho_i \cdot V_i \le V^* \tag{3}$$

and side constraints:

$$0 < \rho_{\min} \le \rho_i \le \rho_{\max}, \quad i = 1,..NFE \tag{4}$$

for each density variable.

The cost function above is chosen to maximize the return loss bandwidth and corresponds to a minimization of the highest return loss among sampled frequency points N_{freq}. The volume constraint is imposed to limit material usage. That is, a maximum volume V* of the material is allowed within the design domain. The actual material is comprised of the density ρ_i and volume V_i of each design cell in the FE domain. The side constraints are needed to allow for material usage within prescribed limits of the available materials with $\rho_{\min}$ being the normalized lower bound vector and $\rho_{\max}$ the normalized upper bound vector.

The above design problem (2)-(4) is easily recognized as a general non-linear optimization problem with usually several thousand variables. This makes the use of gradient-based optimization techniques such as Sequential Linear Programming (SLP) a must for the solution of the optimization process. The SLP is described in the next section.

Optimization Routine

The iterative optimization scheme chosen here is the sequential linear programming (SLP) method employing the DSPLP package in the SLATEC library due to its well-known efficiency and reliability. Other intuitive routines such as the GA or SA would be impossible to use considering its CPU requirements for a real 3D design composed of many design cells. The essence of the SLP routine is to replace the objective function and constraints by a linear approximation obtained from a Taylor series expansion about the current design point at each iteration. The most critical aspect in doing so is to employ the gradients or the derivatives of the mathematical functions in the optimization model with respect to the design variables as derived in the next section. The linear programming sub-problem is then posed to find the optimal design changes from the current design point. It is of great importance to impose constraints for the design changes known as move limit bounds to ensure convergence. Typically, during one iteration, the design variables are allowed to change by 5-15% of their original values.

Sensitivity Analysis

The computation of the required derivatives of the objective function f with respect to the design variables is referred to as the sensitivity analysis and is of great importance for any gradient based optimization technique. We briefly discuss it here. For our design problem, the objective is a mathematical function in terms of the return loss $|s_{11}|$ at each frequency j defined as:

$$|s_{11}|_j = \frac{|Z_{in_j} - Z_0|}{|Z_{in_j} + Z_0|} \ (dB) \tag{5}$$

where Z_{inj} is the input impedance at the feed location at frequency j and Z_0 is the reference impedance. In general terms, the objective function is a function of Z_{in} relying on the unknowns solved for via the FE simulator. More specifically,

$$|s_{11}| = f(\mathrm{E}(\varepsilon), \varepsilon) \tag{6}$$

where ε refers to the element dielectric permittivity, the material property of the device to be optimized. The real function is differentiated with respect to a complex variable by using an appropriate approximation [4] and the chain rule as:

$$\frac{d|s_{11}|}{d\varepsilon} = \left\{ \frac{\partial |s_{11}|}{\partial \mathrm{Re}(s_{11})} \mathrm{Re}\left[\frac{\partial s_{11}}{\partial \varepsilon}\right] + \frac{\partial |s_{11}|}{\partial \mathrm{Im}(s_{11})} \mathrm{Im}\left[\frac{\partial s_{11}}{\partial \varepsilon}\right] \right\} \tag{7}$$

where the chain rule is employed to determine the derivative of the complex return loss functional and yields:

$$\frac{\partial s_{11}}{\partial \varepsilon} = \frac{\partial s_{11}}{\partial E} \frac{\partial E}{\partial \varepsilon} \tag{8}$$

The derivative term of the edge unknowns E requires the differentiation of the system matrix $[A]E = f$ of the FE-BI formulation with respect to the permittivity in each design cell as follows:

$$\frac{\partial [A]}{\partial \varepsilon} E + [A] \frac{\partial E}{\partial \varepsilon} = f \quad \Rightarrow \frac{\partial E}{\partial \varepsilon} = [A]^{-1} \left(\frac{\partial f}{\partial E} - \frac{\partial [A]}{\partial \varepsilon} E \right) \tag{9}$$

Substituting this into (8) results in:

$$\frac{\partial s_{11}}{\partial \varepsilon} = \frac{\partial s_{11}}{\partial E} [A]^{-1} \left(\frac{\partial f}{\partial E} - \frac{\partial [A]}{\partial \varepsilon} E \right) \tag{10}$$

Realizing that the first term requires a huge matrix inversion process, the solution of an adjoint problem to the original FE system seems to be more appropriate. More specifically, denoting the first term as λ and taking its transform will result in:

$$\lambda^T = [A]^{-1} \left(\frac{\partial s_{11}}{\partial E} \right)^T \tag{11}$$

Due to the symmetric nature of matrix [A], (11) can be rewritten as:

$$[A]\{\lambda\}^T = \left\{ \frac{\partial s_{11}}{\partial E} \right\}^T \tag{12}$$

The key part of the whole sensitivity analysis is based on the solution for the adjoint vector λ^T using the original FE system equations with the RHS replaced by the term as above for each iteration only once. The final sensitivities in (7) for each design cell are obtained by substituting the adjoint variables in (12) and carrying out the outlined steps above. It is important to note that the term in the parantheses of (10) are carried out on the local element matrix level of each design cell the permittivity of differentiation refers to. This whole process allows for significant savings in the CPU requirement while maintaining the accuracy of analytical differentiation.

Design Algorithm

The ultimate algorithm for the proposed design cycle is displayed in Fig. 1. It consists of the following iterative steps: 1) Simulation of the device performance using the FE-BI solver with specified initial data, 2) Solution of the adjoint system equations of the original problem for the sensitivity analysis, 3) Optimization of the volumetric material distribution of the dielectric substrate using an SLP algorithm and 4) Updating the design variables (densities/permittivities) relying on the interpolation scheme of the SIMP design method. Convergence is achieved when the changes in the objective function value drops below a certain value like 0.001. Specified initial data include design variables, which correspond to an initial homogenous dielectric substrate with a certain permittivity value. Certain design parameters are also specified at this step but do not change during the design cycle. These are the patch geometry and material characterization, like the dielectric block dimensions. Also, the feed location and amplitude and the frequency range of operation are specified.

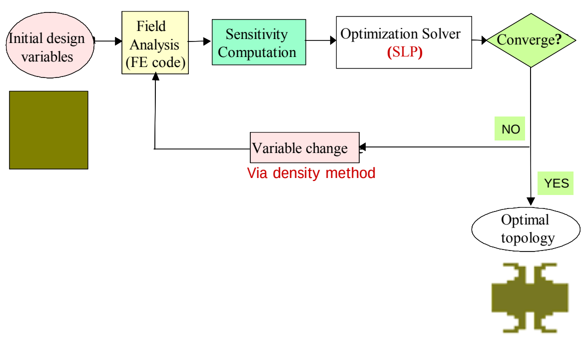

Fig. 1 Design Optimization Flowchart

Design Example

The main goal here is to improve the bandwidth performance of a chosen simple patch antenna by designing its substrate material employing the design procedure outlined above. As is well known, microstrip patch antennas are attractive, low- weight, low-profile antennas, which however suffer from low bandwidth. Moreover, its bandwidth is further reduced as the substrate dielectric constant is increased for miniaturization. In this section, we will demonstrate bandwidth improvement of a chosen simple patch antenna by introducing a new (metamaterial) substrate texture whose properties are not found in nature.

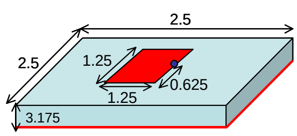

Fig. 2 Schematic of the patch antenna on the dielectric block substrate (dimensions are in cm).

The chosen geometry is a square patch fed with a probe/coax feed and the details of the whole structure are displayed in Fig. 2. The frequency range of interest is 1-2 GHz sampled over 21 frequency points. For this design, the volume was set to 70% with respect to the initial substrate dielectric permittivity to ensure better miniaturization for the designed substrate. The volume constraint is also necessary to avoid trivial bandwidth improvement via lower dielectric constant.

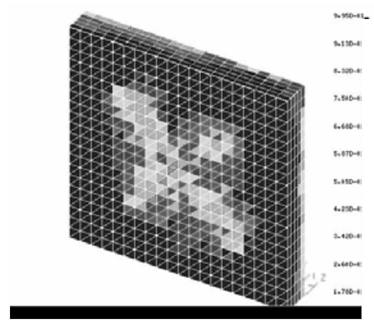

Fig. 3 Optimally designed metamaterial texture

The initial design using a homogenous substrate having ε =42 resulted in a 5dB return loss bandwidth of 6.7% and we were not able to obtain the typical 10dB bandwidth because of the capacitive nature of the high contrast material. By pursuing the above discussed design procedures, with each design cell being updated via the SIMP method and the SLP routine, a heterogeneous design was obtained in 20 iterations. The converged material distribution is displayed in Fig. 3 as a 3D color coded block with each color pixel corresponding to a certain density/permittivity value. The corresponding return loss behavior of the optimized dielectric distribution is depicted in Fig. 4 and compared to the initial performance.

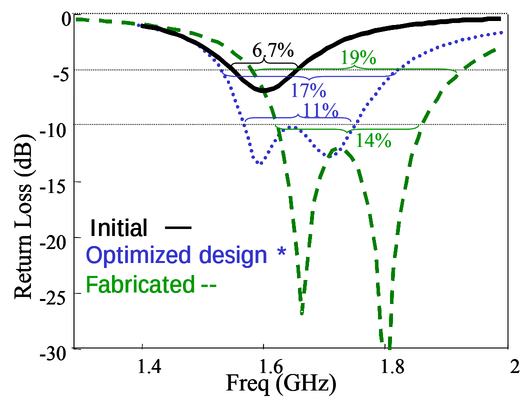

Fig. 4 Return loss behavior for initial and designed textured substrate

The computation time for the entire design process with a design domain of 4000 finite elements/design cells and 21 frequency points for each iteration was 17 hours on a Pentium 3 Processor. Given the poor bandwidth at the starting point of the design, the attained bandwidth performance (with material design only) is truly remarkable.

To fabricate the design, certain post processing/image processing needed to be applied on the design to transform it into a two material composite of available material. Adaptive Image Processing with a simple filtering idea based on a cut-off value of 0.64 for the densities has been adapted to solidify and fabricate the 3D material composite substrate (Fig. 5) using Thermoplastic Green Machining. More specifically, first a thermoplastic compound was prepared by mixing commercially available low-temperature cofirable ceramic (ULF 101) powder with melted binder systems. Once compounded, it was warm-pressed and the dielectric block in its "green body" state was obtained. The material is machinable at this stage and has slightly larger dimensions than the original design. After removing material via a computer-controlled equipment (Modela; Roland DG Corp., Japan) according to the filtered design geometry, this substrate is sintered. During machining, it is also slightly modified for machinability and considering shrinkage after sintering. The return loss behavior of the fabricated design compared to the initial substrate and the volumetric graded design. It is important to note that the attained BW has slightly changed for the fabricated design. This demonstrates the power of integrating robust optimization techniques with simple filtering processes for manufacturable substrates with desired performance.

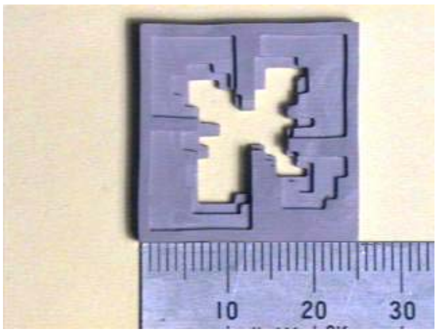

Fig. 5

Conclusion

The aim of this paper was to demonstrate the capability of designing for metamaterial substrates using the SIMP method. This has been done by designing for variable material substrates to improve antenna performance and more specifically bandwidth. The design is also filtered and solidified to achieve a manufacturable design. To achieve a 250% improvement in a fixed size patch antenna, the SIMP method has been extended along with the SLP routine for the solution. Key to the success of the optimization was the integration of optimization tool with fast, full wave FE-BI solver and the utilization of the sensitivity analysis. The fabricated final design using TGM demonstrates, by virtue of the generality and efficiency of the proposed method, there is great potential for improving antenna performance or other RF devices.

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