Transverse Segmentation: A Novel Technique for the Efficient CAD of 2 N-Port Branch-Guide Couplers

F. Alessandri, M. Mongiardo, and R. Sorrentino

Abstract—**Two novel field-matching techniques, the cellular technique (CT) and the transverse segmentation technique (TST), for the CAD of 2N-port branch-guide couplers have been developed and are compared with the bifurcation technique (BT) already adopted by other authors. By comparison with experimental data on 6- and 8-port couplers, all techniques exhibit excellent accuracy, but different numerical efficiency. The TST is shown to be eight times faster than the BT and five times faster than the CT. All methods can also be applied to other waveguide components.**

I. Introduction

MULTIPORT-POWER dividers/combiners are receiving considerable interest as novel circuit elements in the realization of beam forming networks for modern satellite antennas. Such components are fabricated using integrated waveguide technology. A multiport divider consists of a set of N rectangular waveguides coupled via a number of waveguide branches. It therefore represents a generalization to 2N ports of the conventional 4-port branch-guide coupler (BGC). The latter is a key element in the construction of beam forming networks for sophisticated antenna functions. The use of multiple coupled waveguide sections allow the same functions to be realized with a reduced number of components (thus a more compact network) than using conventional BGC's. A few studies have been published on the analysis and design of 6-port BGC. Most of them neglect higher order mode interaction between discontinuities [1], [2] or require a notable computational and algorithmic effort for the CAD of 8-port couplers [3]. In addition to the bifurcation technique (BT) used in [3], we present here two alternative field matching techniques for the rigorous yet efficient CAD of 2N-port BGC's.

A. The Bifurcation Technique (BT)

Fig. 1 shows the decomposition of a 6-port BGC for application of the bifurcation technique. Broken lines have been drawn across the structure at each discontinuity. Three types of bifurcations can occur between consecutive planes, as already pointed out in [3]. A generalized scattering matrix can be computed for each discontinuity. The complete analysis is obtained by cascading the generalized scattering matrices of the discontinuities with the connecting uniform waveguide sections. In the example of Fig. 1, 18 generalized scattering matrices of discontinuities have to be cascaded. During the numerical optimization, the geometry of the BGC has to be modified according to the optimization strategy. As a consequence, the planes of the bifurcations are shifted back and/or forward and both the number and the type of discontinuities also change. In the numerical optimization procedure, no general equivalent circuit topology can be established for the multiport BGC.

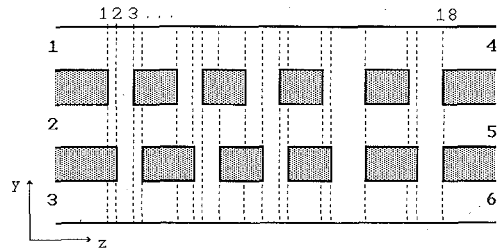

Fig. 1. Segmentation according to the bifurcation technique.

B. The Cellular Technique (CT)

Fig. 2(a) shows the segmentation of the same BGC according to the cellular technique. This is a field matching technique similar to that already adopted in [4]. The structure is subdivided into parallelepipedal cells. These are either *branch cells* (e.g., cells 1, 10, 19, 3, 12, 21, etc.) or *waveguide cells* (2, 11, 20, 4, 13, 22, etc.) A waveguide cell is simply a waveguide section, while the branch cell can be viewed as a resonant cavity coupled to the adjacent cells through rectangular apertures. The EM field is expanded inside each branch cell in terms of resonant modes [5], while over the apertures and inside the waveguide cells it is expanded in terms of rectangular waveguide modes. The resulting equivalent circuit of the BGC structure is shown in Fig. 2(b). Each cell is represented by a generalized multiport network, where each port is associated to a waveguide mode. As a consequence of the orthogonality between waveguide modes, multiports representing waveguide cells are characterized by simple diagonal matrices. The number of cells equals $N \times (2M - 1)$, M being the number of branches and N half of the number of ports of the divider. $N \times M$ are branch cells, $N \times (M - 1)$ are waveguide cells. In the

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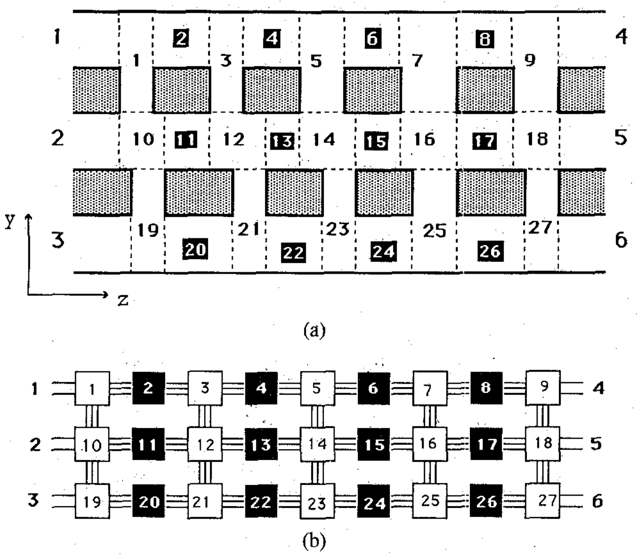

Fig. 2. (a) Segmentation according to the cellular technique. (b) Equivalent circuit of the BGC according to the segmentation of (a).

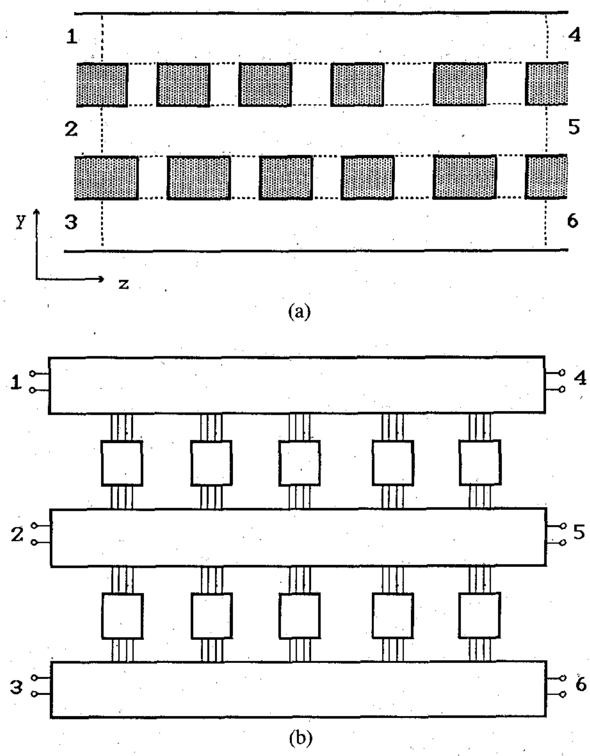

Fig. 3. (a) Segmentation according to the TST technique. (b) Equivalent circuit of the BGC according to the segmentation of (a).

example of Fig. 2(a), ($N = 3$, $M = 5$) the number of cells is 27.

C. Transverse Segmentation Technique (TST)

This approach is based on the transverse resonance concept [6]. A number of waveguide discontinuity problems can be simplified substantially by looking into a transverse direction, i.e., considering the EM field as resonating between the side walls of the structure. In the present case, since the multiport coupler consists of waveguide sections of uniform heights, only four discontinuities are seen looking into the y-direction. Fig. 3(a) shows the segmentation of the BGC according to the TST, the equivalent network being represented in Fig. 3(b). Using the admittance matrix formulation [7], the matrix descriptions of the constitutive multiport networks are obtained in a straightforward manner. Consider, for instance, one of the "longitudinal" networks of Fig. 3(b) (e.g., that with terminal pairs 1 and 4). Recall that the admittance matrix elements are obtained by short circuiting all ports except one. To evaluate the transconductances between one external port (say port 1) and the internal ports, a mere waveguide section short circuited at the far end has to be considered. By choosing the terminal planes far enough from the end branches, only the dominant TE_{10} mode has to be taken into consideration, and no series expansion is involved in the evaluation of the transadmittances.

The "transverse" networks of Fig. 3(b), corresponding to the branches of the coupler, are mere waveguide sections characterized by diagonal matrices.

III. Comparisons and Results

The main advantages, disadvantages and numerical features of the previous techniques are detailed in this section.

Bifurcation technique: It allows waveguide sections with nonuniform heights to be treated. However, this seems to be the only advantage of this technique. The number of subnetworks constituting the overall equivalent circuit, in fact, is much higher than using TST and cannot be stated *a priori,* but depends on the impedances of the branch waveguides. This complicates substantially the optimization routine, which becomes more and more involved as N (number of coupled waveguides) increases. In addition, discontinuities (n-furcations) are often very close, thus interacting. This requires a high number of modes, thus large matrix sizes, in the generalized multiport description of the n-furcations.

As far as the accuracy of the numerical results is concerned, the number of modes at each n-furcation should be chosen according to the relative convergence criterion [8]. This guarantees an excellent accuracy even with a relatively low number of modes. Five to six modes are generally sufficient at the output ports of the coupler.

Cellular technique: In contrast with the bifurcation technique, the same equivalent circuit for the overall structure holds regardless of the impedances of the branches (thus the z dimension of cells no. 1, 3, 5, etc., Fig. 2(a)) The computer optimization is therefore much easier than with the BT. Compared to the latter, the cellular technique is numerically more efficient, in spite of the generally higher number of subnetworks involved. The computer effort, in fact, is associated mainly with the modeling of only the $N \times M$ branch cells, since the waveguide cells are represented by diagonal matrices. Moreover, the typical $\lambda/4$ size of the cells is large enough to make discontinuities non-, or very little, interacting, so that a small matrix size is involved (one or a few ports connecting adjacent discontinuities). Moreover, contrary to the BT, the extension to a higher number of ports ($N \geq 4$) is straightforward.

One difficulty with the CT is that it involves a two-dimensional expansion, thus a pair of indexes. In such a case lesser evidence exists as far as the choice of the modal ratio is

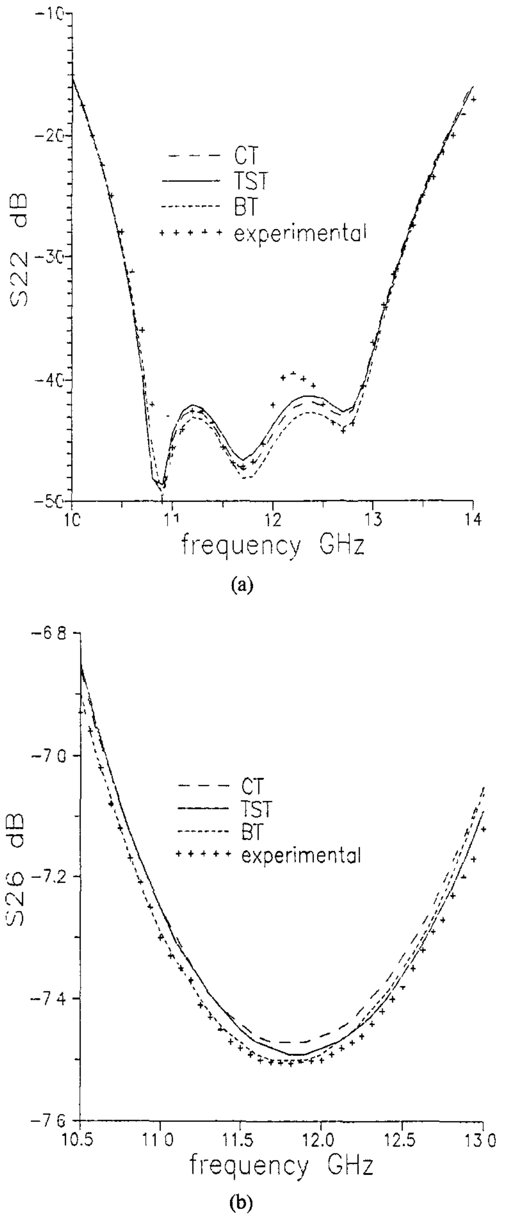

Fig. 4. Experimental (from [2]) and theoretical responses of a 6-port 5-branch coupler.

concerned. According to our experience, however, no critical values have been observed, and the general rule of having the same highest spatial frequency in both direction seems to give good results.

Transverse Segmentation Technique: Taking advantage of the uniform heights of the waveguide sections the number of discontinuities is drastically reduced. Combined with the admittance matrix formulation, a very small computer expenditure is involved. As for the BT, the modal ratio is simply determined according to the relative convergence criterion. As for the CT, the discontinuities are $\lambda/4$ apart, so that small matrices are involved; in addition, extension to $N \geq 4$ is extremely easy. The TST therefore appears the most efficient technique.

The three methods have been implemented to analyze 6- and 8-ports BGC's. An extensive comparison with experimental data has shown that all methods provide excellent accuracy. Fig. 4 shows a comparison between the experimental results of [2] and our computed results on a 5-branch 6-port coupler. An excellent agreement is observed in all cases. A substantial improvement (more than 5 dB) with respect to the theory in [2] has been obtained.

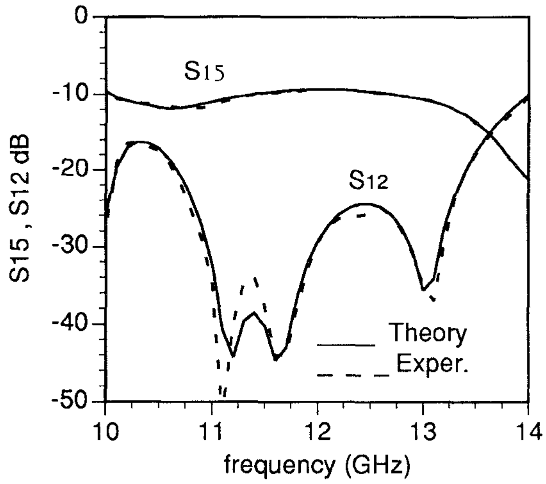

Fig. 5. Experimental and computed responses of an 8-port 7-branch coupler using TST.

The computer time associated with the three methods is remarkably different. It was found that, for a given accuracy, the TST is, in the average, *eight times* faster than the BT and *five times* faster than the CT.

As the most efficient technique, the TST has been applied to the case of 7-branch 8-port couplers. A comparison between theory and experiment is shown in Fig. 5. Using TST, the computation of the scattering matrix of the coupler at one frequency point requires less than 10 s on a 386-16 MHz machine.

III. Conclusion

Two novel field matching techniques, the cellular technique (CT) and the transverse segmentation technique (TST), for the CAD of $2N$-port branch guide couplers have been developed and compared with the bifurcation technique (BT) already adopted by other authors. By comparison with experimental data on 6- and 8-port couplers, all techniques exhibit excellent accuracy, but considerably different numerical efficiency. The TST is shown to be eight times faster than the BT and five times faster than the CT. All methods can be applied to many other waveguide components.

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