SPACE MAPPING OPTIMIZATION OF WAVEGUIDE FILTERS USING FINITE ELEMENT AND MODE-MATCHING ELECTROMAGNETIC SIMULATORS

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ABSTRACT

For the first time, we apply aggressive space mapping to automatically align electromagnetic models based on hybrid mode-matching/network theory simulations with models based on finite-element (FEM) simulations in design optimization of microwave circuits. The parameter extraction phase of space mapping is given special attention. A statistical approach to parameter extraction involving ℓ_1 and penalty concepts facilitates a key requirement by space mapping for uniqueness and consistency. Electromagnetic optimization of an H-plane resonator filter with rounded corners illustrates the advantages as well as the challenges of our approach.

INTRODUCTION

Direct exploitation of electromagnetic (EM) simulators in the optimization of arbitrarily shaped 3D structures at high frequencies is crucial for first-pass success CAD. Recently, we reported successful automated design optimization of 3D structures using FEM simulations [1].

In this paper we apply, for the first time, aggressive space mapping optimization [1,2] through automatic alignment of the results of two separate EM simulation systems. For fast/coarse simulations in the so-called optimization space (OS) we use the RWGMM library of waveguide models based on mode matching (MM) [3]. It is linked with the network theory optimizers of OSA90/hope [4]. For the so-called EM space or "fine" model we have selected Maxwell Eminence [5], accessed by Empipe3D [4]. The space mapping procedure executes all these systems concurrently.

The parameter extraction phase is the key to effective space mapping optimization. The methodology, however, is sensitive to nonunique solutions or local minima. We address this issue by offering an approach based on statistical parameter extraction involving a powerful ℓ_1 algorithm and penalty terms.

We demonstrate aggressive space mapping optimization of an H-plane resonator filter with rounded corners. These rounded corners make RWGMM simulations somewhat less accurate.

SPACE MAPPING OPTIMIZATION USING MM/NETWORK THEORY AND FEM

In the space mapping optimization procedure, the MM waveguide library serves as the OS model and the FEM simulator as the EM model. The flow diagram of our space mapping procedure is outlined in Fig. 1. We address the design of the H-plane resonator filter shown in Fig. 2. The waveguide cross-section is 15.8 × 7.9 mm, while the thickness of the irises is t = 0.4 mm. The radius of the corners is R = 1 mm. The iris and resonator dimensions d_1, d_2, l_1 and l_2 are selected as the optimization variables.

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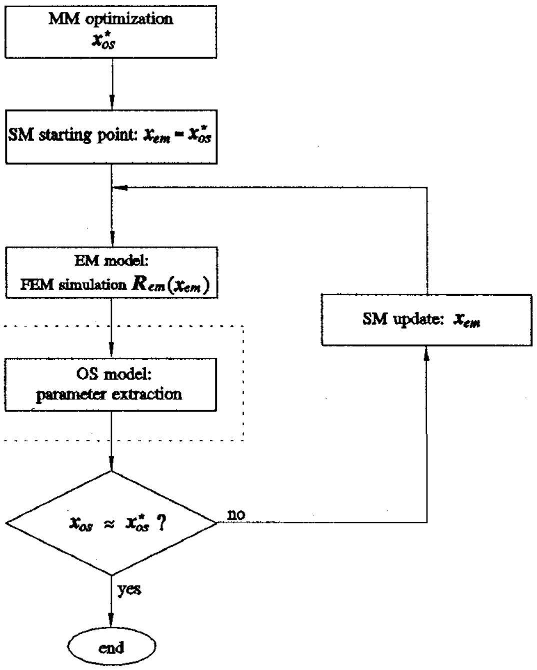
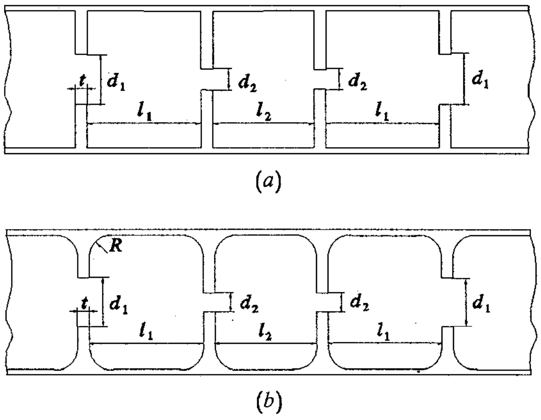


Fig. 1. Flow diagram of the space mapping optimization (SM) procedure concurrently exploiting the hybrid MM/network theory and FEM techniques and statistical parameter extraction.



(*a*)

(*b*)

Fig. 2. Structures for space mapping optimization: (*a*) OS model, for hybrid MM/network theory; (*b*) fine model, for FEM analysis.

First, minimax optimization of the OS model (Fig. 2(a)) is performed with the following specifications provided by Arndt [6]

$|S_{21}|$ (dB) < -35 for $13.5 \leq f \leq 13.6$ GHz
$|S_{11}|$ (dB) < -20 for $14.0 \leq f \leq 14.2$ GHz
$|S_{21}|$ (dB) < -35 for $14.6 \leq f \leq 14.8$ GHz

The minimax solution x_{os}^* is $d_1 = 6.04541$, $d_2 = 3.21811$, $l_1 = 13.0688$ and $l_2 = 13.8841$. It yields the target response for space mapping. Focusing on the passband, we treat responses in the region $13.96 \leq f \leq 14.24$ GHz. The responses obtained using both models at the point x_{os}^* are shown in Fig. 3. Some discrepancy is evident.

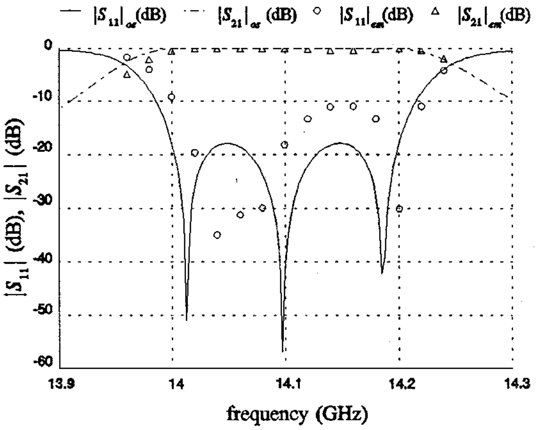


Fig. 3. Magnitudes of S_{11} and S_{21} of the H-plane filter before space mapping optimization, as simulated using RWGMM (curves) and by Maxwell Eminence (points).

The optimized response shown in Fig. 4 corresponds to point $d_1 = 6.17557$, $d_2 = 3.29058$, $l_1 = 13.0282$ and $l_2 = 13.88411$. The solution was obtained after only 4 simulations by Maxwell Eminence. Fifteen sample points were used with Maxwell Eminence.

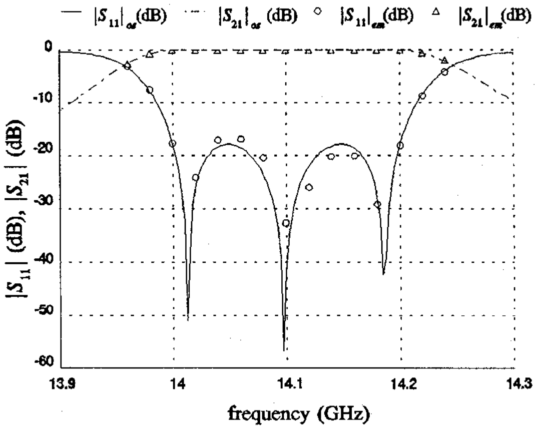


Fig. 4. Space mapping optimized FEM responses (points) of the H-plane filter compared with the target OS responses (curves).

We verified the space mapping results by directly optimizing the H-plane filter using Empipe3D driving the Maxwell Eminence solver. Essentially the same solution was found.

OBJECTIVE FUNCTIONS FOR PARAMETER EXTRACTION

A natural choice in formulating the objective function for the parameter extraction phase of space mapping is to use the responses for which the specifications are given. In the case of the H-plane filter it is $|S_{11}|$ in dB for the passband. We are, however, free to use any formulation that could allow us to align the models.

The results reported in the preceding section were obtained using $|S_{21}|$. With that formulation the space mapping iterations proceeded flawlessly. No difficulty in the parameter extraction phase could be noticed.

We also took a close look at the ℓ_1 objective function formulated in terms of $|S_{11}|$ in dB. Fig. 5 shows this function for the second iteration of space mapping plotted in terms of two selected parameters. This multimodal behavior with many local minima provided us with an excellent opportunity to investigate the uniqueness of the parameter extraction phase in space mapping, as well as to improve its robustness.

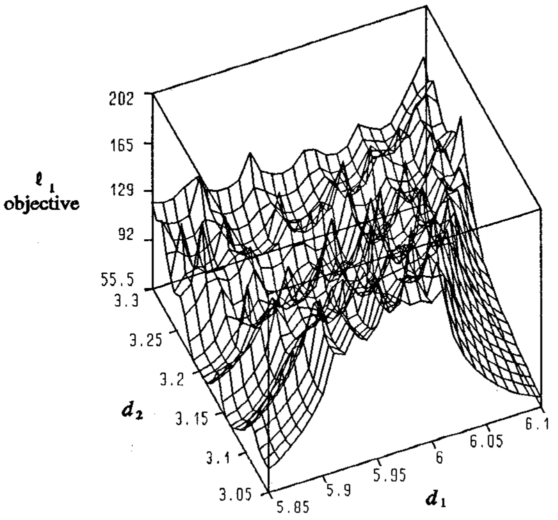


Fig. 5. Variation of ℓ_1 objective defined in terms of $|S_{11}|$ (dB) w.r.t. iris openings d_1 and d_2. Other parameters were held fixed at values corresponding to x_{os}^*.

STATISTICAL PARAMETER EXTRACTION

We propose an automated statistical parameter extraction procedure to overcome potential pitfalls arising out of inaccurate or nonunique solutions [1].

The flow diagram of the statistical parameter extraction is shown in Fig. 6. This diagram provides details of the dotted box of Fig. 1.

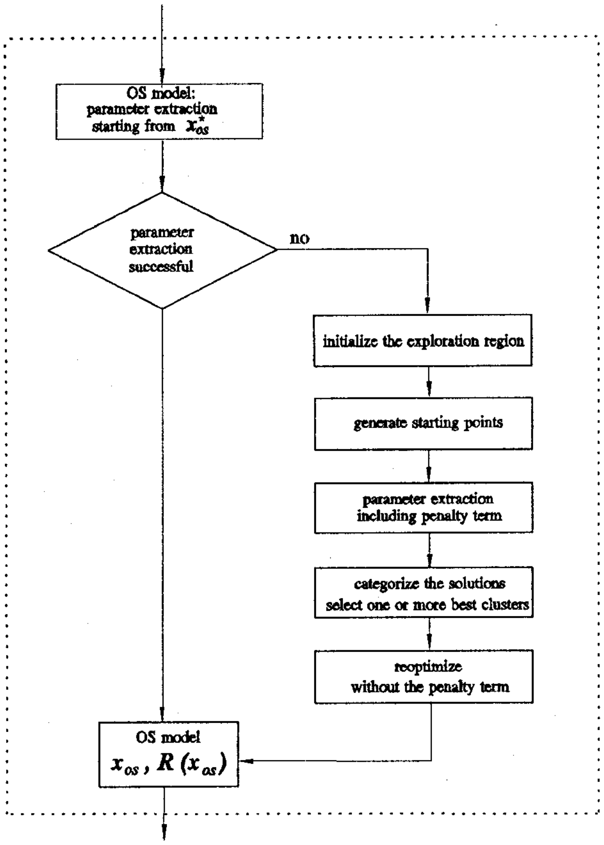


Fig. 6. Flow diagram of the statistical parameter extraction procedure.

First, we perform standard ℓ_1 parameter extraction [7] starting from x_{os}^*. If the optimized response matches well the EM model response (the ℓ_1 objective is small enough) we continue with the space mapping iterations. Otherwise we turn to statistical exploration of the OS model.

The key to statistical parameter extraction is to establish the exploration region. If, for the kth step, we define the multidimensional interval δ as

$$\delta = x_{os}^{k-1} - x_{os}^{*} \qquad (1)$$

the statistical exploration may be limited to the region defined by

$$x_{osi} \in [\, x^*_{osi} - 2\,|\,\delta_i\,|,\ x^*_{osi} + 2\,|\,\delta_i\,|\,] \qquad (2)$$

A set of N_s starting points is statistically generated within the region (3) and N_s parameter extraction optimizations are carried out. These parameter extractions can be further aided by a penalty term [8]. The resulting solutions (expected to be multiple) are categorized into clusters and ranked according to the achieved values of the objective function. Finally, the penalty term is removed and the process repeated in order to focus the clustered solution(s).

This approach has been automated using a three-level Datapipe architecture, similar to [1]. Furthermore, it can be parallelized since the N_s parameter extractions considered are carried out independently.

To illustrate the robustness of the approach, we have applied it to the ℓ_1 objective function defined in terms of $|S_{11}|$ (dB), as shown in Fig. 5.

A set of 100 starting points is statistically generated from a uniform distribution within the range (3). The solutions are scattered, confirming our observation that the ℓ_1 objective function has many local minima as seen in Fig. 5. Among the 100 solutions a cluster of 15 points converged to the same solution, as depicted in Fig. 7. Using this formulation we repeated the entire process of space mapping and essentially the same solution was found.

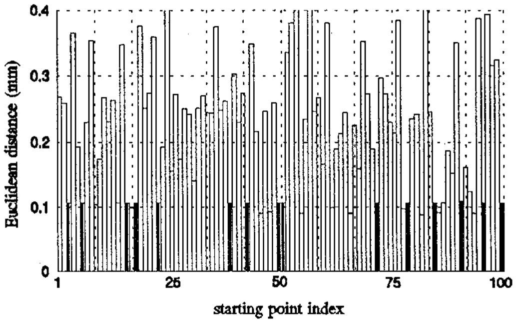


Fig. 7. Euclidean distances measured from x^*_{os} to converged point after the second stage of statistical parameter extraction.

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CONCLUSIONS

We have presented new applications of aggressive space mapping to filter optimization using MM/network theory and FEM simulation techniques. A statistical approach to parameter extraction incorporating the ℓ_1 objective and penalty function concepts has effectively addressed the requirement of a unique and consistent solution. Among important extensions of this work we envisage a highly efficient means for Monte Carlo analysis of microwave circuits carried out with the accuracy of FEM simulation.

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