Efficient Optimization of *S*-Parameters of Systems and Components in Microwave Heating

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Advanced computer simulation of processes and systems of microwave (MW) power engineering finds now more applications in both R&D and industrial projects [1, 2]. However, straightforward application of even highly sophisticated computational tools for analysis of the problem may not bring many direct recommendations as to how the construction of the system should be changed to improve its performance. Optimization options available in a number of electromagnetic (EM) simulators [3] appear to be general-purpose and slowly converging procedures, which are characterized by heavy demand on computer resources. Alternatively, there are examples of optimization of MW heating structures (e.g. [4]), when analysts reserve themselves to some faster and simpler computational kernels, such as methods of moments, which, compared to FDTD and FEM is neither so powerful, nor accurate, and is applicable only to certain classes of systems.

Development of efficient optimization techniques for the most advanced numerical methods in high frequency electromagnetics (such as time domain techniques conforming to curvilinear surfaces [3]) requires many challenging issues in numerical mathematics, programming, and computing to be solved. Analysis of common features of processes and systems of MW heating suggests that there are two EM characteristics mostly deserving optimization: reflections from the cavity and pattern of heating. While non-uniformity of the latter is a well-known subject of concern, the first issue is also very important since efficiency of the system strongly depends on behavior of the reflection coefficient $|S_{11}|$ in the frequency range adjacent to the operating frequency f_0.

This paper deals with optimization of the form of the frequency characteristic of $|S_{11}|$ which is a function of geometrical parameters of the system. We describe a deterministic optimization algorithm along with analysis of its performance and present examples of its application to practically meaningful elements and systems of MW power engineering. The procedure implemented in Matlab 6 is interfaced with *QuickWave-3D*, the 3D full-wave conformal FDTD EM simulator (www.qwed.com.pl), which serves as a powerful computational kernel implementing accurate numerical solution of the EM problem.

Optimization Algorithm. The optimization problem under consideration can be reduced to determination of geometrical characteristics for which $|S_{11}|$ at f_0 is not large and there are no strong resonances in its closest neighborhood. That is, we seek a function $S(\mathbf{x})$, where $\mathbf{x} = [x_1 \cdots x_{n+1}]^T = [f \; z_1 \; z_2 \cdots z_n]^T$ is the vector of structure parameters, f is frequency, $z_1, \ldots, z_n$ are n geometric characteristics of the system, and $S = |S_{11}|$, to be less than certain (reasonably small) value S_0 everywhere in the frequency range $f_1 < f_0 < f_2$. The values of $S(\mathbf{x})$ outside this range do not matter; neither does an actual behavior of this function *below* S_0. The set $z_1, \ldots, z_n$ for which the above requirement is fulfilled specifies the optimal configuration, i.e., the system generating minimal reflections. We consider an $(n+1)$-dimensional "hypersurface" $S(\mathbf{x})$, for which we wish to pick up an appropriate analytical approximation which is subsequently supposed to be minimized by an appropriate technique of constrained optimization. We choose a quadratic model proven to be suitable and successful [5] to approximate $S(\mathbf{x})$ in the form

$$Q(\mathbf{x}) = a_0 + \sum_{i=1}^{n+1} a_i x_i + \sum_{\substack{j,\, i=1 \\ j \ge i}}^{n+1} a_{ij} x_i x_j \tag{1}$$

The important feature making this algorithm efficient is that we allow the number of actual FDTD simulations required for an accurate model to be less than that needed for a full and unique quadratic approximation. When constructing $Q(\mathbf{x})$, evaluation of $S(\mathbf{x})$ is performed at some specific base points $\mathbf{x}^i$, $i = 1, \ldots, m$, such that many coefficients of the quadratic and mixed terms conveniently approach zero. Regression analysis is then applied to the obtained reduced polynomial (an objective function) to evaluate an error associated with this approximation. The accuracy of fitting is supposed to be satisfactory as long as the error term $\varepsilon = |Q(\mathbf{x}) - S(\mathbf{x})|$ is characterized by the normal distribution. Finally, the objective function and the indicated constraints are considered to be subject to nonlinear programming leading to $Q(\mathbf{x})$ with a minimum at particular $z_1, \ldots, z_n$. If this polynomial is built with evaluation of $S(\mathbf{x})$ on a coarse FDTD mesh, then we generate more accurate optimal frequency characteristic of $|S_{11}|$ running simulation for the optimized geometric characteristics on a finer mesh.

The described deterministic technique converges much quicker than techniques of global optimization (simulated annealing used in [4], genetic algorithm, or stochastic methods) suitable here. It can be similarly used for optimization (maximization) of transmission coefficient $|S_{21}|$; this may be convenient when the designer needs a certain magnitude of the field far away from the feed. The algorithm currently constructs well only relatively smooth functions $Q(\mathbf{x})$, i.e., no strongly oscillating characteristics of S-parameters could be taken into account. This issue will be addressed at the next stage of the project, but even now the approach allows us to deal with many important MW systems. Indeed, its efficiency and simplicity are achieved at the expense of some modeling accuracy not guaranteeing that the minimum of $Q(\mathbf{x})$ corresponds to the actual global minimum of $S(\mathbf{x})$. However, there is no reason to be discontented with the latter as long as the optimized characteristics correspond to the solution satisfying the applied constraints.

Example: Slotted Waveguide. The presented optimization scheme has been applied to a slotted waveguide as a radiating element, which can be considered an alternative to the open-end feeds and waveguide-horn structures traditional for MW ovens. The configuration of five narrow inclined slots in the broad wall of WR430 (Fig. 1) has been optimized for the fixed slot's sizes (w = 8 mm, l = 65 mm) and variable distance from the fifth slot to the waveguide end ($z_1 = d$), separation of the slots ($z_2 = s$), and their inclination ($z_3 = \theta$). Imposing appropriate ranges for the geometrical parameters ($30 < d < 120$ mm, $30 < s < 70$ mm, $0 < \theta < 60^0$) and assuming f_1 = 2.4 GHz, f_2 = 2.5 GHz, and S_0 = 0.3, instead of complete polynomial (1), we get the objective function in the form:

$$Q(\mathbf{x}) = 0.217 - 0.062\theta - 0.046s - 0.015d + 0.026f - 0.019\theta s + 0.007\theta d - 0.074\theta f + 0.034sd + 0.032s^2 + 0.119f^2,$$

which reaches its constrained minimum when d = 118 mm, s = 56 mm, and $\theta = 27^0$. Fig. 2 presents $|S_{11}|$ versus f for the accidental (curves 1, 2) and optimal (curve 3) configurations of the slotted waveguide.

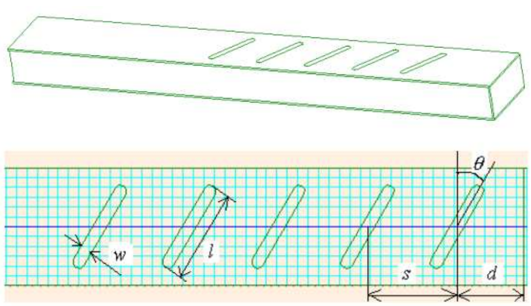

Fig. 1.

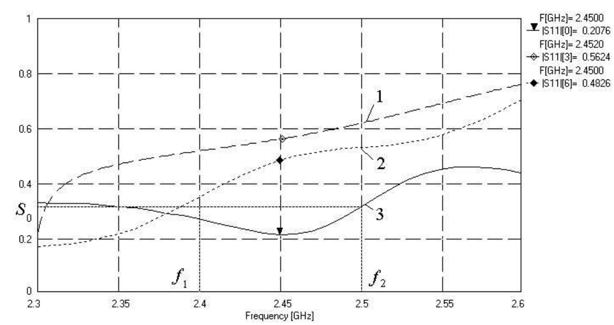

Fig. 2.

Conclusion. This paper outlines the major aspects of the efficient algorithm suitable for optimizing the S-parameters in systems of MW heating. The shown example of the optimized slotted waveguide is characterized by high radiation efficiency (at 2.45 GHz, $|S_{11}| \sim 0.2$, i.e., about 96% of EM power leaves the waveguide for the outer space) that allows its use as a radiating element without a matched load. Other illustrations include optimization of a matching post in a waveguide T-junction and determination of the best location and the geometry of the cylindrical absorbing load in a waveguide.

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