AUTOMATED DESIGN OF MICROWAVE DEVICES USING FULL EM OPTIMIZATION METHOD

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Abstract- A relevant automated electromagnetic (EM) optimization method is presented. This optimization method combines a rigorous and accurate global EM analysis of the device performed with a finite element method (FEM) and a fast analytical model deducted from its segmented EM analysis. First we describe our automated optimization method with the definition of the analytical model, then we apply it to optimize two volumic dielectric resonator (DR) filters. The accuracy of this automated method is demonstrated considering the good agreement between theoretical optimization results and experimental ones.

I. INTRODUCTION

Recent advances in microwave computer aided design (CAD), growing computer capabilities and new available tools suggest designers to implant electromagnetic (EM) simulators in optimization system loops in order to develop powerful automated hybrid EM-CAD optimizers [1], [2], [3].Generally complex microwave devices are analyzed applying analytic or EM methods. Typical analytic simulators have the advantage to be fast but they do not allow rigorous studies of whole complex devices. These structures are divided into several segments which are modeled independently from each other. But the device response defined with the combination of all the segments responses cannot take into account the indirect coupling between the segments which occur at microwave frequencies. This problem is overcame with rigorous and global EM methods which consider all physical phenomena and electrical properties in the whole device to establish its response. So, these methods give accurate results but requires a lot of memory space and time and also are not used for direct optimization of complex devices. Memory can be saved applying a segmented EM analysis of the device. In this case the device is split in several segments which are characterized by their generalized [*S*] matrices. Of course the accuracy of the method depends on the structure complexity and on the number of modes preserved between segments. This method is already commonly used in our laboratory, and theoretical results obtained show good agreement with experimental ones [4]. Nowadays, the new tendency is to integrate EM simulations into circuit design processing and also perform hybrid EM- CAD optimizations. In the general case, the developed optimization methods combine a rigorous EM analysis of the device (such as the method of moments, the finite difference or the finite elements analyses) in spectral or time domains ; and a fast circuit model of the same device based on element libraries defined by decomposition, space mapping, neural networks or relevant numerical techniques. With respect to space mapping for example, the automated hybrid optimization method presented in this paper does not use an empirical model of the device, but it combines a segmented EM analysis and a global EM analysis applying a finite element method software. This software which has been presented in several papers [5], permits rigorous three dimensional EM analysis of complex microwave structures in the frequency domain in free or forced oscillations. Theses structures can be closed by electrical wall conditions and/or distributed access or open using absorbing layers. They may be composed of linear media, isotropic media or not, with dielectric and metallic losses or not. Our finite element software allows to define the resonant frequencies of the structure, the Q factor, couplings between elements, the EM field distribution and/or the scattering matrix between structure access. It can be applied to characterize components and to design complex passive or passive/active devices, introducing active domains using lumped access [4].

Applying our optimization method, we first divide the studied structure into several segments. For each segment, the corresponding generalized [*S*] matrix is established applying the FEM. Then, these matrices are approximated using neural networks or a data base to define analytical models. These models are implanted in a circuit simulator and are chained together to define an analytical model of the whole device. The analytical

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model we define, permits to explore rapidly different optimization starting points in order to obtain the device basic dimensions and afterwards, to correct these dimensions for each iteration of the structure optimization applying the global EM analysis. We can note here that this optimization method performs all segmented and global analyses applying EM methods. In the first part of this paper, we describe the optimization method, then in the second one, we apply it to design two dielectric resonator (DR) filters. Finally, comparisons between theoretical and experimental results show good agreement.

II. Description of the Optimization Method

Our hybrid optimization may be applied to design a wide range of passive and/or active microwave devices such as volumic or monolithic microwave integrated circuits (MMIC) structures. We first present the optimization method then we apply it to design two DR filters in order to demonstrate its feasibility.

Step1) : The first step of our method is to define an analytical model of the device in physical and geometrical optimization domains. According to the complexity of the device, the structure is divided in several segments Si which are characterized by their generalized matrices [*Si*] using the FEM. The generalized [*S*] matrices are computed using a number of modes such as we keep a good balance between the number of modes and a correct agreement between the segmented EM analysis and the global EM analysis. Then each matrix [*Si*] is approximated applying a software based on neural networks [6], and is implanted on a commercial circuit software to define an analytical element for each segment Si. Then these elements are chained together to define an analytical model of the whole device. At least the whole device analytical response named $R_A[\Phi_A{}^{(1)}{}_j, \Phi A^{(2)}{}_j ...]$, where $\Phi_A{}^{(1)}{}_j$, $\Phi_A{}^{(2)}{}_j$... are the analytical parameters, is established.

Step2) : In the second step, the basic dimensions are defined applying the analytical model, from the filtering pattern fixed by the designer. In this way, we perform optimizations using the analytical model, and its basic response $R_A[\Phi_A{}^{(1)}{}_0, \Phi_A{}^{(2)}{}_0 ...]$ which agrees the filtering pattern, becomes the objective response named R_{OBJ}. Then we will have to satisfy R_{OBJ} using the global EM analysis to end the optimization.

Step3) : In the last step, the whole device is analyzed applying the global FEM. The first EM global response named $R_G[\Phi_G{}^{(1)}{}_0 = \Phi_A{}^{(1)}{}_0, \Phi_G{}^{(2)}{}_0 = \Phi_A{}^{(2)}{}_0 ...]$, is established, where $\Phi_G{}^{(1)}{}_0$, $\Phi_G{}^{(2)}{}_0$... are the global analysis parameters. Then $R_G[\Phi_G{}^{(1)}{}_0, \Phi_G{}^{(2)}{}_0 ...]$ is compared with R_{OBJ}, and if R_G disagrees, a mathematical link T is established between the different parameters as well as :

$$R_A[\Phi_A{}^{(1)}{}_{j+1}, \Phi_A{}^{(2)}{}_{j+1} ...] = R_G[\Phi_G{}^{(1)}{}_j, \Phi_G{}^{(2)}{}_j ...],$$

$$\text{with } [\Phi_A{}^{(1)}{}_{j+1}, \Phi_A{}^{(2)}{}_{j+1} ...] = T[\Phi_G{}^{(1)}{}_j, \Phi_G{}^{(2)}{}_j ...],$$

Then the global parameters are determined for another optimization iteration applying the opposite link T^{-1} :

$$[\Phi_G{}^{(1)}{}_{j+1}, \Phi_G{}^{(2)}{}_{j+1} ...] = T^{-1}[\Phi_G{}^{(1)}{}_j, \Phi_G{}^{(2)}{}_j ...],$$

We proceed the loop presented on the optimization chart on Fig.1 as long as the objective response R_{OBJ} is not satisfied by R_G.

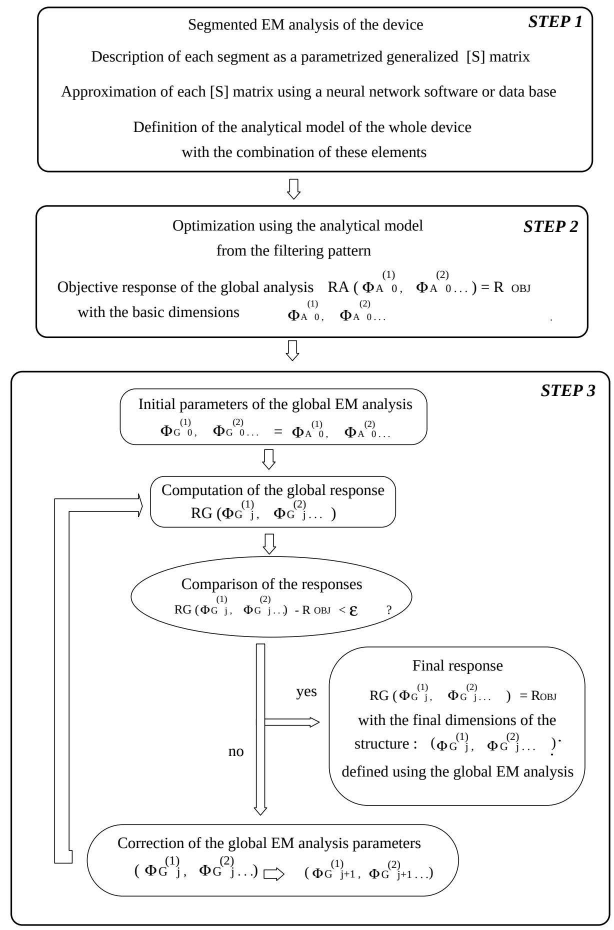

Fig.1. Optimization chart

III. Microwave Filter Design Applying the Hybrid Optimization Method

Our optimization method is applied to design two volumic DR filters but the same approach is possible with other microwave devices.

A. *Single pole filter* :

The first example we present to demonstrate the optimization method feasibility is the design of a volumic filter composed of a cylindrical dielectric resonator embedded in a teflon support and adjusted in a cylindrical metallic cavity. The structure is excited with two input/output rectangular irises connected to standard rectangular waveguides. The device is presented on

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Fig.2. Applying our optimization technique described here, this device is first split in two independant segments. Then the generalized [*S*] matrix of the segment S_1 is defined as a function of the iris length (L_I) which determines the input/output coupling and of the frequency (*f*). The generalized [*S*] matrix of the segment S_2 is established as a function of the dielectric resonator height (H_{DR}) which determines the central frequency of the filter and of the frequency (*f*). In order to compute the generalized [*S*] matrices, four modes are required at the segmentation plane between S_1 and S_2 to obtain similar responses between the segmented EM analysis and the global one. These functions are approximated with a neural network software [6] in order to define an analytical element for each segment. The analytical model defined by the combination of these elements, characterizes the considered device with its analytical response $R_A[L_{IAj},H_{DRAj}...]$ and its analytical parameters L_{IAj} and H_{DRAj}. The filter analytical model permits to define the objective response $R_{OBJ} = R_A[L_{IA0},H_{DRA0}...]$, and to determine the basic dimensions L_{IA0} and H_{DRA0}. Then the global EM response $R_G[L_{IG0},H_{DRG0}...]$ is established, with $L_{IG0} = L_{IA0}$ and $H_{DRG0} = H_{DRA0}$. The global EM response is compared with the filtering pattern (equivalent to R_{OBJ}) and as long as it disagrees the global EM parameters are modified as below :

$$L_{IGj+1} = L_{IGj} - (L_{IAj+1} - L_{IG0})$$

$$\text{and } H_{DRGj+1} = H_{DRGj} - (H_{DRAj+1} - H_{DRG0}).$$

In our case, the filter dimensions are optimized in order to obtain a transmission response characterized by a central frequency equal to 4.25GHz and a 30MHz bandwidth at -3dB. The optimization of the analytical model gives the following basic dimensions :

$$L_{IA0} = 22.47\text{mm and } H_{DRA0} = 5.8\text{mm}.$$

After an EM optimization of the whole device applying only 2 iterations, the final values of the optimized dimensions are given by :

$$L_{IG2} = 22.00\text{mm and } H_{DRG2} = 6.0\text{mm}.$$

The computing time is around 20min for each iteration on a HP735 workstation. The filter is then built and tested. We can see the complete optimization example and the good agreement between theory and experimentation on Fig. 3. In fact, the difference between theoretical and experimental frequencies is equal to 0.2%, and for the bandwidth at -3dB, the error is under 2%.

B. *Dual mode filter :*

The second filter we study is presented on Fig. 4. The notched DR is excited on its first hybrid $HEM_{11\delta}$ dual mode. The two polarizations of the mode are coupled with a rectangular notch placed at 45 degrees angle from the excitation axes. The notch placed in the DR permits to couple the two polarizations of the mode and to obtain a dual mode filter [7]. To apply our optimization method, this device is divided into several segments.

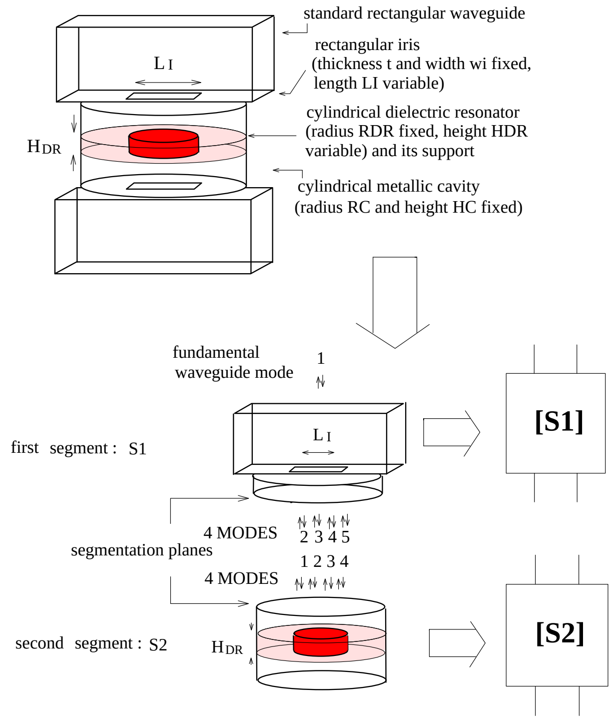

Fig.2. Single pole filter

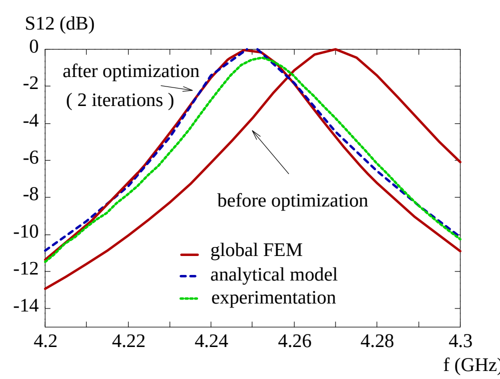

Fig.3. Complete optimization and experimentation of the single pole filter

The first generalized [*S*] matrix [S_1] is already a function of the iris length (L_I) and of the frequency (*f*). The second one [S_2] is a function of the DR height (H_{DR}) and of the frequency (*f*) and now we add an other parameter, the notch depth (D_N) which rules the coupling between the two polarizations of the dual mode filter. The generalized [*S*] matrices are computed using fourteen modes at the segmentation planes in order to limit the number of modes and to keep a correct agreement between the segmented EM analysis. In the first step, we determine L_{IA0} , D_{NA0} and H_{DRA0} in order to initialize the global EM analysis. As in the first example, for each optimization iteration we compute the corrected global EM parameters :

$$L_{IGj+1} = L_{IGj} - (L_{IAj+1} - L_{IG0})$$
$$D_{NGj+1} = D_{NGj} - (D_{NAj+1} - D_{NG0})$$
$$\text{and } H_{DRGj+1} = H_{DRGj} - (H_{DRAj+1} - H_{DRG0}).$$

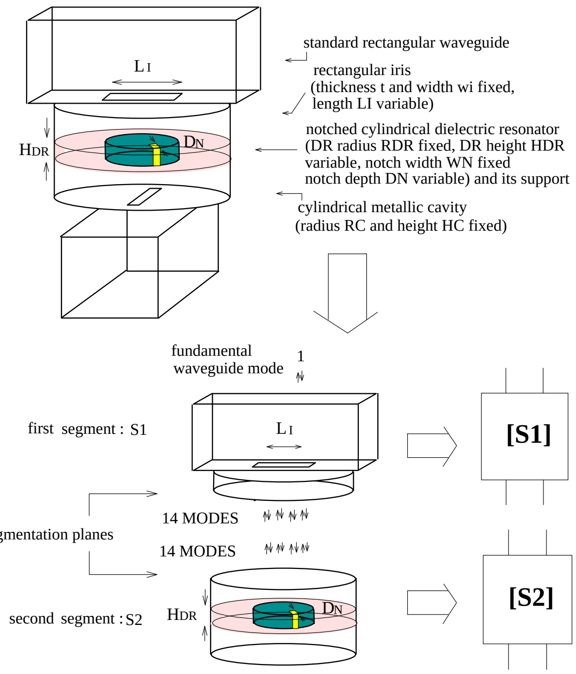

Fig.4. Dual mode filter

The filter dimensions are optimized in order to obtain a transmission response characterized by a central frequency at 4.37GHz and a 30MHz bandwidth at -3dB. The optimization of the analytical model gives the following basic dimensions :

L_{IA0} =22.20mm, D_{NA0} =1.3mm and H_{DRA0} = 5.8mm.

As we can see on Fig. 5, after an EM optimization of the whole device applying two iterations, the final values of the optimized dimensions are given by :

L_{IG2} =23.40mm, D_{NG2} =1.5mm and H_{DRG2} = 6.0mm.

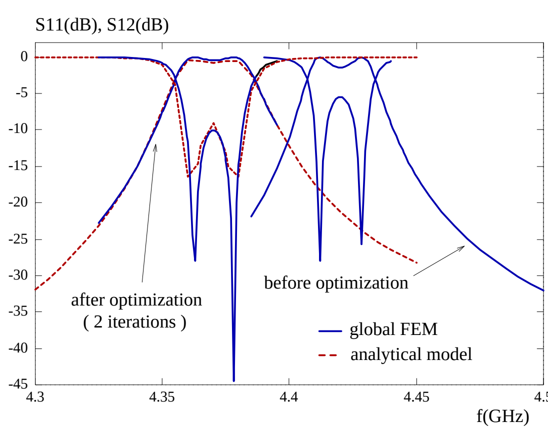

Fig.5. Complete optimization of the dual mode filter

The computing time is around 120min for each iteration on a HP735 workstation. The filter is not tested yet but such topologies were studied in our laboratory and show good agreement between theoretical and experimental results [7].

IV. Conclusion

During these studies, we have developed an hybrid EM optimization based on the combination between an analytical model established from a segmented FEM analysis and a rigorous and accurate global FEM analysis of the device. We have demonstrated the efficiency of this method applied to design two DR filters with few iterations. Moreover, the good agreement between theoretical and experimental results proves the method accuracy. We have now to apply this method to more complex planar (MMIC) and volumic microwave devices, then to establish progressively new library elements for circuit analysis and optimization.

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