AGGRESSIVE SPACE MAPPING WITH DECOMPOSITION: A NEW DESIGN METHODOLOGY

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Abstract

This paper presents several issues related to electromagnetic (EM) design optimization of microwave circuits. This includes various approaches of exploiting structure decomposition, particularly in conjunction with our recent aggressive space mapping optimization technique. In this procedure, the accurate but computationally intensive full-wave EM model (the fine model) is used sparingly only to calibrate less accurate, but computationally much more efficient models (the coarse models). Coarse models can be coarse EM, empirical, or a combination of both types of models. Decomposition is employed to further accelerate the coarse model simulation. Applying our approach to interdigital filter design, a desirable filter response is obtained requiring only three EM fine model simulations.

I. INTRODUCTION

Advances in full-wave EM simulation techniques provide designers with the tools to accurately simulate passive microstrip circuits. However, it is commonly perceived that the practical utilization of EM simulators is limited by their heavy demand on computer resources. EM simulators are mostly employed to validate designs obtained using less CPU-intensive means, such as synthesis and circuit optimization.

This paper presents a new EM design methodology which combines two powerful techniques: decomposition and space mapping (SM), in a coherent strategy. The decomposition technique partitions a complex structure into a few smaller substructures [1]. Each of them is analyzed separately and the results are combined to obtain the response of the overall structure. More efficiently, 2D analytical methods or even empirical formulas can be used for the calculation of some non-critical regions while full-wave 3D models are adopted for the analysis of the key substructures.

The other cornerstone of our methodology is the SM technique which has aroused excitement and increasing attention as a fundamentally new concept in engineering-oriented optimization practice [2,3]. A mapping is established between two spaces, namely, between a coarse model and a fine model. We expect to obtain a rapidly improved design after each fine model simulation while the bulk of the computation involved in optimization is carried out in the coarse model space. This is much more efficient than a "brute force" optimization directly driving fine model EM simulations.

Our new approach is applied to the design optimization of interdigital filters, driving a well-recognized simulator (***em*** [4]). A desirable filter response emerges after only three EM fine model simulations, demonstrating the efficiency and accuracy of aggressive SM with decomposition.

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II. AGGRESSIVE SPACE MAPPING METHOD

Consider models in two distinct spaces: the EM space, denoted by X_{em}, and the optimization space, denoted by X_{os}. We call the X_{em} model a fine model, assuming that it is rigorous and accurate, but its simulation is CPU intensive. In comparison, the X_{os} model is less accurate but faster to compute, hence we call it a coarse model. The designable parameters in these two models are denoted by x_{em} and x_{os}, respectively.

We wish to find a mapping P between these two spaces

$$x_{os} = P(x_{em}) \tag{1}$$

such that

$$R_{os}(P(x_{em})) \approx R_{em}(x_{em}) \tag{2}$$

where $R_{em}(x_{em})$ and $R_{os}(x_{os})$ denote the responses of the fine model and the coarse model, respectively.

Our aim is to avoid direct optimization in the CPU-intensive X_{em} space. Instead, the bulk of the computation involved in optimization is carried out in the X_{os} space.

The optimal solution is mapped from the X_{os} space to the X_{em} space using the inverse mapping P^{-1} derived from (1). The mapping function is updated employing a quasi-Newton iteration with first-order derivative approximations based on the classic Broyden formula [5]. The detailed algorithm related to this procedure can be found in [2].

III. THE FILTER MODELS AND DECOMPOSITION

A five-pole interdigital filter is shown in Fig. 1. The material parameters and basic geometrical dimensions are summarized in Table 1.

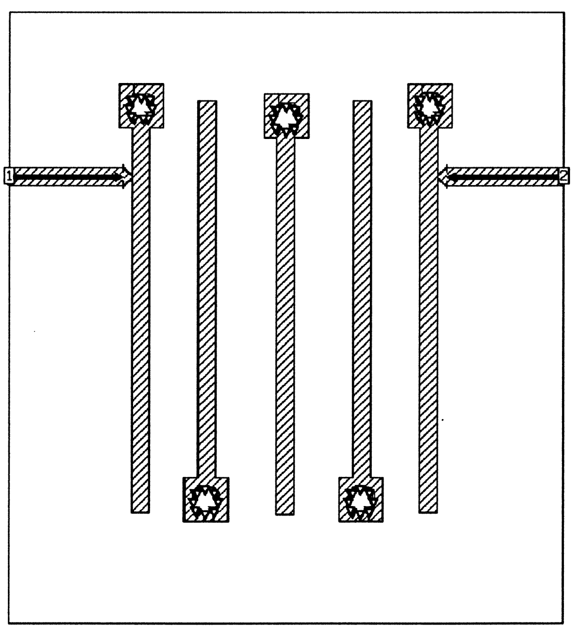

Fig. 1. A five-pole interdigital filter.

TABLE 1
FILTER MATERIAL PARAMETERS AND GEOMETRICAL DIMENSIONS

Parameter	Value	Parameter	Value
substrate dielectric constant	9.8	shielding cover height (mil)	75
substrate thickness (mil)	15	width of input/output lines (mil)	10
conducting metal thickness (mil)	0	width of each resonator (mil)	10
substrate dielectric loss tangent	0/0.001*	via diameter (mil)	13
conductivity of the metal	$\infty/5.8\times10^{7}$*	via pad dimensions (mil × mil)	25 × 25

* The values for loss tangent and conductivity are for simulations without and with losses, respectively.

To achieve a good accuracy using the full-wave simulator ***em***, the grid size for the whole filter structure has to be sufficiently small, which translates into considerable EM simulation time. The simulation time with a fine grid size of 1 × 1 mil is about 1.5 CPU hours per frequency point on a Sun SPARCstation 10 (much longer if losses are included). A direct optimization approach would require many EM analyses and consequently an excessive amount of CPU time.

In order to employ the aggressive SM strategy, we need a fine model and a coarse model. The fine model is the filter simulated by ***em*** as a whole with the grid size of 1 × 1 mil. The coarse model is constructed using decomposition, as illustrated in Fig. 2. The decomposed substructures are analyzed separately using a combination of EM models with a coarse grid and empirical models.

Referring to Fig. 2, the center shaded 12-port network is analyzed by ***em*** with a very coarse grid: 5 × 10 mil. Off-grid responses, when needed during optimization, can be obtained by linear or quadratic interpolation. The via is analyzed by ***em*** with a grid of 1 × 1 mil. All the other parts including the microstrip line sections and the open ends are analyzed using the empirical models in OSA90/hope [6]. The results are then connected through circuit theory to obtain the responses of the overall filter.

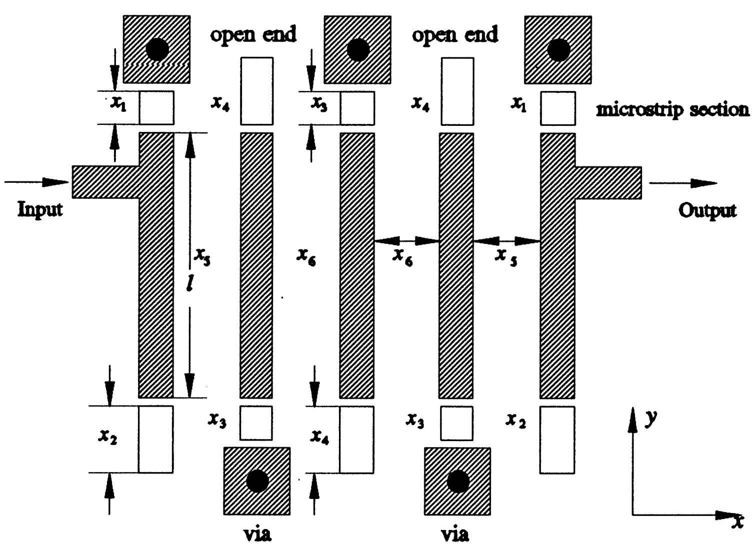

Fig. 2. A coarse model of the interdigital filter using decomposition.

Using the coarse model it is possible to obtain the S-parameter response of the filter in less than 1 CPU minute per frequency point on a Sun SPARCstation 10. Since the coarse model retains most of the adjacent and non-adjacent couplings, it provides reasonably accurate results at dramatically faster speed.

The design variables x_1, x_2, ..., x_6 are also shown in Fig. 2. These include the two gaps between the resonators and the four lengths of microstrip lines from an appropriate position of a resonator to its ends. The size of the vias is fixed. The dimensions of the fine model are determined according to the parameter values.

IV. NUMERICAL RESULTS

To demonstrate our design methodology, we optimize an interdigital filter design with respect to the following specifications:

Passband cutoff: f_1 = 4.9 GHz, f_2 = 5.3 GHz	Passband ripple: r = 0.1 dB
Isolation bandwidth: BWI = 0.95 GHz	Isolation: DBI = 30 dB

The order of the filter can be determined to be 5 according to Matthaei *et al.* [7]. We choose 15 mil thick alumina substrate with ε_r = 9.8. The width of each microstrip is chosen to be 10 mil for a good quality factor. The length of each resonator is a quarter wavelength. All other dimensions including the gaps and the positions of the tapped lines are obtained by synthesis techniques [7].

First, we optimize the filter using the coarse model. A minimax solution x_{os}^* is obtained. We check this coarse model solution using the fine model. The EM simulation results using the fine model at a few selected frequencies are shown in Fig. 3. Not surprisingly, the fine model responses deviate significantly from the optimized coarse model responses. The passband return loss is only about 11 dB. Also, notice that in the lower stopband near 4.7 GHz the insertion loss is about 8.5 dB, which means the bandwidth is widened. This is most likely due to the fact that some of the couplings between resonators in Fig. 1 are not taken into account by the coarse model of Fig. 2.

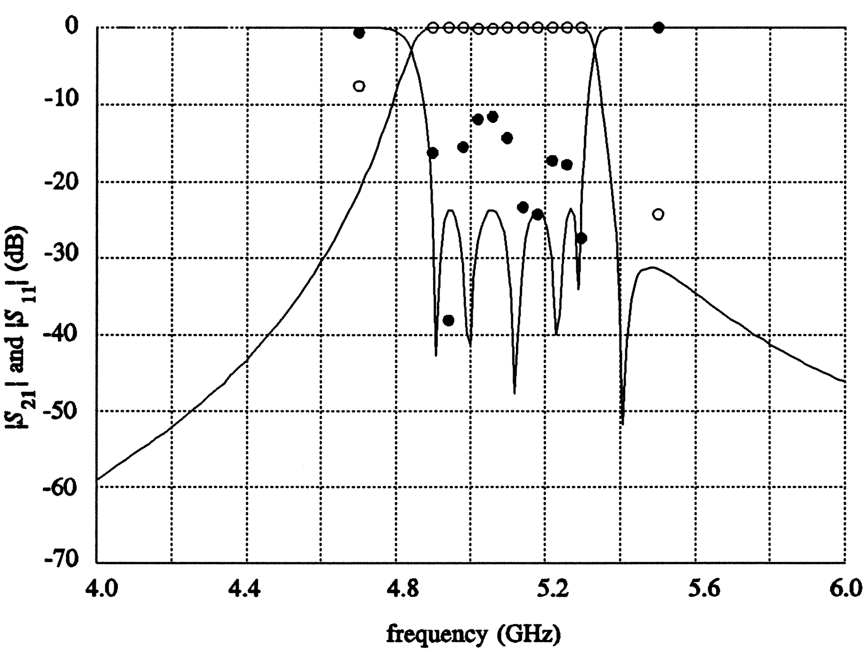

Fig. 3. The solid lines represent the optimized $|S_{11}|$ and $|S_{21}|$ responses of the coarse model at x_{os}^*. The circles represent the fine model responses (○ ○ ○ $|S_{21}|$, ● ● ● $|S_{11}|$).

The SM optimization starts with $x_{em}^{(1)} = x_{os}^*$. After the first iteration, a new point $x_{em}^{(2)}$ in the X_{em} space is obtained. The fine model responses of this new point are compared with the coarse model optimal responses in Fig. 4. It shows significant improvement over the starting point. With this iteration, we have achieved two major accomplishments. The scattered points of the return loss have been improved and the bandwidth has been reduced on the lower frequency side.

Another iteration of SM is performed. The fine model responses after this iteration are shown in Fig. 5, where we have included the conductor and dielectric losses in the simulation. Clearly, we have achieved an excellent design. The passband return loss is better than 18.5 dB. Only 3 EM simulations of the fine model are needed.

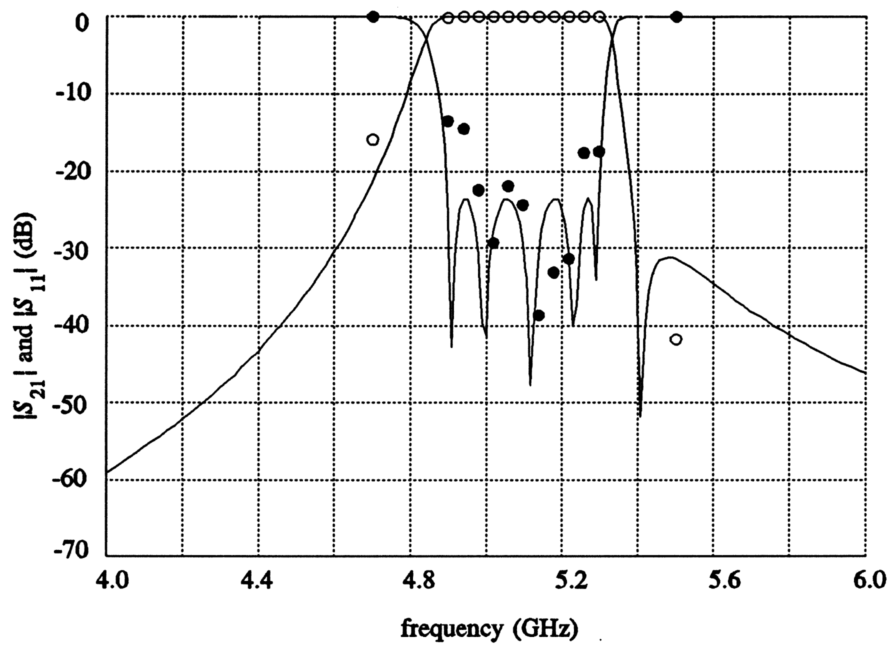

Fig. 4. The fine model responses calculated by ***em*** (○ ○ ○ $|S_{21}|$, • • • $|S_{11}|$) after the first aggressive SM iteration. The solid lines represent the optimized responses of the coarse model at x_{os}^*.

V. CONCLUSIONS

We have presented a new design methodology for EM optimization. A coherent framework has been developed to combine the power of the aggressive SM strategy and the decomposition technique. An intelligent decomposition approach has enabled us to construct highly efficient coarse models to carry out the bulk of the computational loads speedily. With a few carefully aligned fine model simulations, we were able to map the optimized solution from the coarse model space into the fine model space.

Our new approach has been demonstrated through the EM design optimization of an interdigital filter. The results have shown that rapid and significant improvements have been achieved after each iteration. A properly aligned design with desirable responses has been obtained after just 3 fine model EM simulations. Furthermore, we have been able to select only 13 frequency points for the fine model simulation, far fewer than would have been needed for a direct optimization of the fine model responses over the same frequency band. In fact, the total EM simulation effort in our design is equivalent to a single fine model EM simulation with 39 frequency points. It means that with a proper strategy one can execute EM optimization of practical designs with essentially the same magnitude of effort as that of a detailed EM simulation.

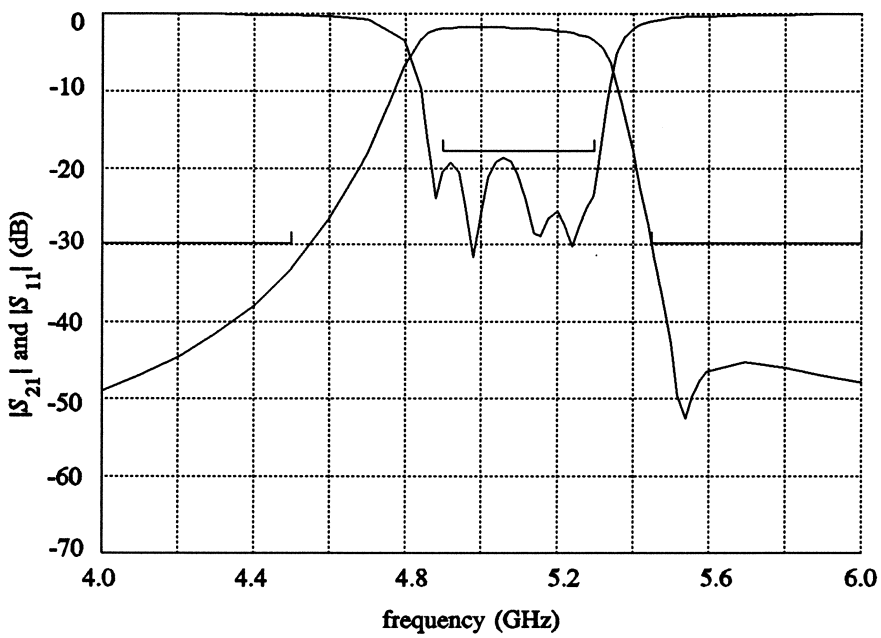

Fig. 5. The fine model responses calculated by ***em*** after two aggressive SM iterations. Dielectric and conductor losses are included in the EM simulation.

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