RECENT RESULTS IN ELECTROMAGNETIC OPTIMIZATION OF MICROWAVE COMPONENTS INCLUDING MICROSTRIP T-JUNCTIONS

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Abstract

This paper presents some recent advances in automated electromagnetic (EM) optimization of microwave components and circuits. We review the challenge of EM optimization and present illustrative examples, involving both direct optimization using commercial EM simulators and space mapping optimization. We review a robust new algorithm for EM optimization called TRASM (Trust Region Aggressive Space Mapping), which integrates a trust region methodology with the aggressive space mapping (ASM) technique. The trust region ensures that each iteration results in improved alignment between the coarse and fine models and recursive multi-point parameter extraction improves the conditioning of the extraction phase. We exploit Sonnet's ***em***, MATLAB, OSA90, Datapipe, interpolation and database techniques and Geometry Capture. Examples include the EM optimization of microstrip T-junctions and an HTS filter.

INTRODUCTION

Future CAE systems for high-speed, wireless and microwave circuits and systems will not be regarded as complete without available powerful EM simulators integrated with optimization capabilities. Optimal design of active and passive devices, circuits and systems is expected to be physically and electromagnetically based, to include electrical, mechanical and thermal effects. Future developments in integrated CAE tools must concurrently link geometry, layout, physical, EM and process simulations, with performance, yield, cost, system specifications, manufacturability and testability in a manner transparent to the designer [1].

The significant features of EM simulators over empirical model/circuit-theory based simulators is their unsurpassed accuracy, extended validity ranges, and their capability of handling more arbitrary geometrical shapes. Increasingly more complex structures are being simulated accurately and quickly as computational techniques improve, making optimization more practical and attractive with tools such as HP HFSS [2]. As was discussed in the 1997 ACES Conference [3] EM simulators will not realize their full potential to the designer unless they are optimizer-driven to automatically adjust designable parameters [4,5,6].

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This paper presents some recent advances in automated EM optimization of microwave components and circuits. We review the challenge of EM optimization and present illustrative examples, involving both direct optimization using commercial EM simulators and space mapping (SM) optimization [7,8]. SM optimization is not yet available in user-friendly form in a commercial package. The powerful SM concept uses a "coarse" model to carry out the bulk of computations in the optimization process. The coarse model can be an empirical model, an equivalent circuit model or an EM model with a coarse resolution. A "fine" or accurate EM model is used to align the coarse model and guide the optimization process.

We review what is claimed to be a robust new algorithm for EM optimization called Trust Region Aggressive Space Mapping (TRASM) [9], which integrates a trust region methodology with the aggressive space mapping (ASM) technique [8]. The trust region is to ensure that each iteration results in improved alignment between the coarse and fine models needed to execute ASM. A recursive multi-point parameter extraction process is proposed to improve the conditioning of the extraction phase.

We exploit Sonnet's ***em*** [10], MATLAB [11], OSA90 [12] and Empipe [12]. In addition we implement OSA's Datapipe technology, interpolation and database techniques, as well as Geometry Capture [12]. Examples include the direct EM optimization of microstrip T-junctions and the space mapping optimization of an HTS filter.

DIRECT OPTIMIZATION: DESIGN OF OPTIMAL MICROSTRIP T-JUNCTIONS

"Direct" optimization has been reported by Bandler *et al.* [4,5,13]. We describe here some new results. We compare four different configurations to compensate discontinuities in a microstrip T-junction by optimization over a broad frequency range. Three of them are taken from the literature, one is introduced here. The T-junctions are optimized to achieve the minimum possible mismatch at the three ports.

The T-junction configuration is symmetric and is connected to three 50 Ω microstrip lines. The first configuration shown in Fig. 1(a) was suggested by Chadha and Gupta [14]. The discontinuity is compensated by removing a triangle portion from the basic T-junction. The configuration of Fig. 1(b) was introduced in [15] but no optimization was performed. Here, the compensation is done by modifying the common arm and the two corners. The T-junction in Fig. 1(c) is introduced here: it is similar to that in Fig. 1(b). The one in Fig. 1(d) is suggested by Dydyk [16] but no optimization was applied. The T-junctions of Figs. 1(a) and 1(b) were compared by Swanson [17] without optimization. The optimization variable for Fig. 1(a) is the side length r at θ equal to 30°, 45° and 60°. For Figs. 1(b), 1(c) and 1(d) the optimization variables are x and y. These variables are adjusted to satisfy the theoretical simultaneous match condition which is 9.54 dB (20 log (1/3)) return loss at the three ports. The specifications are $|S_{11}| \leq 1/3$, $|S_{22}| \leq 1/3$ in the frequency range 2 GHz to 16 GHz. The width w, the height h and the relative dielectric constant ε_r are fixed during optimization. We use Sonnet's ***em*** [10] to compute the S parameters of the different T-junction configurations, the minimax optimizer in OSA90/hope [12] to perform optimization and Empipe [12] to parameterize the geometry of the T-junctions.

Optimization Results

The side length r of the triangle in Fig. 1(a) is optimized for θ equal to 30°, 45° and 60°. Table I shows the results. The T-junctions in Figs. 1(b), 1(c) and 1(d) are optimized here with respect to x and y, each from five starting points. Unique solutions are reached (Table II). Fig. 2 compares responses in the frequency range 2 GHz to 20 GHz for the optimized T-junctions in Fig. 1. It is clear that the T-junction in Fig. 1(a) with θ equal to 30° gives the worst results. The other T-junctions give satisfactory results with minor differences. Fig. 3 compares responses for the optimized T-junctions of Figs. 1(b), 1(c) and 1(d). The T-junction of Fig. 1(d) gives the best response. The response of the T-junction of Fig. 1(c) introduced here is slightly better than the T-junction of Fig. 1(b).

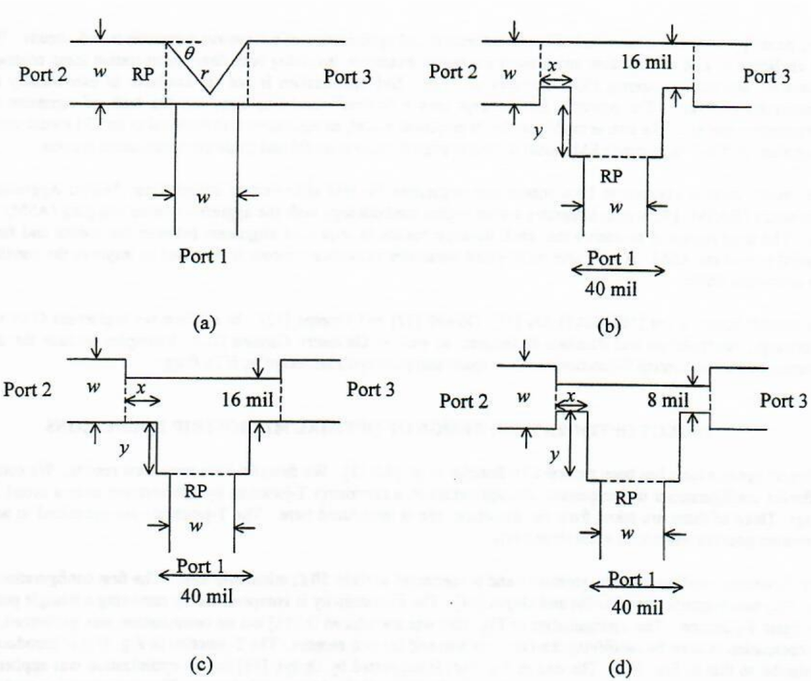

Fig. 1. Four different T-junctions with w= 24 mil, h=25 mil and ε_r=9.9.

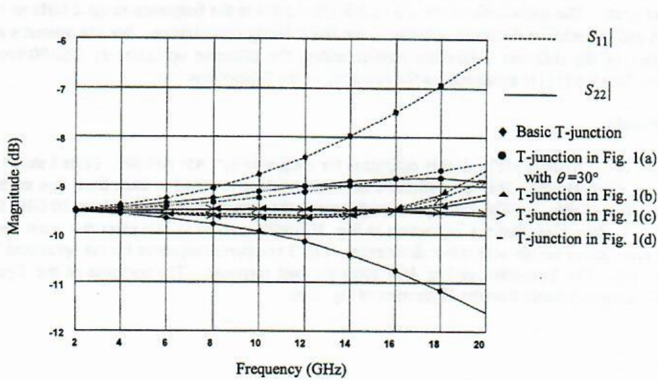

Fig. 2. $|S_{11}|$ and $|S_{22}|$ for the basic T-junction and the optimized T-junctions of Fig. 1.

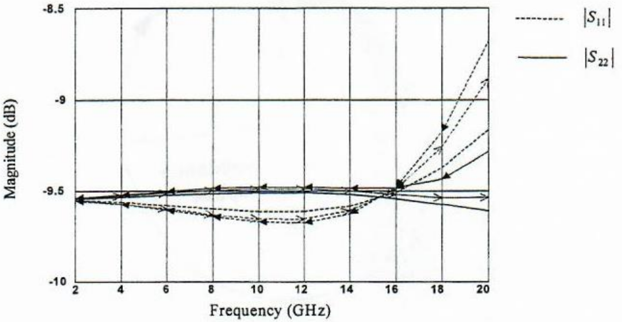

Fig. 3. $|S_{11}|$ and $|S_{22}|$ for the optimized T-junctions of Figs.1(b), 1(c) and 1(d). The range is expanded w.r.t. Fig. 2.

TABLE I
THE OPTIMAL VALUE OF r AT θ EQUAL TO 30°, 45° AND 60° FOR THE T-JUNCTION IN FIG. 1(a)

θ	The optimal value of r
30°	1.556 w
45°	1.355 w
60°	1.158 w

TABLE II
THE OPTIMAL VALUES OF THE PARAMETERS x AND y FOR THE T-JUNCTIONS IN FIGS. 1(b), 1(c) AND 1(d)

T-junction	Optimal value of x	Optimal value of y
Fig. 1(b)	0.9250 w	0.583 w
Fig. 1(c)	0.7271 w	0.7917 w
Fig. 1(d)	0.1 w	0.9167 w

OPTIMIZATION THROUGH SPACE MAPPING

Space mapping (SM) aims at aligning two different simulation models: the so-called "coarse" model, typically an empirical circuit simulation and a "fine" model, typically a full wave EM simulation [1, 7-9]. The concept is illustrated in Fig. 4, where the coarse model is called the "optimization" model and the fine model is identified as the "validation" model.

The technique combines the accuracy of the fine (validation) model with the speed of the coarse (optimization) model during the circuit optimization process. Parameter extraction is a crucial part of the technique. During this step the parameters of the coarse model whose response matches the fine model response are obtained. The extracted parameters may not be unique, causing the technique to fail to converge to the optimal design.

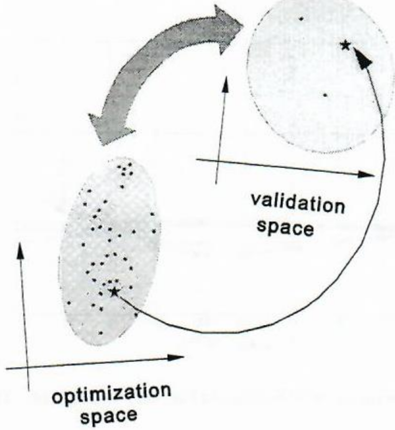

Fig. 4. Concept of aligning two spaces by the space mapping approach [8].

We briefly review aggressive space mapping (ASM) EM optimization. The vector of parameters of the fine model is referred to as $\boldsymbol{x}_{em}$. The vector of parameters of the coarse model is referred to as $\boldsymbol{x}_{os}$. The first step of the ASM technique is to obtain the optimal design of the coarse model $\boldsymbol{x}_{os}^{*}$. The technique aims at establishing a mapping $\boldsymbol{P}$ between the two spaces [8]

$$\boldsymbol{x}_{os} = \boldsymbol{P}(\boldsymbol{x}_{em}) \tag{1}$$

such that

$$\left\| \boldsymbol{R}_{em}(\boldsymbol{x}_{em}) - \boldsymbol{R}_{os}(\boldsymbol{x}_{os}) \right\| \leq \varepsilon \tag{2}$$

where $\boldsymbol{R}_{em}$ is the vector of fine model responses, $\boldsymbol{R}_{os}$ is the vector of coarse mode responses and $\| \ \|$ is a suitable norm. The error function

$$\boldsymbol{f} = \boldsymbol{P}(\boldsymbol{x}_{em}) - \boldsymbol{x}_{os}^{*} \tag{3}$$

is first defined. The final fine model design is obtained and the mapping is established if a solution for the system of nonlinear equations

$$\boldsymbol{f}(\boldsymbol{x}_{em}) = \boldsymbol{0} \tag{4}$$

is found.

Let $\boldsymbol{x}_{em}^{(i)}$ be the ith iterate in the solution of (4). The next iterate $\boldsymbol{x}_{em}^{(i+1)}$ is found by a quasi-Newton iteration

$$\boldsymbol{x}_{em}^{(i+1)} = \boldsymbol{x}_{em}^{(i)} + \boldsymbol{h}^{(i)} \tag{5}$$

where $\boldsymbol{h}^{(i)}$ is obtained from

$$\boldsymbol{B}^{(i)}\,\boldsymbol{h}^{(i)} = -\boldsymbol{f}(\boldsymbol{x}_{em}^{(i)}) \tag{6}$$

and $\boldsymbol{B}^{(i)}$ is an approximation to the Jacobian of the vector $\boldsymbol{f}$ with respect to $\boldsymbol{x}_{em}$ at the ith iteration. The matrix $\boldsymbol{B}$ is updated at each iteration using Broyden's update [18].

It is seen from (1)-(3) that the vector function $\boldsymbol{f}$ is obtained by evaluating $\boldsymbol{P}(\boldsymbol{x}_{em})$. This can be achieved through the process of parameter extraction. Parameter extraction involves solving a subsidiary optimization problem.

During parameter extraction the parameters of the coarse model whose response matches the fine model response are obtained. It can be formulated as

$$\underset{x_{os}}{minimize} \left\| R_{em}(x_{em}^{(i)}) - R_{os}(x_{os}) \right\| . \tag{7}$$

The extracted parameters may not be unique, causing the space mapping optimization technique to fail.

A TRUST REGION AGGRESSIVE SPACE MAPPING ALGORITHM FOR EM OPTIMIZATION

The TRASM algorithm [9] depicted in Fig. 5 integrates a trust region methodology [19] with ASM. The trust region is to ensure that each iteration results in improved alignment between the coarse and fine models needed to execute ASM. To improve the uniqueness of the extraction phase Bakr *et al.* [9] developed a recursive multi-point parameter extraction process, which exploits all available EM simulations already performed. TRASM automates the selection of fine model points used for the multi-point parameter extraction process. Also, the current approximation to the mapping between the two spaces is integrated into the parameter extraction step.

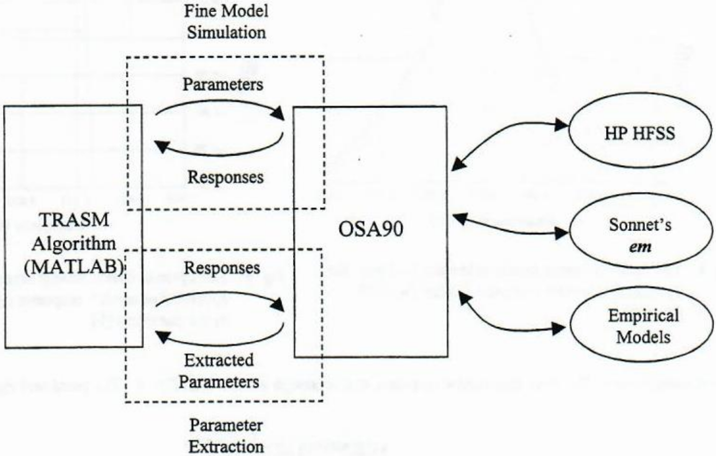

Fig. 5. The current implementation of the TRASM algorithm [9] using MATLAB [11].

HIGH-TEMPERATURE SUPERCONDUCTING FILTER EXAMPLE

We review optimization of a narrow band high-temperature superconducting (HTS) filter [20] (Fig. 6). The specifications are $|S_{21}| \geq 0.95$ in the passband and $|S_{21}| \leq 0.05$ in the stopband, where the stopband includes frequencies below 3.967 GHz and above 4.099 GHz and the passband lies in the range [4.008 GHz, 4.058 GHz]. The optimization variables are L_1, L_2, L_3, S_1, S_2 and S_3. We take L_0 = 50 mil and W = 7 mil. For complete details see [9] and [20]. The coarse model exploits the empirical microstrip line models, coupled lines and open stubs available in OSA90/hope. The fine model employs a fine-grid ***em*** simulation. The coarse model is first optimized using the OSA90/hope minimax optimizer. The corresponding fine model response is shown in Fig. 7. The final EM design was obtained in 5 iterations which required 8 fine

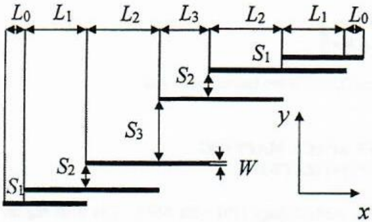

Fig. 6. The structure of the HTS filter [20].

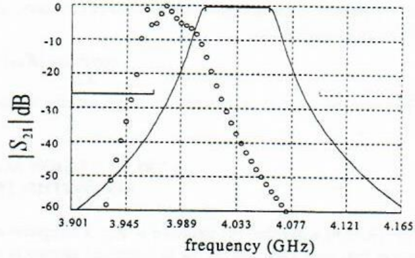

Fig. 7. The optimal coarse model response (—) and the fine model response (o) at the starting point for the HTS filter [9].

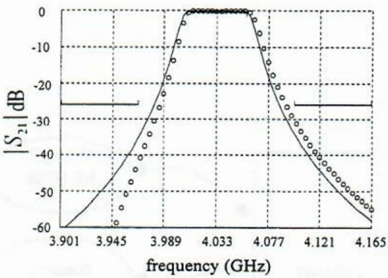

Fig. 8. The optimal coarse model response (—) and the optimal fine model response (o) for the HTS filter [9].

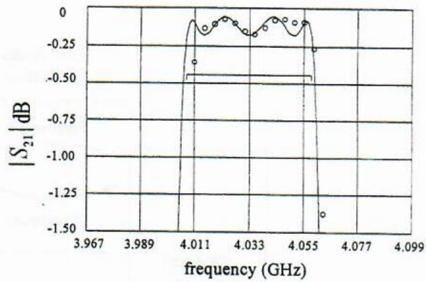

Fig. 9. The optimal coarse model response (—) and the optimal fine model response (o) for the HTS filter in the passband [9].

model simulations. The final fine model response at this design is shown in Fig. 8. The passband ripples are shown in Fig. 9.

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CONCLUSIONS

Advances in computational electromagnetics and optimization technology allow direct exploitation of EM simulation techniques in circuit design optimization. In this paper we have reviewed recent advances in EM optimization of microwave components and circuits. We presented illustrative examples, involving both direct optimization using commercial EM simulators and space mapping optimization. The space mapping technique is a powerful approach to design optimization when extremely CPU intensive simulators are used, combining the speed of circuit-level optimization with the accuracy of EM simulations. We reviewed a new algorithm for EM optimization called TRASM.

Examples include the EM optimization of microstrip T-junctions and an HTS filter. In particular, we compared four different configurations to compensate discontinuities in a T-junction. A new configuration has been introduced here. The HTS filter is a particularly challenging optimization problem, characterized as it is by narrow bandwidth (about 1.24 %) and high dielectric constant (about 24) [20].

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