Rigorous and Efficient Fabrication-Oriented CAD and Optimization of Complex Waveguide Networks

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ABSTRACT

A sophisticated CAD and optimization tool of complex microwave networks, incorporating fabrication and realizability constraints has been developed. Rigorous full wave models based on the mode matching technique are adopted along with specific algorithms to speed up both the analysis and optimization of the entire microwave structure.
A beam-forming Butler matrix in waveguide technology characterized by 238 geometrical parameters has been designed and globally optimized. The full wave analysis required less than 1 second per frequency point, while the entire optimization was performed in less than one hour, using an IBM RS6000 250T.

Introduction

Extremely accurate design capabilities are required in many modern applications in order to minimize costs of manufacturing, to determine the effects of mechanical tolerances, to predict the effects of imperfections in the fabrication process, etc.. This is not only true in the area of (M)MIC's, but also in the more conventional area of waveguide circuits. A typical example is that of space applications. Sophisticated antenna performances of modern satellite communication systems involve the design of very complex microwave networks, consisting of tenths of complicated components with very strict requirements [1].
The higher the accuracy of the model, however, the higher the associated computational effort. As a consequence, while the rigorous EM design and optimization of a single microwave component (a filter, a phase shifter, etc.) can be performed by using very efficient and sophisticated analysis and optimization tools, the complexity of a network consisting of numerous microwave components is such that the design and optimization procedure becomes extremely computer intensive when not unaffordable.
The optimization of the network as a whole rather than of the individual components, however, can enhance the network performance by exploiting a higher number of free parameters in such a way as to identify optimum structures that could never be found by individual optimization. In particular, in contrast with the conventional design procedure, global optimization allows single components and discontinuities to be cascaded at very close distances where higher order mode interaction takes place.
A number of constraints arising from physical realizability, topological compatibility, fabrication requirements, etc. usually impose the insertion in the physical structure of additional components that are not necessary from the point of view of the electrical performance (such as bends, waveguide sections, twists, etc.) and are usually not included in the first design. Such components modify the network performance and make it necessary to perform an experimental tuning. It appears that the possibility to incorporate the fabrication constraints into the optimization procedure makes the entire CAD tool extremely effective, since it can yield a first pass design, provided that the theoretical model is accurate enough. Because of the extremely high computational effort required, a global optimization cannot be performed using EM simulators, except for relatively simple components.
In this paper, thanks to a number of specific features implemented, a computational tool are presented that allow microwave networks of rather high complexity to be optimized on the basis of a rigorous EM simulator [2]. The EM model is based on the mode matching technique as a rigorous analysis method of elementary components (building blocks) [3], including higher order mode interaction. The mode matching method is implemented in conjunction with suitable numerical algorithms to achieve a high numerical efficiency both in the analysis and the optimization phases. The efficiency achieved is such that an entire microwave network can be optimized as a whole, i.e. as a single component. In addition to that, fabrication, topological and realizability constraints are

incorporated into the numerical model of the network, in such a way that the structure designed can be fabricated without any further tuning.
The suitability of the method is demonstrated at the example of the design and optimization of a 4x4 Butler matrix in waveguide technology, consisting of 6 branch couplers and 4 phase shifters. Based on the EM simulation, the analysis of the entire structure consisting of 62 geometrical parameters is performed in less than 1 second per frequency point, while its optimization has been performed in about an hour on an IBM RS6000 250T.

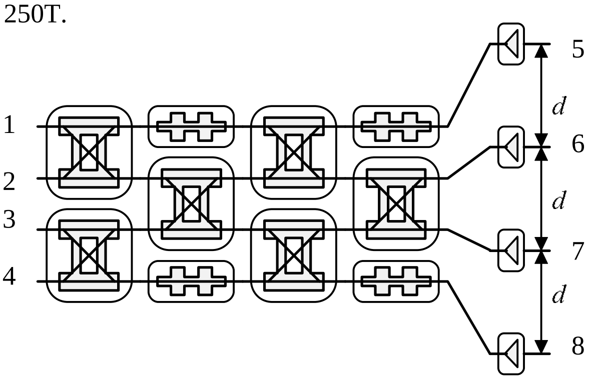

Fig. 1a : The schematic of the Butler matrix.

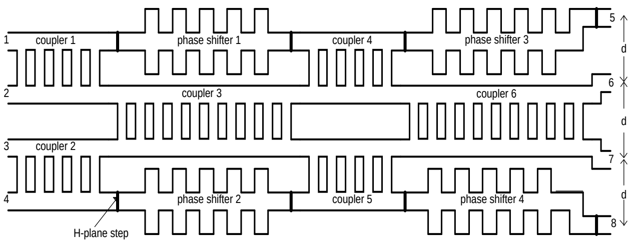

Fig. 1b : The layout of the Butler matrix.

The Method

As an example, consider a 4x4 beam-forming network (Butler matrix). The electrical scheme, consisting of four phase shifters and six 90° directional couplers, is shown in Fig. 1a. With respect to the basic scheme of the Butler matrix, two additional directional couplers and two phase shifters are employed. The former are used to realize the crossovers, while the latter are used to compensate for the phase shift produced by the second crossover. This configuration has been chosen since it allows the matrix to be fabricated using a planar waveguide technology, as shown in Fig. 1b. This structure can be manufactured in a single planar board. The signal incident on one port has to be divided equally among the ports located at the opposite side. The network is required to provide a phase distribution at the r.h.s. ports 5-8 in such a way as to produce 4 different beams when fed from the four input ports 1-4 [4]. The angular spacing between the beams is determined by the distance d between the output ports. Four elbows have thus been inserted in the waveguide structure of Fig.1b in order to allow the distance *d* to be varied according to the specifications.
The Analysis and Optimization procedures implemented in the CAD tool are briefly described here.

<u>Analysis</u>

Each waveguide component of the structure can be segmented into elementary cells or building blocks: steps, stubs and T-junctions. Using the mode matching technique, each cell is rigorously modeled in terms of Generalized Admittance Matrix (GAM) [5]. This is a rigorous representation that fully accounts for higher order mode interaction.
The segmentation of each component is performed in such a way as to minimize the numerical effort [6]. To further speed up the numerical analysis procedure of each component, an optimum numbering of the cells is adopted that minimizes the bandwidth of the system matrix [7]. This additional feature leads to a speed up factor of more than one order of magnitude.
Once the GAM of each component has been derived, the model of the entire network is obtained by conventional network analysis.
On setting up the network layout, geometrical constraints must be satisfied in order to guarantee physical realizability. This specific feature has been implemented in the analysis package. The physical compatibility of all geometrical dimensions is expressed by a number of specific equations provided by the user.

<u>Optimization.</u>

The optimization is performed using a quasi-Newton procedure, the gradient of the objective function being automatically computed with the analysis through the Adjoint Network Method (ANM) [2].
Several types of constraints are handled by the optimization package.
Linear relationships among geometrical dimensions pertaining to different elements/components of the network are imposed in order to ensure its physical realizability or to comply with additional specific requirements. As an example, the distance d between output ports of the Butler matrix must be given. This implies an equation to be imposed involving a number of

geometrical variables of the network. The degrees of freedom of the optimization are reduced correspondingly. Moreover, by using the same variable name for different geometrical dimensions, equality among such dimensions is enforced. Possible symmetry properties of the whole network or some of its components can be imposed in this way. Also in this case, the number of degrees of freedom is reduced.
Other constraints are expressed in terms of inequalities. This allows one to limit the possible values of some dimensions, depending on various physical or technological constraints.

Results

A Butler matrix operating in the frequency band 10.95-12.75 GHz in waveguide technology, as depicted in Fig.1b, has been designed first. In the first design no elbows nor bends were incorporated. The distance d was therefore determined by the dimensions of the components of the matrix.
Each component has been designed individually [8,9]. The resulting network contains 226 geometrical parameters. Once all constraints (including symmetries) have been incorporated, the free parameters reduce to 40. The network has then been optimized as a whole so as to obtain the response shown in Fig. 2. For brevity, only some of the scattering parameters are plotted. Reflection coefficients $|s_{11}|$, $|s_{22}|$, $|s_{55}|$ and $|s_{66}|$ along with $|s_{21}|$ and $|s_{65}|$ are plotted in Fig. 2a. Couplings between l.h.s. and r.h.s. ports are plotted in Fig. 2b. The phases of the S-parameters (not shown for brevity) match the specifications in the whole frequency band within $\pm$ 0.5 degrees. As can be seen the performance is quite satisfactory.
The inclusion of 4 elbows to adjust the distance between consecutive output ports from d= 15.57 mm to d=18 mm is such as to heavily degrade the performance of the network, as shown by Fig. 3a, b. Although the couplings do not differ much from the nominal value of 6 dB, insertion loss as low as 15 db and phase errors (not shown for brevity) of the order of 10 degrees are obtained.
To recover the original performance of the matrix it would be necessary to patiently tune the network realized. A more efficient alternative is to re-optimize the whole network, including the 4 additional elbows. This makes equal to 62 the number of optimization parameters, as in this case phase-shifters 3, 4 and 6 are not symmetric. Fig. 4a, b shows the results obtained. It is observed that the newly optimized structure exhibits the same good performance as the original one without elbows. The optimization has required about 1 hour on an IBM RS6000 250T. The software can be tested via Internet at the web site
http ://albinoni.istel.ing.unipg.it/brochure/ brochure.htm.
In the same way, further modifications of the structure of the network can easily be incorporated without degrading the overall performance.

Conclusions

A sophisticated CAD and optimization tool of complex microwave networks has been developed. The main features are:
- rigorous full wave models, based on mode matching technique, are used for the analysis.
- to speed up the analysis of each network component, specific algorithms has been implemented, such as: proper segmentation to minimize the number of higher order modes to be included in the analysis, optimum port numbering to minimize the bandwidth of the system matrix.
- automatic gradient computation using the Adjoint Network Method to speed up the optimization
- incorporation of fabrication and realizability constraints into the optimization procedure, in such a way that the network designed can be directly manufactured without any additional verification.

To demonstrate the effectiveness of the tool, a beam-forming Butler matrix in waveguide technology consisting of 62 free parameters has been repeatedly optimized in order to compensate for the degradation due to additional components introduced to comply with layout constraints. The full wave analysis required less than 1 second per frequency point, while the entire optimization has been performed in less than one hour, using an IBM RS6000 250T.

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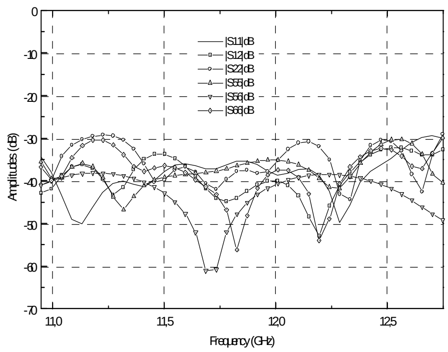
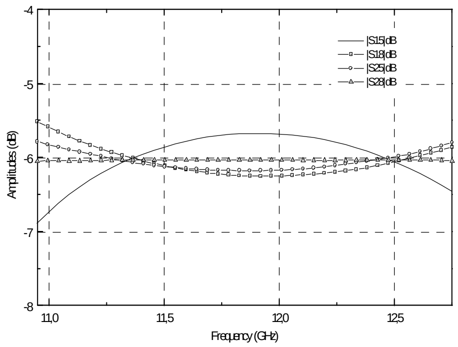
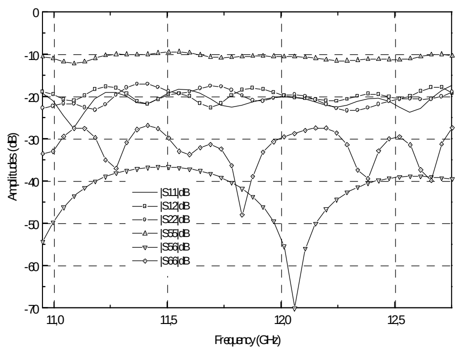


a)

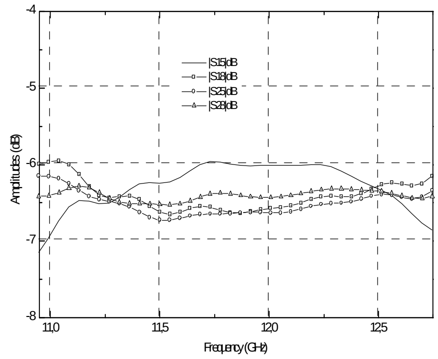


b)

Fig. 2: Butler matrix of Fig. 1b without elbows,
a) Return loss and isolation, b)Couplings

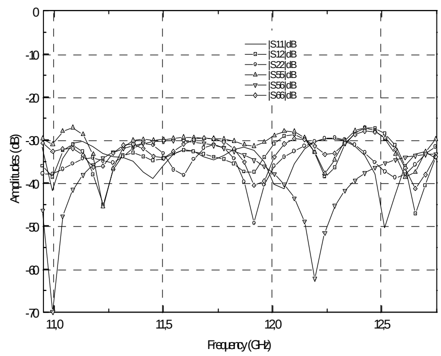


a)

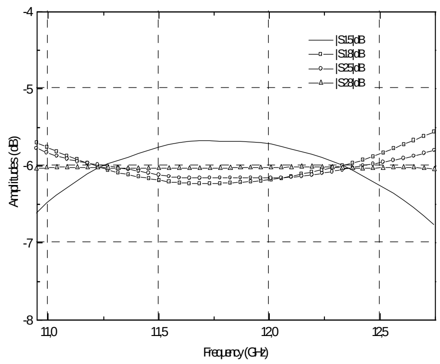


b)

Fig. 3: Same as: a) Fig.3a, b) Fig. 3b, after inserting elbows



a)



b)

Fig. 4: Optimized 4x4 Matrix with elbows
a) Return loss, b) Couplings