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Automated design of waveguide filters using Aggressive Space Mapping with a segmentation strategy and hybrid optimization techniques

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***Abstract*— Microwave waveguide filters are key elements present in many communication systems. In recent times, increasing efforts are being devoted to the development of automated Computed Aided Design (CAD) tools of such devices. In this paper a novel CAD tool which improves the efficiency and robustness of the classical Aggressive Space Mapping (ASM) technique is presented. The use of a new segmentation strategy and the hybridization of various optimization algorithms is proposed. The CAD tool has been successfully validated with the design of a real H plane filter for an LMDS application.**

I. Introduction

Microwave waveguide filters are key devices in the equipment of many telecommunication systems, such as communication satellites, mobile communication systems and radio links [1]. Over the past years, the extremely fast development of precise electromagnetic tools, as well as the increase in the computation capabilities of modern computers, have made possible the accurate simulation of very complex waveguide structures in reduced computation times. However, from a designer point of view, more efforts should be devoted to the integration of such fast and accurate simulation tools into automated Computer Aided Design (CAD) tools. This topic is receiving a considerable attention in the recent literature [2].

The accurate design of electromagnetic structures requires a trade-off between accuracy and computation time. When designing complex structures the use of an accurate simulation tool can be unaffordable. The well-known Aggressive Space Mapping (ASM) technique [3] can then be used to reduce the computational burden by using two different simulation tools: an efficient but not very accurate tool (*coarse model*) in the optimization space (OS), and an accurate but not very efficient tool (*fine model*) in the validation space (VS). This procedure moves the computational burden to the OS, thus reducing the overall computation time, while the accuracy is still guaranteed by the use of the *fine model*.

The traditional parameter extraction procedures operate on all the rectangular waveguide parameters at the same time [4]. When designing complex structures, such as inductively coupled filters, with a high number of design parameters, the speed and robustness of the optimization process can be greatly improved by decomposing the structure as recently proposed in [5]. This new technique takes profit of the particular nature of the structure under design by dividing the parameter extraction process into a number of simple steps. In each step there is only a small number of design parameters so that the efficiency and robustness of the overall design process is increased. Moreover, the design process can still be improved in each step if a suitable combination of several optimization algorithms is used instead of using a single all-purpose technique, such as genetic algorithms [6].

In this work a novel CAD tool for the design of waveguide filters is presented. This tool implements the ASM technique, where the same modal simulator has been used in the OS and VS for designing rectangular waveguide filters. In each space the different accuracy and efficiency is achieved by using a different number of guided modes and Method of the Moments (MoM) basis functions. The use of a new segmentation strategy together with hybrid optimization is proposed in this work in order to improve the performance of ASM. These extensions to ASM have been implemented into the CAD tool, and its performance has been tested with the design of several H plane filters. Proceeding in this way, the overall design time has been reduced by a factor of 7 due to the use of the segmentation strategy, and by a factor of 2 thanks to the hybrid optimization. The robustness and quality of the final design is also improved. A real filter for use in an LMDS signal distribution system has also been designed and manufactured, and the measurements are successfully compared to the results provided by the CAD tool.

II. Parameter Extraction

The parameter extraction consists on finding the design parameters Φ that minimize an objective function $U(\Phi)$ that evaluates the difference between the response of our EM model and an objective response. The ASM requires two different types of parameter extraction procedures. In the first place, a parameter extraction must be performed in order to obtain x_{OS}^*, the optimum point in OS. This procedure minimizes the difference between the coarse model response $R_c(x_{OS}^*(\Phi))$ and an ideal response which satisfies the specifications of the

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filter that we are designing (Θ). Next, a parameter extraction must be performed in each ASM iteration in order to find the point $x_{OS} = P(x_{EM})$ that minimizes the difference between the coarse model response x_{OS} and the fine model response to x_{EM}.

A. Objective function

In order to improve the robustness and the efficiency of the optimization process, the authors have experienced that the objective function should be defined as follows

$$
\begin{aligned}
U &= \alpha_{11}\, U_{11} + \alpha_{21}\, U_{21} \\
U_{ii} &= \|\omega \cdot U_{ii}\|_H = \sum_n \left(\omega^n \rho_k(U_{ii}^n)\right) \\
U_{ii}^n &= \begin{cases} \left|\frac{\rho_k(e^n(\Phi))}{X^\Theta}\right| & \text{if } X^\Theta \in [X_d, X_u] \\ 0 & \text{if } X^\Theta \notin [X_d, X_u] \end{cases} \\
\rho_k(f) &= \begin{cases} f^2/2 & \text{if } |f| \le k \\ k|f| - k^2/2 & \text{if } |f| > k \end{cases} \\
e^n(\Phi) &= \left|X^s - X^\Theta\right| \\
X^s &= 20\,\log_{10}\left(|S_{ii}^s(f^n, \Phi)|\right) \\
X^\Theta &= 20\,\log_{10}\left(|S_{ii}^\Theta(f^n, \Phi)|\right)
\end{aligned}
\tag{1}
$$

where S_{ii}^Θ is the ideal response, S_{ii}^s is the simulated response, α_{ii} is the weight of the error function related to the S_{ii} scattering parameter, $\|\cdot\|_H$ is the Huber norm, $\rho_k(f)$ is the Huber function [7], f^n is the n-th frequency point, k is a positive constant, and w^n are weighting coefficients that are used to give priority to some frequency intervals. X^d and X^u are lower and upper limits to the objective function that avoid the possible existence of huge errors at some frequency points when using logarithmic scale, i.e. at the position of the zeros. The upper limit is always set to 0 dB, and the lower limit is set to $-\infty$ dB for the transmission coefficient S_{21} and $-2\,L_R$ for the reflection coefficient S_{11}, L_R being the maximum return loss of the filter specifications in the pass band. If these limits where not applied, the optimization process would be distorted as we would try to fit the simulated and ideal responses at very low levels (even below the accuracy of the simulation tool) at the expense of not fitting properly the responses at higher levels. The normalization of the error function e^n avoids the excessive contribution to the overall error of small differences at low reflection or transmission levels when there is no normalization.

The ideal response, Θ, that satisfies the specifications of the filter response is obtained using an equivalent network, based on ideal impedance inverters and half-wavelength transmission lines, proposed in [8].

III. Segmentation Strategy and Hybrid Optimization Techniques

A. Segmentation

The design of an inductive filter with N cavities and $N+1$ coupling windows is divided into several steps, as proposed in [5]. Basically, the ordinary step of this strategy consists on designing at each step i only the parameters related to the i-th cavity (dimensions of that cavity and some of the previous one), and using for the rest of the dimensions of the $i-1$ first cavities the values obtained in the former iterations. At each step i only the the transmission coefficient S_{21} of the first i cavities is computed and compared with an objective response for that structure. This segmentation technique transforms a slow multidimensional design process into several efficient and robust design steps where a small number of parameters are designed at the same time. There is the risk, however, that the coupling among all cavities (not just among adjacent cavities) is not properly designed due to the segmentation strategy.

This problem has been solved in this work adding new steps to the segmentation technique:

Coupling Step. Each time that three consecutive cavities have been designed, a new parameter extraction process adjust at the same time all the design parameters of the i first cavities. This achieves the required small changes in the values of the parameters due to cavity coupling. In this step the S_{21} coefficient is used again in the construction of the error function.

*Central cavity step.*For symmetric filters, when the central cavity is reached, and the first half of the filter has been designed step by step, a new optimization is performed where the whole structure of the filter is simulated at the same time, so that the design of the dimensions of the central cavity is finely adjusted considering the coupling among all cavities. The error function is computed comparing only S_{21}.

Full structure step. A final step is made in order to refine the design and take into account all possible interactions among cavities. The whole filter is simulated and all the dimensions are designed at the same time, being the starting point the result of the previous steps. As we are near the minimum, the reflection coefficient S_{11} is used to construct the error function.

B. Hybrid optimization

The efficiency and robustness of the design process has been improved in each step of the segmentation strategy using a suitable combination of optimization algorithms instead of using a single one. The following optimization methods have been used:

1) Direct Search with Coordinate Rotation (DSCR): We have developed in this work a variation of the methods described in [9] and [10]. In this work the step length after each coordinate rotation iteration is set according to the distance advanced in that iteration. If no advance has been made, the step length is increased in order to explore farther regions. Furthermore, in the direct search iteration across a line, only steps that reduce the error function are accepted.

2) Downhill simplex method: This well-known method [11] performs better than DSCR when we are not very close to the minimum, but worse than gradient methods when we are very close. Some simplex algorithms form the new vertexes of the initial simplex adding a fix quantity to each coordinate of the starting point [12]. When the design parameters are not equal range, it is better to form the new vertexes of the initial simplex adding a percent increase on each coordinate of the starting point, as we have done in this work.

3) Broyden Fletcher Goldfarb Shanno (BFGS): The BFGS method [12] combines the advantages of the Steepest descent and the Newton-Raphson methods. The implementation of this method used in this work includes a restart at each iteration where there is no significant change in the gradient of the error function, as happens in some practical situations in filter design where the error function is locally a tilted plane and the standard BFGS stops before reaching the minimum. In the implementation used in this work the restart enables the advance in the steepest descent direction in the next iteration, going down the tilted plane.

4) Hybridization: The most suitable combination of optimization algorithms depends on the confidence that we have on the proximity of the starting point to the minimum. Therefore, at each step of the segmentation strategy a different hybridization of algorithms is used:

Ordinary step. The optimization starts with the DSCR algorithm in order to approach the minimum. This search is then continued with the simplex method. At this point we are close to the minimum, and the BFGS method is used.

Coupling step. In this case we must be near to the minimum, so only a BFGS optimization is performed.

Central cavity step. Two optimization algorithms are used (simplex and BFGS) since the starting point is probably not close enough to the minimum to use only a gradient-based algorithm.

Full structure step. As we are near the minimum, the simplex and BFGS algorithms are used to minimize the error.

IV. Results

The novel CAD tool implemented in this work has been applied to the design of a symmetric inductively coupled rectangular waveguide filter. The ideal transfer function is a standard seven-pole Chebyshev response of 300 MHz bandwidth and 0.02 dB ripple centered at 17.55 GHz. The cavity lengths and coupling aperture widths of the filter have been chosen as design parameters. The input and output waveguides of the filter, as well as the resonant cavities, are standard WR-62 waveguides (a=15.80 mm, b=7.90 mm). The length of all the coupling windows is 3.60 mm. All the weight coefficients w^n in (1) has been set to 1, so that no frequency interval has been given priority. The k constant in the Huber function has been chosen equal to 5, in order to accelerate the convergence of the optimization process.

The inductive filter was also designed with ASM and hybrid optimization, but not using the segmentation strategy. The same design was repeated without ASM in a Pentium IV at 2.4 GHz. Table I shows in each case the computation time, the value of the objective function in OS for x^*_{OS}, and the termination error for ASM $\|P(x_{EM})-x^*_{OS}\|_2$, clearly showing that the use of segmentation improves the robustness of the whole design procedure. In fact, and spite of using the same initial point, the two optimizations performed without segmentation converged to a local minimum far from the optimum solution. Therefore, the CPU time obtained in the different cases studied reveals that there is an important increase in the efficiency due to the segmentation strategy proposed (around 8 times faster than the design without segmentation if we use ASM and 26 times faster if ASM is not used).

TABLE I

Segmentation + Hybrid + ASM		
Time(s)	$U(x^*_{OS})$	$\|P(x_{EM})-x^*_{OS}\|_2$
175 s	0.0240857	0.00267937

Hybrid+ASM		
Time(s)	$U(x^*_{OS})$	$\|P(x_{EM})-x^*_{OS}\|_2$
1341	6.11255	9.66854

Segmentation+Hybrid		Hybrid	
Time (s)	$U(x_{EM})$	Time (s)	$U(x_{EM})$
215	0.0467588	5627	71.972

In order to prove the advantages of the use of the hybrid optimization technique, the inductive filter was designed using only one optimization algorithm in each step of the segmentation strategy. Table II shows a comparative study in terms of the CPU time required and the value of the error function in each case. The results reveal that the use of hybrid optimization also improves the efficiency and accuracy of the whole design process (the design procedure based on the hybrid optimization technique is at least 2 times faster than using a unique optimization algorithm).

TABLE II

Hybrid+Segmentation		Coordinate Rotation+Segmentation	
Time(s)	$U(x^*_{OS})$	Time(s)	$U(x^*_{OS})$
69	0.0240857	110	5.50028

Simplex+Segmentation		BFGS+Segmentation	
Time(s)	$U(x^*_{OS})$	Time(s)	$U(x^*_{OS})$
138	0.0214008	133	1.77161

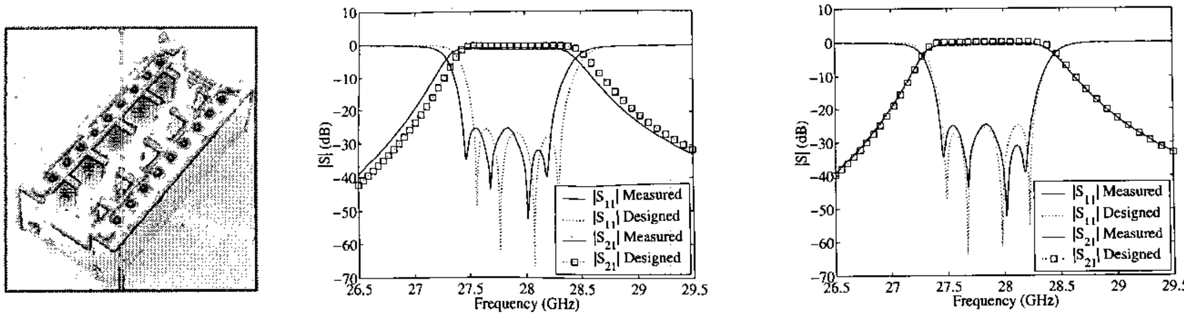
Simple Genetic Algorithm + Segmentation	
Time(s)	$U(x^*_{OS})$
14221	14.4553

TABLE III

Segmentation + Hybrid + ASM	Segmentation + Hybrid
175 s	215 s

The inductive filter was also designed using directly the fine model (accurate simulation tool) and not using ASM. In both cases the segmentation technique and the hybrid optimization technique have been used. The results in table III show that the use of ASM does not significantly reduce the overall design time. This is due to the fact that we are designing simple structures and our simulation tool is very fast in the VS. In the case that we were designing more complex structures or the simulation tool in VS were not so fast, the time improvement of ASM would be more significant.

The CAD tool has been finally used for the design of a 4-pole microwave filter in the 28 GHz band. The bandwidth



(a) Longitudinal section (b) Before tolerance analysis (c) After tolerance analysis

Fig. 1. Manufactured prototype of an LMDS filter at 28 GHz

of this filter is 600 MHz and it is used as a part of a receiver in an LMDS distribution system. The input and output waveguides of this filter are standard WR-28 (a=7.112 mm, b=3.556 mm), whereas the cavities widths are all equal to 8.636 mm (non-homogeneous structure). The length of all the coupling windows is 2.5 mm. The lengths of the cavities and the widths of the coupling windows have been chosen as the design parameters. A prototype of the LMDS filter was manufactured in order to validate the design. Figure 1(a) shows a longitudinal section of the prototype, where the cavities and coupling windows of the inductive filter can be appreciated. A comparison between the simulated response of the designed filter and the measurements of the manufactured prototype is shown in figure 1(b). A slight deviation between the theoretical and measured results of 80 MHz can be appreciated. This deviation is due to the mechanical tolerances of the manufacturing process. The dimensions of the prototype were precisely measured, and a typical deviation of +15 microns was observed in all the waveguide dimensions. The real dimensions of the prototype were used in the CAD tool, thus providing a closer response to the measurements, as shown in figure 1(c).

V. Conclusion

An efficient and accurate CAD tool for the automated design of waveguide filters has been presented in this paper. The CAD tool improves both the efficiency and robustness of ASM using a new segmentation procedure and a suitable hybridization of several optimization algorithms. The performance of these extensions to ASM has been tested with the design of several H plane filters, showing that the overall CPU time is reduced approximately by a factor of 14 with regard to classical ASM implementations. Finally, this novel CAD tool has been applied to the design of a real LMDS filter at 28 GHz. A prototype has been manufactured and measured, thus proving the reliability of the tool developed. The aim of the authors is to use this tool in the automated design procedure of more complex passive waveguide structures, such as evanescent mode filters, corrugated filters, filters with dielectric posts, low cost manufactured filters (with rounded corners), and manifold diplexers and multiplexers.

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