

OPTIMUM DESIGN AND FABRICATION OF VOLUMETRIC GRADED SUBSTRATE FOR A BROAD BAND MINIATURE ANTENNA

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INTRODUCTION

With the increasing use and reliance of commercial and military wireless communications, sophistication in terms of technology, level of integration, and miniaturization is also increasing. There is a necessity for space/volume reduction and increased antenna functionality.

Printed antennas are very attractive for a variety of commercial and military applications. However, they suffer from narrow bandwidth and large size as the frequency is lowered. So far, material and general shape/topology optimization have not been pursued primarily due to challenges associated with the fabrication of inhomogeneous materials and limited access to versatile analysis tools. However, solid proof for the innovations that new material designs can add to this field are already demonstrated [1], [2]. Few methods in the context of material design were also employed to overcome the intrinsic disadvantages of patch antennas [3], [4]. Although these efforts showed the trends to achieve significantly enhanced performance, the ultimate designs still rely on design expertise or offer restricted design freedom.

Topology optimization is by far more general than any other existing design technique, since it draws from a broader class of design solutions as compared to conventional design methods. Consequently, systematic design methods employing topology optimization, should be able to improve existing designs considerably by designing for topology and material to deliver entirely new and more efficient devices with increased functionality. Topology optimization methods have been applied successfully to many industrial problems and have reached a level of maturity in the structural mechanics area for almost 20 years [5]. However, there are very few examples for topology optimization of electromagnetic devices and the majority of these dealt with problem specific, restricted or semi-analytic tools for magneto-static applications [6-8].

In this study, a topology optimization method, more specifically the SIMP [6] design method is extended for the first time to EM design. As an example, high-contrast 3D dielectric material is designed and fabricated using thermoplastic green machining for a microstrip patch antenna subject to pre-specified bandwidth and miniaturization criteria. A key element of this extension is the use of the latest fast algorithms. For design optimization, the Sequential Linear Programming (SLP) [9] and an exact sensitivity analysis based on the solution of the adjoint problem [7] is employed. The sensitivity analysis is crucial to integrating the solver with the SLP optimizer and for allowing problem convergence. The proposed novel design approach effectively combines FEA with topology optimization techniques and allows for full flexibility in geometry and material specifications across three dimensions for possible antenna and filter applications.

DESIGN PROCEDURE

All numerical design methods are composed of at least two modules linked together within a loop: one module is the field analysis and the other contains the optimization tool. Our proposed design approach is based on the integration of the optimizer with fast and robust hybrid finite element-boundary integral simulations. 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 and its $O(N)$ memory demand and CPU complexity, this module is an ideal candidate for practical printed antenna designs without limitations on antenna shape and topology, or substrate material distribution. Accurate results have already been obtained for scattering and radiation applications demonstrating the method's capability [10].

As our design method, we employ the topology optimization method based on the SIMP approach. SIMP has been accepted as a simplified design tool for many years. It allows for novel shape designs by distributing material within a given design domain without a-priori information on the initial shape or topology of the device. In practice, to specify the material properties, the design domain is discretized into material cells/finite elements. A key aspect of the approach is the introduction of the density variable, a normalized continuous variable for each FE/design pixel. The artificial density is related to the physical material parameter (the permittivity), mathematically manifested in the form of the empirical relationship: $\rho = (\epsilon_{\text{int}} - \epsilon_{\text{air}}) / (\epsilon_{\text{orig}} - \epsilon_{\text{air}})^{1/n}$ where n is a penalization factor; ϵ_{int} and ϵ_{orig} refer to the intermediate and original solid material permittivities, respectively. Thus, graded material can be modeled by assigning different density values from 0 to 1 in each cell to represent a material variation from cell to cell. This allows for image-based representation of a device with any topology or material composition. As n increases, intermediate values for the permittivity are less likely to occur.

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. In this case, the densities are the design variables in the non-linear optimization framework. 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:

$$f(\rho) = \min \left[\max(|s_{11}|_j) \right] \quad j = 1, \dots, N_{\text{freq}} \quad \text{subject to a material volume constraint: } \sum_{i=1}^{NFE} \rho_i \cdot V_i \leq V^* \quad \text{and side}$$

constraints (0/1) for each density variable. Minimization of the highest return loss among sampled frequency points N_{freq} is known to maximize the return loss (S11) bandwidth and the volume constraint basically limits the available amount of material. The design problem is easily recognized as a general non-linear optimization problem with several thousand variables/FEs, which makes the use of gradient-based optimization techniques a must for the solution of the optimization process. The iterative optimization scheme chosen here, due to its well-known efficiency and reliability is the Sequential Linear Programming (SLP) method, employing the DSPLP package in the SLATEC library [11]. The essence of the SLP routine is to replace the objective function and constraints by their linear approximations at each iteration. Updates of the design variables are pursued thru the use of gradient information obtained thru the adjoint variable method, which is an efficient method and permits full interface with the FE-BI electromagnetic solver. This sensitivity analysis is crucial to integrating the solver with the SLP optimizer.

The ultimate algorithm for the proposed design cycle consists of the following iterative steps: 1) Simulation of the device performance using the FE-BI solver with pre-specified 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 10^{-3} .

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. The details of the whole structure are displayed in Figure 1. An initial homogenous substrate with $\epsilon=42$ is chosen for the frequency range of interest (1-2 GHz sampled over 21 frequency points). The volume constraint is set to 70% to avoid trivial bandwidth improvement via lower dielectric constant. With each design cell being updated via the SIMP method and the SLP routine as above, a graded volumetric design was obtained in only 20 iterations. The computation time for the entire design process with 4000 finite elements and 21 frequency points per iteration, was 17 hours on a Pentium 3 Processor. The converged material distribution is displayed in Figure 1 as a 3D color-coded block with each color pixel corresponding to a certain permittivity value. The corresponding return loss behavior for the optimized and initial dielectric distribution is compared in Figure 2. Given the poor bandwidth at the starting point of the design, a 5dB return loss bandwidth of 6.7%, the attained bandwidth performance (with material design only) is truly remarkable. Specifically, the designed substrate delivered a 5 dB return loss bandwidth of 17% and a 10 return loss bandwidth of 11%.

To fabricate the design, certain post processing/image processing were necessary to transform it into a two material composite. Adaptive Image Processing with a simple filtering idea based on a cut-off value of 0.64 for the densities was adapted to solidify and fabricate the 3D material composite substrate (Figure 2) 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, the substrate is finally sintered. During machining, it is also slightly modified for machinability and shrinkage considerations after sintering. The return loss behavior of the fabricated design is compared to the initial substrate and the volumetric graded design in Figure 2. It is important to note that the attained bandwidth is even improved for the fabricated design. This demonstrates the power of integrating robust optimization techniques with simple filtering processes for manufacturable substrates with improved performance.

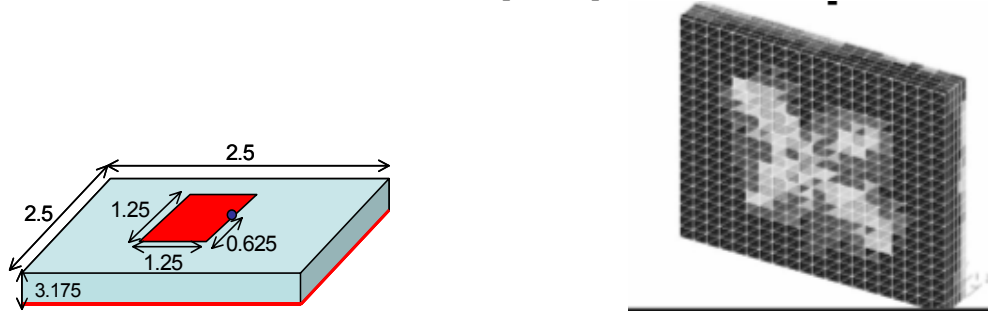


Figure 1. (Left) Schematic of patch antenna on initial homogeneous substrate (dimensions are in cm) and optimized volumetric graded substrate (right)

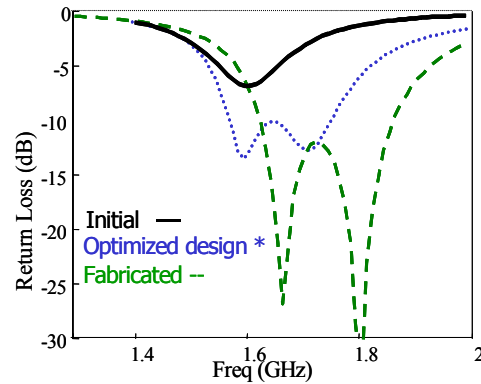


Figure 2. (Left) Fabricated substrate after filtering and modifications and its return loss performance comparison with initial and optimized volumetric graded substrate (right).

CONCLUSION

A novel design procedure based on the integration of full wave FEA and the SIMP design method employing SLP for the optimization was introduced. The capability was demonstrated by achieving a 250% BW improvement for a probe fed patch antenna through design of only the dielectric substrate while size is kept constant. The design is filtered and solidified to achieve a manufacturable state. The fabricated final design using TGM is indeed a remarkable demonstration of our ability to design and manufacture novel material compositions with dramatically new applications.

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