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A METHODOLOGY FOR THE DESIGN OF MICROWAVE SYSTEMS AND CIRCUITS USING AN EVOLUTIONARY ALGORITHM

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Abstract—This work presents a methodology for the development of microwave systems and circuits. Starting from the system decomposition, the proposed method is aimed at estimates the requirements of each component of the system taking into account the effects on the whole system and the interactions with the others microwave components. The obtained requirements are then used to design or optimize each device with standard design methodologies or CAD tools. The problem is recast as an optimization one by defining a suitable cost function able to take into account the interactions between all the components of the system. The cost function is then minimized with an evolutionary optimization technique, namely the particle swarm optimizer. The obtained preliminary results, concerning the design of a broad-band bidirectional amplifier, demonstrate the potentialities of the proposed approach.

1. INTRODUCTION

The design of complex microwave circuits and systems is mandatory in several important areas for civil and military telecommunication systems, industrial and medical equipments. The conventional microwave design techniques are quite effective for the design of basic microwave active as well as passive devices [1–4], but these techniques are not able to models the interactions between the different

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components of the system with efficacy. The design of complex microwave systems usually requires complex design techniques, high level of expertise, microwave models, and a final tuning phase that could dramatically increase the costs and the time to market of the device, and increase the number of design/fabrication cycles. In this framework microwave CAD tools [5, 6] offer a possible solution to reduce the time to market. In fact, these tools can analyse, design and modify, microwave devices in an unsupervised manner. Certainly they can't completely replace an experienced microwave engineer but they can help the designer to strongly reduce the time necessary to design a complex microwave system/circuit. Since that CAD tools are able to reduce the computational time typical of the standard design/fabrication methodologies, in recent years CAD tools [5, 7] have been successfully adopted in many areas of applied electromagnetics, such as antenna design [8, 9], control [10] and other interesting practical applications [11, 12]. In these tools, the design problem is usually recasted as an optimization problem, that can be handled by means of an optimization algorithm and a suitable cost function. The latter represents the distance between the required performances and the obtained trial solution. The trial device performances are analyzed step by step through numerical methods such as FEM, FDTD, and MoM. These design tools usually consist of an optimizer and a commercial numerical simulator, and in recent years they have been integrated into commercial microwave simulators (e.g., Optimetric by Ansoft). In this work we propose a design approach based on a powerful evolutionary technique, the particle swarm optimizer (PSO) [13–16]. In particular the proposed methodology permits to estimate the characteristics of each microwave device, that compose the system, starting from the system requirements. The key of force of this method is that it takes into account the different interactions and coupling phenomena, always present when a complex microwave system or circuit is developed. At the end of the optimization procedure the proposed method provides, not the design of a single device or sub-system (a well known methodology widely used in scientific literature [17–44]) but the requirements of each microwave component mandatory to design they, to made the whole system, and to respect the initial system requirements. For the knowledge of the authors this is the first CAD tool able to provide this objective.

2. DESIGN METHODOLOGY

Let us consider the generic microwave system, shown in Fig. 1, characterized by N ports, and composed by M different heterogeneous

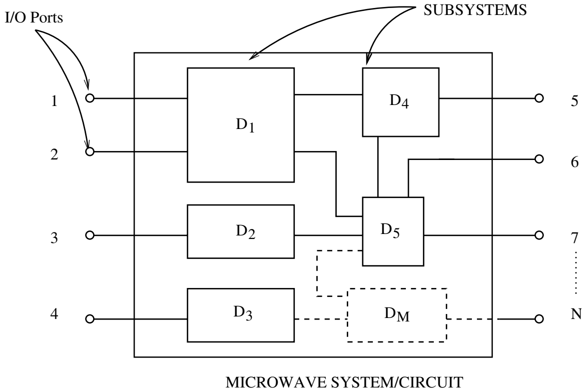

Figure 1. Problem geometry. Representation of a generic complex microwave system/circuit by mean of its M sub-systems and the scattering parameters at the N input/output ports.

microwave sub-systems (i.e., filters, combiners, couplers). The system can be completely described by its scattering matrix:

$$[\mathbf{S}(f)] = \begin{bmatrix} S_{11}(f) & \dots & S_{1j}(f) \\ \vdots & \ddots & \vdots \\ S_{N1}(f) & \dots & S_{NN}(f) \end{bmatrix} \tag{1}$$

where i and j are the indexes of the system ports, and f is the working frequency. A set of constraints, related to the scattering parameters of the device ports and valid for a given frequency range, are expressed with the following set of inequalities:

$$S_{ij}^{\min}(f) \leq S_{ij}(f) \leq S_{ij}^{\max}(f) \quad i, j = 1, \dots, N \tag{2}$$

The first step of the approach considers the general scheme of the system in Fig. 1, the set of constraints (2), and it estimates the following array of unknowns which represents the scattering parameters requirements for each port of the M sub-systems:

$$\boldsymbol{\Psi} = \left\{ S_{p,q}^{m} (h\Delta f)\, ;\ m = 1, \dots, N;\ p, q = 1, \dots, N_m;\ h = 1, \dots, H \right\} \tag{3}$$

where m and M are the sub-system index and the sub-systems number respectively, p, q and N_m are the ports indexes and the ports number of the m-th sub-system. $\boldsymbol{\Delta} f$ and h are the sampling frequency step and the indexes $f = \Delta \cdot f$. In order to satisfy the project guidelines determining the array of unknowns $\boldsymbol{\Psi}$, the problem is recast as an optimization problem. In particular the following cost function, that defines the difference between requirements (2) and the estimated unknowns vector (3), has been considered:

$$\phi^{(1)}\left(\mathbf{\Psi}_k^w\right)=\left\{\sum_{h=1}^{H}\alpha\left[\sum_{i=1}^{N}\max\left[0,\frac{S_{ii}^{trial}(\mathbf{\Psi}_k^w)-S_{ii}^{\max}(h\cdot\Delta f)}{S_{ii}^{\max}(h\cdot\Delta f)}\right]\right]\Bigg|_{i=j}\right.$$
$$\left.+\beta\left[\sum_{i=1}^{N}\sum_{j=1}^{N}\max\left[0,\frac{S_{ij}^{\min}(h\cdot\Delta f)-S_{ij}^{trial}(\mathbf{\Psi}_k^w)}{S_{ij}^{\min}(h\cdot\Delta f)}\right]\right]\Bigg|_{i\neq j}\right\} \quad (4)$$

where α and β are two real constants used to weight the different terms of the cost function (4). In particular the α constant is used to weight the return loss requirement at the ports of the sub-systems, while β has been introduced to control the pass-through characteristics of the sub-systems. $\mathbf{\Psi}_k^w$ is the trial array unknowns (w and k being the trial array index; and the iteration index, $k = 1, \ldots, K$ respectively). To minimize (4) and according to the guidelines given in [12], a suitable implementation of the PSO [13] has been used in conjunction with a circuital generator and a microwave circuital simulator able to take into account all the interactions between all sub-systems. Starting from each of the trial arrays $\mathbf{\Psi}_k^w$ defined by the PSO, the circuital generator changes the scattering parameters of each sub-system and then it generates the corresponding system structure. The corresponding scattering parameters $S_{ij}^{trial}(\mathbf{\Psi}_k^w)$ of the whole system, are computed by means of a circuital simulator, which take into account the presence of dielectric substrate, the mutual coupling effects between all the subsystems, and it is used to estimate the cost function (4). The iterative process continues until $k = K_{\max}$ or when a convergence threshold on the cost function (4) is reached. Then the array $\mathbf{\Psi}_k^w = \mathbf{\Psi}_{opt}$, that contains the requirements for each sub-systems in terms of the scattering parameters is stored and used as starting point for the design of each component of the microwave system. The flowchart of the proposed design methodology is reported in Fig. 2.

3. NUMERICAL RESULTS AND EXPERIMENTAL ASSESSMENT

In this section, to assess the potentialities of the proposed approach, the design of a broad band bidirectional amplifier will be considered. In particular, the characteristics of each sub-system of the amplifier will be estimated. Then the obtained results can be used to design the subsystems by mean of standard design methodologies or suitable CAD tools. The schema of the considered bi-directional amplifier

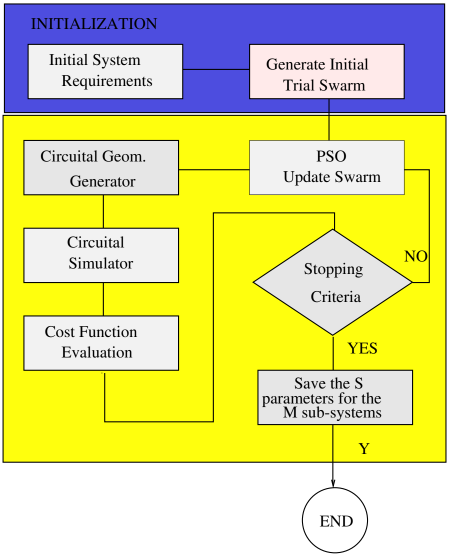

Figure 2. Flowchart of the proposed methodology. The steps enclosed in the blue rectangle represent the initialization, while the steps belonging the yellow rectangle represent the optimization procedure.

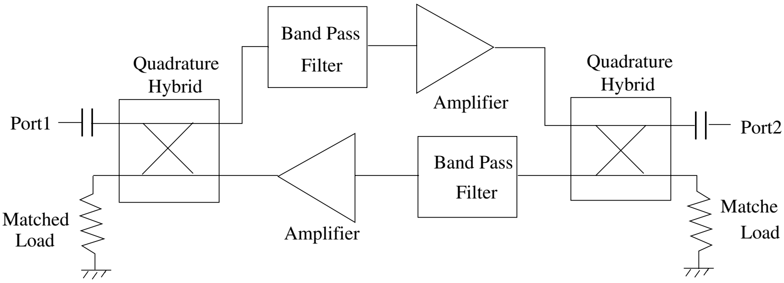

Figure 3. Schema of the broadband bidirectional amplifier, consisting of two MMIC monolitic amplifiers, two microstrip quadrature hybrid rings, and two band pass filters.

is reported in Fig. 2. The amplifier includes the design of two quadrature hybrid rings, two MMIC amplifiers, and two band-pass filters. Mechanical constraints and matching problems, must be taken into account to avoid mutual coupling effects that could strongly afflict the system performances. The amplifier structure is shown in Fig. 3. The bidirectional amplifier must satisfy the following requirements; a gain $G = 10\,\text{dB}$ in both directions, a reflection coefficient $S_{11} = S_{22} < -10\,\mathrm{dB}$ and an insertion loss less than $-3\,\mathrm{dB}$. The considered bidirectional amplifier must be operative in the whole X-band in particular in a frequency range from 9.0 GHz up to 12.0 GHz. As far as the general structure of the considered system is concerned, six different sub-systems have been used. However considering the symmetry of the structure, and the fact that the off-the-shelf commercial amplifier parameters are fixed, only two subsystems have to be characterized (i.e., the filter and the hybrid ring). The scattering parameters at the ports of the two sub-systems, the hybrid ring (four ports) and the filters (two ports), have to be estimated. For the low cost broad band commercial amplifier two NLB300 MMIC amplifiers (RFMD company) have been considered, since they offer good performances in the whole frequency range of interest despite the

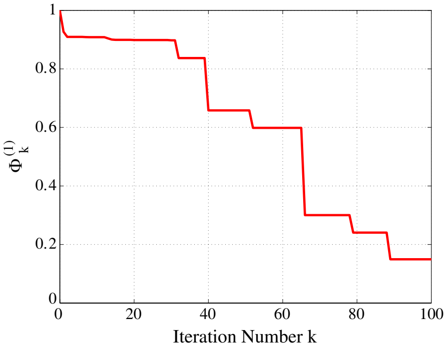

Figure 4. Behaviour of the cost function vs. iteration number obtained at the end of the optimization procedure.

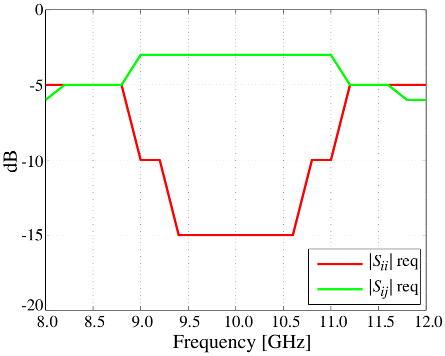

Figure 5. Branchline coupler requirements obtained at the end of the design procedure. The red and green lines represent the reflection coefficient $|S_{ii}|$ and the insertion loss $|S_{ij}|$ requirements respectively.

low-cost. The NLB300 is able to operate in the considered frequency band with a gain of about 10 dB. The measured characteristics of the NLB300 (in terms of scattering parameters) device has been considered in the circuital simulation in order to describe a realistic scenario and they cannot be modified. In particular for the sake of accuracy the measured scattering parameters provided by the RFMD company have been considered during the optimization procedure to correctly estimate the interactions between the different sub-systems. All the sub-systems have been mounted on a ceramic dielectric substrate of thickness $t = 0.8\,\mathrm{mm}$, dielectric permittivity $\varepsilon_r = 3.8$ and $\tan(\delta) = 0.003$. Concerning the PSO parameters, they have been chosen following the guidelines reported in scientific literature in particular a swarm formed by $w = 5$ trial solutions, a constant inertial weight of 0.2, and a maximum number of iterations equal to $K = 100$ have been considered. Also the remaining parameters of the PSO have been set, according to the reference literature [12]. Fig. 4 shows the plot of the cost function (4) versus the iteration number. The optimization required approximately a CPU time of about 0.6 s for each iteration for a total computational time of about one minute, necessary to estimate the requirements of all sub-systems. The results obtained at the end of the procedure are reported in Figs. 5 and 6 respectively. In particular Fig. 5 reports the requirements of the hybrid ring and Fig. 6 the filter requirements. Starting from the requirements reported in Figs. 5 and 6, two multi-arms quadrature hybrid rings and two stepped impedance passband filters have been designed with microstrip technology on a ceramic substrate. The design methodology also provides the distance d between the direct and reverse path necessary to keep low the mutual coupling between the two

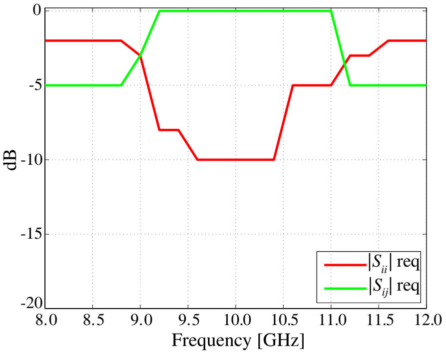

Figure 6. Filter requirements obtained at the end of the design procedure. The red and green lines represent the reflection coefficient $|S_{ii}|$ and the insertion loss $|S_{ij}|$ requirements respectively.

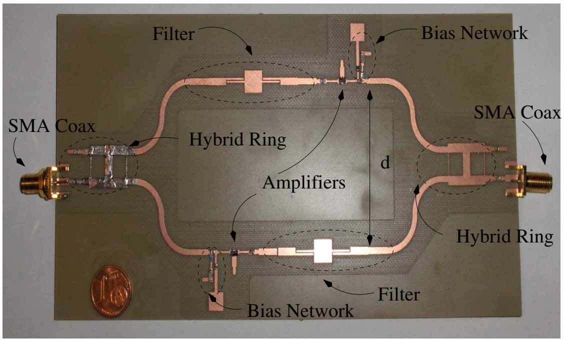

Figure 7. Photography of the amplifier prototype, made with microstrip technology. As it can be noticed two standard coaxial sub-miniature type A (SMA) connector have been connected at the two input/output ports.

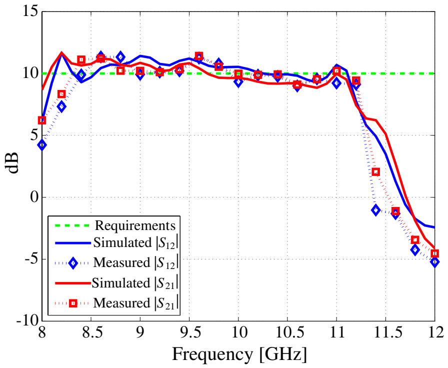

Figure 8. Bi-directional amplifier characteristics. Comparisons between the experimental data obtained with the amplifier prototype of Fig. 7, and numerical data obtained with an electromagnetic simulator (namely Ansoft Designer). Pass-through parameters.

directions. The bidirectional amplifier has been assembled equipped with sub-miniature type A (SMA) coaxial connectors and measured with a vector network analyzer, the measurements has been compared with numerical data obtained with a commercial simulator. The photo of the considered prototype is reported in Fig. 7. The obtained preliminary results concerning the pass-through and the reflection coefficient parameters are reported in Figs. 8 and 9 respectively. As it can be noticed the obtained results are quite satisfactory and clearly demonstrate the potentialities of the proposed methodology.

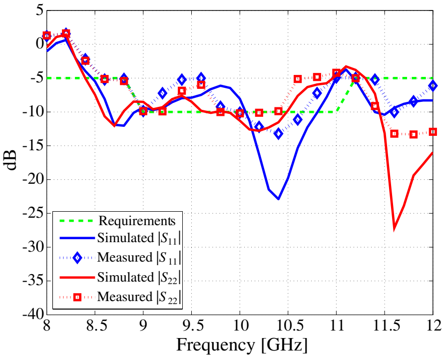

Figure 9. Bi-directional amplifier characteristics. Comparisons between the experimental data obtained with the amplifier prototype of Fig. 7, and numerical data obtained with an electromagnetic simulator (namely Ansoft Designer). Reflection coefficient.

4. CONCLUSION

In this work a methodology for the design of microwave devices and circuits has been proposed. In particular, the proposed methodology, starting from the system requirements expressed in term of scattering parameters of the N ports of the system, estimates the requirements of each subsystem considering the interactions and the effects on the whole system. The requirements for each subsystem are obtained by defining a suitable cost function. The cost function is then minimized with an evolutionary algorithm namely the PSO. The method has been assessed considering the design of a broadband bidirectional amplifier and the obtained preliminary results demonstrated the capabilities of the proposed methodology as effective CAD tool for the design of microwave devices and circuits.

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