SFELP—An Efficient Methodology for Microwave Circuit Analysis

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***Abstract*—A hybrid method based on the Segmentation technique, the Finite-Element method, and a Matrix Lanczos–Padé algorithm (SFELP) for the analysis of microwave circuits is introduced in this paper. This method computes Symmetric matrix-Padé approximations of a matrix transfer function for any number of inputs and outputs via a Lanczos-type process (SyMPVL) for obtaining the generalized admittance matrix of a microwave circuit on a wide band of frequencies. The formulation that provides the three-dimensional finite-element/segmentation method is suitable for applying the symmetric Padé via Lanczos algorithm, except for the frequency dependence of the matrix of excitation vectors. In this paper, this problem is analytically overcome for the case in which excitation vectors correspond to modes of homogeneous waveguides or transmission lines. The accuracy and efficiency of the proposed method are shown by means of different examples.**

***Index Terms*—Finite elements, full-wave segmentation method, Padé via Lanczos.**

I. Introduction

In the past few years, different numerical methods have been applied to the analysis of microwave circuits. One of these methods that has been widely used is the finite-element method (FEM) in the frequency domain due to its ability to analyze arbitrarily shaped structures and the ease with which any kind of media properties can be dealt with.

The main drawback of the FEM is the considerable computer time and memory requirements, which make it unattractive for computer-aided design (CAD) applications, especially for three-dimensional (3-D) problems. Although the rapid growth in the power of modern computers is easing this problem, a great effort is being devoted to the development of techniques that improve its efficiency. In this regard, a hybrid two-dimensional finite-element mode-matching (2-D FE/MM) method and a 3-D FEM based on the segmentation technique that allows a saving in computer time and memory requirements has been presented recently [1]. It is well known that when a 2-D FE/MM method is used to analyze discontinuities between arbitrarily shaped homogeneous waveguides, the generalized scattering matrix (GSM) can be obtained for the whole frequency band by using a simple denormalization, having computed the most expensive part once. However, those parts of the microwave circuits that require a 3-D analysis must be analyzed frequency by frequency unless a fast frequency sweep technique is applied.

A very good way of evaluating the response of a device is to obtain a reduced-order model of the transfer function that describes its behavior. In this sense, two mathematically equivalent methods have been used for obtaining reduced order models up to now: the asymptotic waveform evaluation (AWE) method and the Padé via Lanczos method (PVL). In the past few years, the AWE method has been combined with 3-D FEM for obtaining responses over the bandwidth of interest [2], [3]. Although AWE can be applied to transfer functions described by general matrix polynomials, when the frequency point of expansion is close to a resonance frequency, this method does not provide accurate responses [3]. A more stable and accurate technique was introduced by Freund and Feldmann based on the computation of the Padé approximation of a circuit via the Lanczos process (PVL) [4]. The computation of this method produces higher order approximations compared to AWE, but PVL can only be directly applied, without using frequency approximations, when the transfer function can be expressed as

$$H(s) = L^T[G - sC]^{-1}R$$

where G and C are complex N-by-N matrices, R is a complex N-by-m matrix, and L is a complex N-by-p matrix and these matrices do not depend on the complex frequency s. First, PVL was developed for the single-input single-output case $m = p = 1$, and was subsequently extended to the general m-input p-output case [5].

The PVL method has already been used for the simulation of dispersive multiconductor transmission lines [6]. An adaptive Lanczos–Padé sweep has also been combined with the boundary-element method for the analysis of electromagnetic devices, but, in this case, it is necessary to assume that the matrices of the transfer function do not depend on the frequency even though they do [2]. The characterization of the GAM in the 3-D finite-element/segmentation method (3-D FE/SM) has the advantage of coinciding with the form of the transfer function that allows us to apply the extended PVL method except for the dependence on the frequency of the input and output vectors due to the possibility of strong variation with the frequency of the excitation modes in the ports. In the following, it will be shown how this problem is solved by computing the PVL process with the excitation vectors calculated at the expansion point of frequency. After this, the dependence on

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the frequency can be analytically included if the ports support TEM, TE, or TM modes.

II. 3-D FE/SM

The 3-D FE/SM uses a combination of mode matching and the 3-D FEM for obtaining the GAM of one of the regions in which a passive microwave circuit can be segmented [1]. The formulation of the 3-D FE/SM is derived though the following steps: First, let us consider an arbitrarily shaped 3-D region (V) and apply Galerkin's method to the vectorial wave equation for the magnetic field. This region, i.e., V, may be loaded with anisotropic media described by symmetric tensors. Second, we use Green's identities, imposing essential and natural boundary conditions and consider P ports on the boundary surface, i.e., S, enclosing the region V. Finally, we use modal expansion, expressing tangential electric and magnetic fields in the ports as

$$\mathbf{E}_t^i = \sum_{j=1}^{\infty} V_j^i(z_i)\mathbf{e}_{tj}^i(x_i, y_i) \quad \mathbf{H}_t^i = \sum_{j=1}^{\infty} I_j^i(z_i)\mathbf{h}_{tj}^i(x_i, y_i) \tag{1}$$

where (x_i, y_i, z_i) is a local coordinate system related to each port. By following this procedure, we obtain

$$\int_V \left(\nabla \times \mathbf{W} \cdot [\varepsilon_r]^{-1} \nabla \times \mathbf{H} - k^2 \mathbf{W} \cdot [\mu_r]\mathbf{H}\right) dV = j\omega\varepsilon_0 \sum_{i=1}^{P}\sum_{j=1}^{\infty} V_j^i(z_i) \int_{Si} \mathbf{W} \cdot \left(\mathbf{z}_i \times \mathbf{e}_{tj}^i\right) dSi \tag{2}$$

where $[\varepsilon_r]$ and $[\mu_r]$ are, respectively, the complex relative permittivity and permeability tensors, k is the wavenumber at the angular frequency ω, and $\mathbf{z}_i$ is a normal vector inwards the region on the surface Si of each port.

Discretization of (2), taking a finite number of modes mi in each port, gives

$$[\mathbf{K} - k^2\mathbf{M}]\{\mathbf{H}_c\} = j\omega\varepsilon_0 \mathbf{B}\{\mathbf{V}\}. \tag{3}$$

In this expression, N is the number of degrees of freedom $\mathbf{H}_c$, $\mathbf{K}$, and $\mathbf{M}$, are sparse symmetric complex N-by-N matrices, $\mathbf{V}$ is a Q-dimensional column vector of voltages (Q is the sum of the number of modes used in each port), and $\mathbf{B}$ is the following complex N-by-Q matrix:

$$\mathbf{B} = \left[\{\mathbf{b}_1^1\} \cdot\cdot \{\mathbf{b}_{m1}^1\} \cdots \cdot \{\mathbf{b}_j^i\} \cdots \cdot \{\mathbf{b}_1^P\} \cdot\cdot \{\mathbf{b}_{mP}^P\}\right]$$
$$\{\mathbf{b}_j^i\} = \left\{\begin{array}{c} \displaystyle\int_{Si} \mathbf{F_1} \cdot (\mathbf{z_i} \times \mathbf{e}_{tj}^i)\, dSi \\ \cdots \\ \displaystyle\int_{Si} \mathbf{F}_n \cdot (\mathbf{z_i} \times \mathbf{e}_{tj}^i)\, dSi \\ \cdots \\ \displaystyle\int_{Si} \mathbf{F}_N \cdot (\mathbf{z_i} \times \mathbf{e}_{tj}^i)\, dSi \end{array}\right\}. \tag{4}$$

Here, $\mathbf{F}_n$ is each one of the vectorial interpolation functions used in the discretization. The integrals $\{\mathbf{b}_j^i\}$ are extended to the ith port surface where the jth mode is defined and are nonzero only if any of the components of $\mathbf{F}_n$ is tangential to this port.

If we now use the modal expansion of the magnetic field (1), and consider modal orthogonality, we can write

$$\int_{Si} \mathbf{H} \cdot (\mathbf{z_i} \times \mathbf{e}_{tj}^i)\, dSi = I_j^i(z_i) \int_{Si} \mathbf{h}_{tj}^i \cdot (\mathbf{z_i} \times \mathbf{e}_{tj}^i)\, dSi. \tag{5}$$

The discretization of this expression for every mode of each port leads to the following system:

$$\mathbf{B}^T\{\mathbf{H}_c\} = \mathbf{\Delta}\{\mathbf{I}\} \tag{6}$$

$\{\mathbf{I}\}$ being a Q-dimensional column vector of currents and $\mathbf{\Delta}$

$$\mathbf{\Delta} = \mathrm{diag}\left(\Delta_1^1 \cdot\cdot \Delta_{m1}^1 \cdots \cdot \Delta_j^i \cdots \cdot \Delta_1^P \cdot\cdot \Delta_{mP}^P\right)$$
$$\Delta_j^i = \int_{Si} \mathbf{h}_{tj}^i \cdot (\mathbf{z_i} \times \mathbf{e}_{tj}^i)\, dSi.$$

Equations (3) and (6) lead to an expression for the GAM related to normalized tensions and currents

$$\mathbf{Y}(k) = j\frac{k}{\eta_0}\mathbf{B}_N^T(k)\left[\mathbf{K} - k^2\mathbf{M}\right]^{-1}\mathbf{B}_N(k), \qquad \eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \tag{7}$$

with

$$\mathbf{B}_N = \mathbf{B}\mathbf{\Delta}^{-1/2}. \tag{8}$$

III. Application of the SyMPVL Algorithm

The obtained expression for the GAM is better expressed as

$$\mathbf{Y}(k) = j\frac{k}{\eta_0}\mathbf{B}_N^T(k)\left[\mathbf{G}_0 - (k^2 - k_0^2)\mathbf{M}\right]^{-1}\mathbf{B}_N(k) \tag{9}$$

with

$$\mathbf{G}_0 = \mathbf{K} - k_0^2\mathbf{M} \tag{10}$$

since the Padé approximation will be carried out on a frequency f_0 different from zero.

When the ports of the microwave device connect with arbitrarily shaped homogeneous waveguides or transmission lines, $\mathbf{B}_N$ can be factored as follows:

$$\mathbf{B}_N(k) = \mathbf{B}_N(k_0)\mathbf{J}(k, k_0) \tag{11}$$

with $\mathbf{J}$ being a diagonal matrix given by

$$\mathbf{J}(k, k_0) = \mathrm{diag}\left[J_j(k, k_0)\right]$$
$$J_j(k, k_0) = \begin{cases} 1, & \text{TEM modes} \\ \sqrt{\dfrac{\sqrt{\left(\dfrac{k_{cj}}{k_0}\right)^2 - 1}}{\sqrt{\left(\dfrac{k_{cj}}{k}\right)^2 - 1}}}, & \text{TE modes} \\ \sqrt{\dfrac{\sqrt{\left(\dfrac{k_{cj}}{k}\right)^2 - 1}}{\sqrt{\left(\dfrac{k_{cj}}{k_0}\right)^2 - 1}}}, & \text{TM modes} \end{cases} \tag{12}$$

where k_{cj} is the cutoff wave number of each mode j. In this case, we can write

$$\mathbf{Y}(k) = j\frac{k}{\eta_0}\,\mathbf{J}(k,\,k_0)\mathbf{Y}_N(k,\,k_0)\mathbf{J}(k,\,k_0) \tag{13}$$

where

$$\mathbf{Y}_N(k,\,k_0) = \mathbf{B}_N^T(k_0)\Big[\mathbf{G}_0 - (k^2 - k_0^2)\mathbf{M}\Big]^{-1}\mathbf{B}_N(k_0). \tag{14}$$

The factorization of the $\mathbf{B}_N$ matrix has permitted us to find an expression of the GAM as a product of a diagonal matrix $\mathbf{J}$ and a pseudo-GAM $\mathbf{Y}_N$ that has the property of being dependent on the frequency in the form that is required so that the SyMPVL algorithm can be applied [7]. Thus, if the $\mathbf{LDL}^T$ factorization of the matrix $\mathbf{G}_0$, which can be efficiently obtained taking advantage of its sparse matrix storage, is substituted in (14), we can arrive at the following expression by using elementary matrix operations:

$$\mathbf{Y}_N(s) = [\mathbf{DR}]^T[\mathbf{I}_{dN} - s\mathbf{A}]^{-1}\mathbf{R} \tag{15}$$

with

$$\begin{aligned}\mathbf{A} &= \mathbf{D}^{-1}\mathbf{L}^{-1}\mathbf{M}\mathbf{L}^{-T}\\ \mathbf{R} &= \mathbf{D}^{-1}\mathbf{L}^{-1}\mathbf{B}_N(k_0)\\ s &= k^2 - k_0^2\end{aligned} \tag{16}$$

and $\mathbf{I}_{dN}$ is the N-by-N identity matrix.

In order to evaluate the spectral response of the passive microwave device in an efficient way, an nth matrix-Padé approximant to $\mathbf{Y}_N$ is obtained [8] as follows:

$$\mathbf{Y}_n(s) = [\boldsymbol{\Delta}_n\boldsymbol{\rho}_n]^T[\mathbf{I}_{dn} - s\mathbf{T}_n]^{-1}\boldsymbol{\rho}_n \tag{17}$$

where $\mathbf{I}_{dn}$ is the n-by-n identity matrix, $\boldsymbol{\Delta}_n$, is a complex block diagonal n-by-n matrix, $\mathbf{T}_n$ is a complex n-by-n matrix, and $\boldsymbol{\rho}_n$ is a complex n-by-Q matrix, with $n \ll N$. These matrices are generated by applying a symmetric block-Lanczos algorithm to A that can handle multiple starting vectors [9].

SyMPVL is applicable to this problem because $\mathbf{A}$, $\mathbf{R}$, and $\mathbf{D}$ do not depend on s, and $\mathbf{A}$ is a $\mathbf{D}$-symmetric matrix, i.e.,

$$\mathbf{DA} = \mathbf{A}^T\mathbf{D}. \tag{18}$$

This property makes it unnecessary to use a general algorithm that requires a simultaneous generation of two cluster-wise biorthogonal basis vectors $\mathbf{W}_n$ and $\mathbf{V}_n$ connected by the expression

$$\mathbf{W}_n^T\mathbf{V}_n = \boldsymbol{\Delta}_n \tag{19}$$

because in this case

$$\mathbf{W}_n = \mathbf{D}\mathbf{V}_n \tag{20}$$

and, therefore, the Lanczos vectors are, at least, cluster-wise $\mathbf{D}$-orthogonal [7].

The SyMPVL algorithm also includes: 1) a *deflation* procedure to detect and delete linearly dependent vectors and 2) the so-called *look-ahead* techniques to avoid potential breakdowns or near-breakdowns [5]. When *look-ahead* steps are not necessary, the Lanczos vectors are, in such a case, vector-wise $\mathbf{D}$-orthogonal.

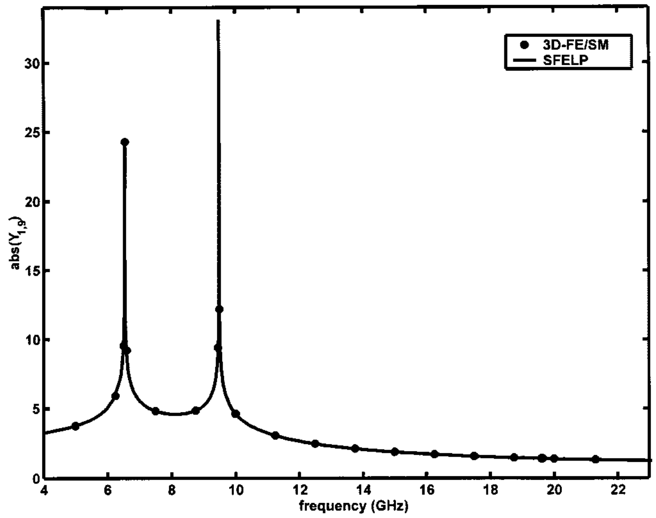

Fig. 1. Magnitude of the Y_{12} parameter between the fundamental modes of the rectangular waveguides for the concentric step discontinuity.

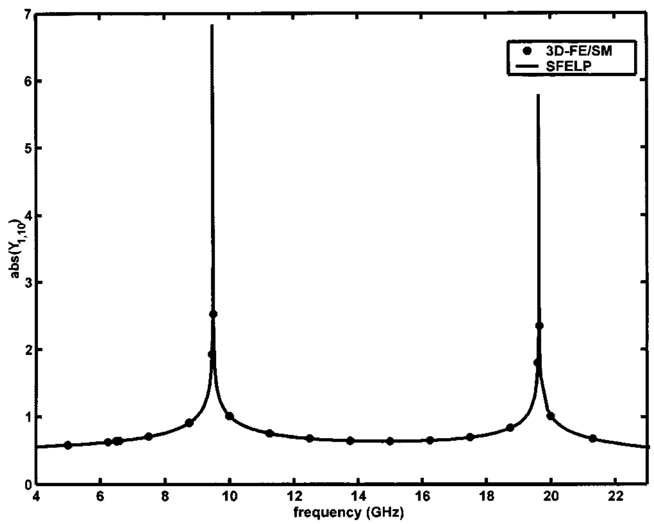

Fig. 2. Magnitude of the Y_{12} parameter between the fundamental mode of the first port and the TE_{30} mode of the second port for the concentric step discontinuity.

The calculation of the nth matrix-Padé approximant $\mathbf{Y}_n$ allows us to estimate the GAM matrix for any frequency by introducing the frequency correction matrix $\mathbf{J}$

$$\mathbf{Y}(k) \approx j\frac{k}{\eta_0}\,\mathbf{J}(k,\,k_0)\mathbf{Y}_n(k,\,k_0)\mathbf{J}(k,\,k_0). \tag{21}$$

IV. SFELP Method

Finally, the GSM matrix can be quickly obtained from the GAM for a broad band and connected with other GSM matrices that correspond to different regions of the segmented device. The segmentation of the circuit can be made very close to discontinuities since high order mode interactions are taken into account with the proposed method and sections of homogeneous

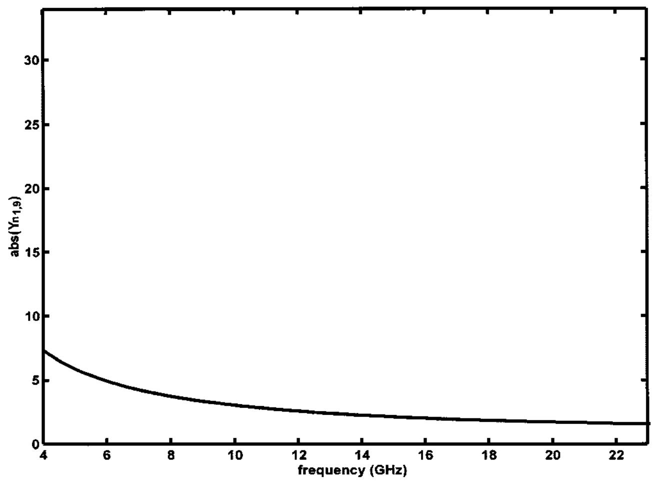

Fig. 3. Magnitude of the Y_{12} pseudo-parameter (without the frequency correction for the excitation vectors) between the fundamental modes of the rectangular waveguides for the concentric step discontinuity.

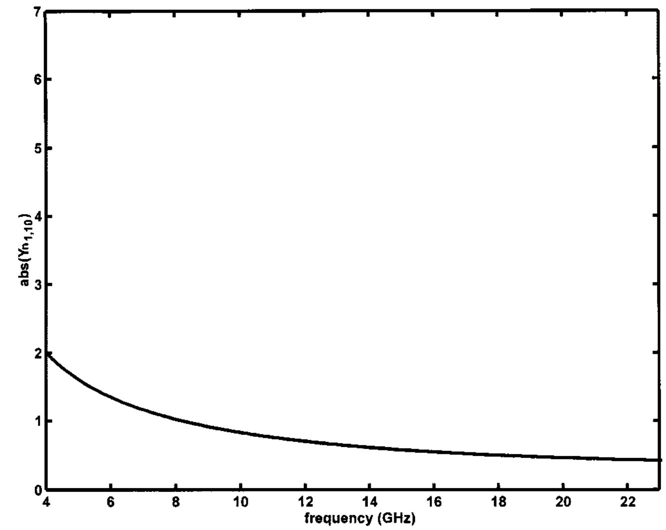

Fig. 4. Magnitude of the Y_{12} pseudo-parameter (without the frequency correction for the excitation vectors) between the fundamental mode of the first port and the TE_{30} mode of the second port for the concentric step discontinuity.

waveguides or transmission lines can be analytically included in the interconnection of the different GSMs. Therefore, the proposed method profits from the capability of reducing the size of the different regions in which the microwave circuit is divided since the order of the matrices involved in the obtaining of the GAM is drastically reduced. Moreover, the possibility of carrying out the analysis of a global circuit for a broad bandwidth of frequencies by means of studying different regions of this circuit by applying the SyMPVL algorithm to each one allows us to use this method as a powerful tool in a design process: any region of the circuit could be modified and quickly analyzed for the required band without the need to study the other regions again.

V. Computational Results

A. Concentric Step Discontinuity Between Rectangular Waveguides

In order to assess the accuracy of the proposed method, we first consider a simple discontinuity between two concentric rectangular waveguides of 15.8 $\times$ 7.9 mm (port 1) and 22.9 $\times$ 10.2 mm (port 2). For the study of this problem with a 3-D method, ports have been fixed 1 mm away from the discontinuity and only a quarter of the discontinuity has been meshed. Eight modes with the symmetry of the first (fundamental) mode for each port have been considered to obtain the different responses that we show.

In this problem, different poles arise at the cutoff frequencies of the modes that we consider. Figs. 1 and 2 show some of the most significative elements of the GAM. In these figures, we can see three poles at the cutoff frequency of TE_{10} (port 1) and TE_{10}, and TE_{30} (port 2), respectively. Since these poles are introduced analytically by means of the frequency matrix correction J, the nth matrix-Padé approximant Y_n does not need to approximate poles in the studied band, as can be seen in Figs. 3 and 4.

Although the poles of the GAM appear at the resonant frequencies of the region and at the cutoff frequencies of the modes

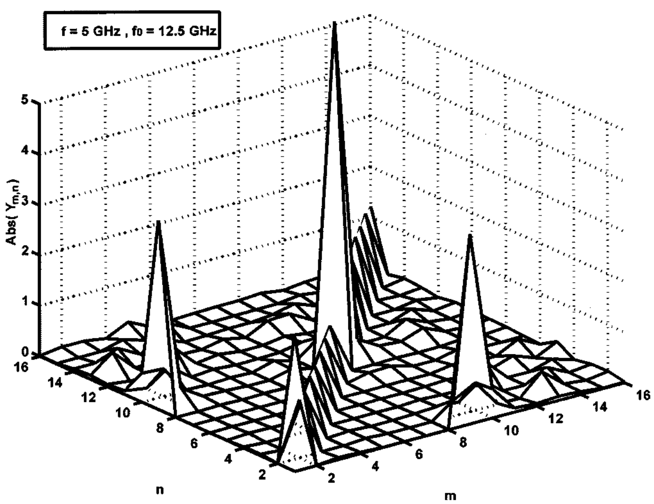

Fig. 5. Magnitude of the elements of the GAM at $f = 5$ GHz obtained by using the SFELP method with an expansion point of frequency equal to 12.5 GHz for the concentric step discontinuity.

of the waveguides of connection, only the former poles are included by the SyMPVL algorithm. Moreover, when we analyze regions of a reduced size, the resonant frequencies are moved to frequency bands higher than the band of interest. In this way, as an additional advantage, we get to work with regions where the order of the matrix-Padé approximant Y_n diminishes in relation to the order which is needed for studying the whole circuit. As a consequence, we have a fast convergence since fewer vectors are needed, and a very good precision is obtained.

The implementation of the segmentation technique by means of multimode-multiport matrices requires a good precision not only for the admittance parameters related to the fundamental mode in each port. It is necessary that admittance parameters related to higher order modes be obtained with an acceptable precision. Figs. 5 and 6 show the GAM matrix that has been obtained by using the SFELP method with f_0 equal to 12.5 GHz for two frequencies situated at the extremes of the studied band.

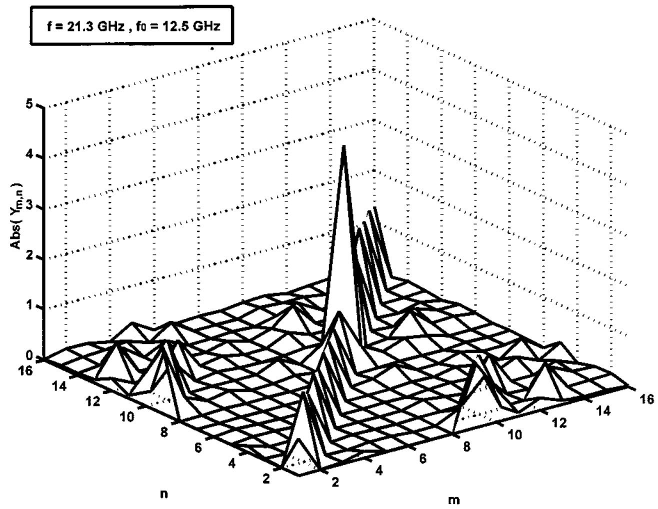

Fig. 6. Magnitude of the elements of the GAM at $f = 21.3$ GHz obtained by using the SFELP method with an expansion point of frequency equal to 12.5 GHz for the concentric step discontinuity.

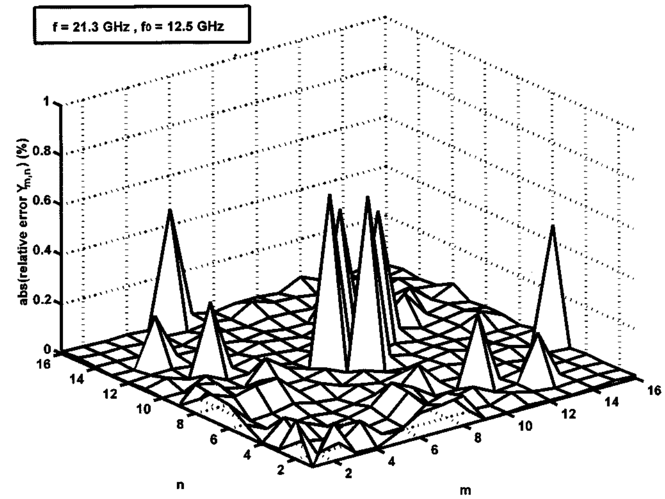

Fig. 8. Relative error in percentage between the elements of the GAM obtained with the 3-D FE/SM at $f = 21.3$ GHz and the elements of the GAM obtained at the same frequency by using the SFELP method with an expansion point of frequency equal to 12.5 GHz.

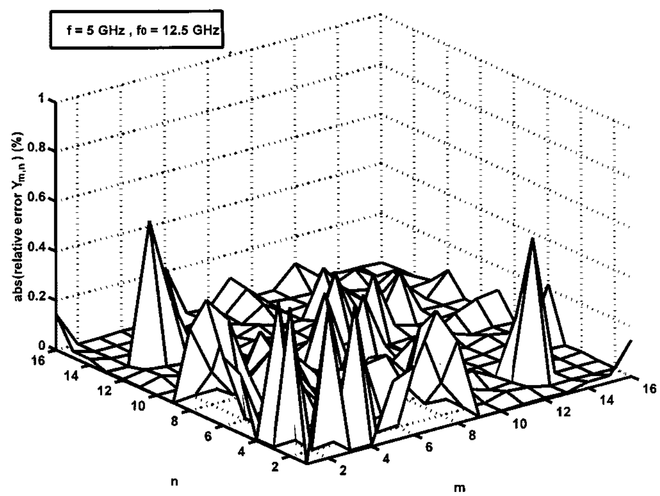

Fig. 7. Relative error in percentage between the elements of the GAM obtained with 3-D FE/SM at $f = 5$ GHz and the elements of the GAM obtained at the same frequency by using the SFELP method with an expansion point of frequency equal to 12.5 GHz.

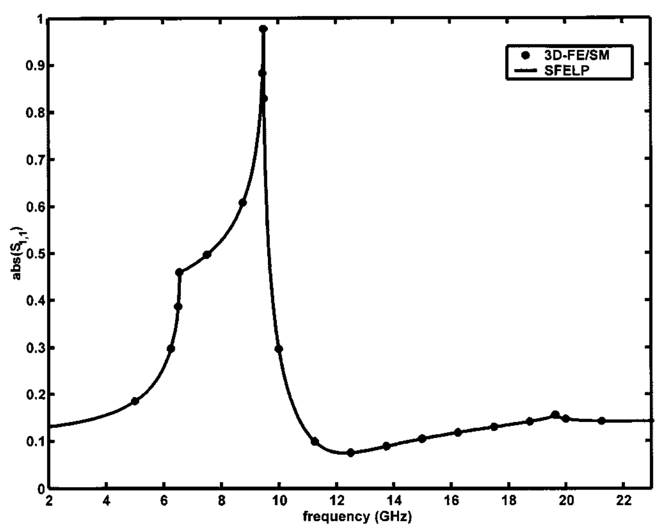

Fig. 9. Magnitude of the reflection coefficient S_{11} of the first mode for the concentric step discontinuity between rectangular waveguides.

Only the first eight modes in each port with the same symmetry as the fundamental mode has been considered since the admittance parameter related to higher modes are very close to zero. In Figs. 7 and 8, the relative error in percentage compared with the GAM obtained with the 3-D FE/SM at this pair of frequencies can be seen. It can be seen that, in the worst case (for the parameters with lower absolute values), the difference between the direct method and the approximation with SyMPVL is less than 0.6%.

Since the elements of the GAM are obtained with a very good precision, the GSM derived from the GAM is also achieved with a very good precision, and not only for the absolute value of the reflection parameter of the first mode (Fig. 9). Thus, a good agreement between the SFELP method and the 3-D FE/SM direct method for higher order parameters of the GSM is obtained as shown in Figs. 10 and 11, where two of these higher order parameters have been calculated for several frequencies.

B. Cylindrical Cavity Resonator

The second analyzed circuit is a cylindrical cavity resonator coupled to input and output WR75 rectangular waveguides through rectangular irises. The cavity length is 100 mm and its radius is equal to 12 mm. The dimensions of the irises are 9.7 mm $\times 3$ mm $\times 1$ mm.

For its study, the whole structure has been assembled by joining two transitions between a rectangular waveguide and a circular waveguide including the coupling iris, by means of a section of circular waveguide. Since the transitions are identical, it is only necessary to analyze one of these. Thus, the global GSM is calculated by linking the GSM of the transition with itself through a section of circular waveguide analytically included (Fig. 12).

Although the computation of the transition can be studied considering only one mode in each port, a multimode analysis

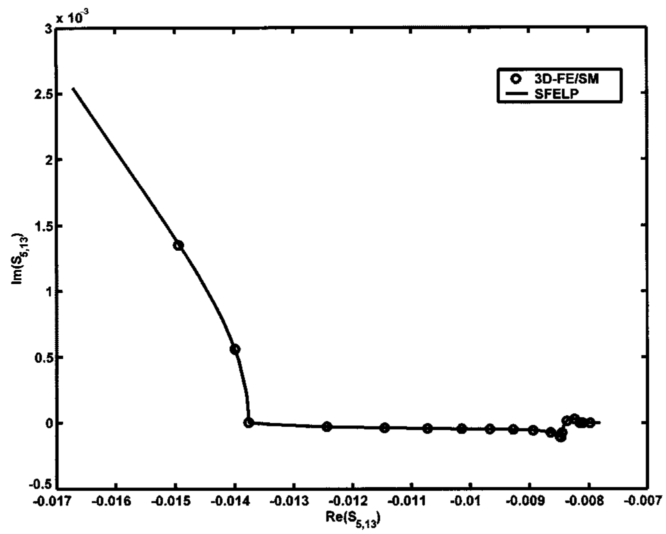

Fig. 10. S_{12}-parameter between the fifth mode considered in the first port and the fourth mode considered in the second port for the concentric step discontinuity between rectangular waveguides.

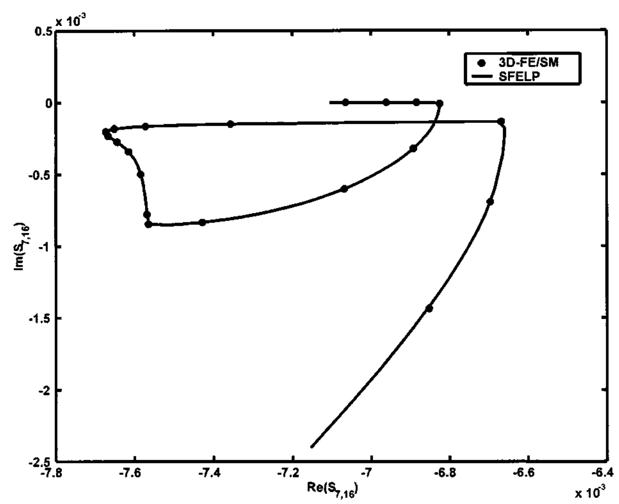

Fig. 11. S_{12}-parameter between the seventh mode considered in the first port and the eighth mode considered in the second port for the concentric step discontinuity between rectangular waveguides.

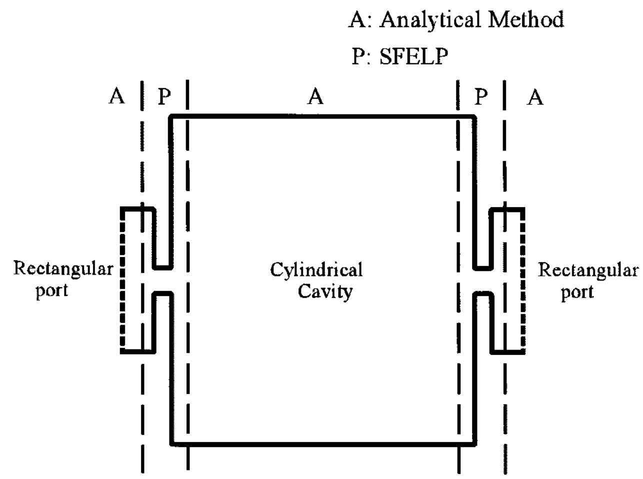

Fig. 12. Segmentation for the analysis of a cylindrical cavity resonator.

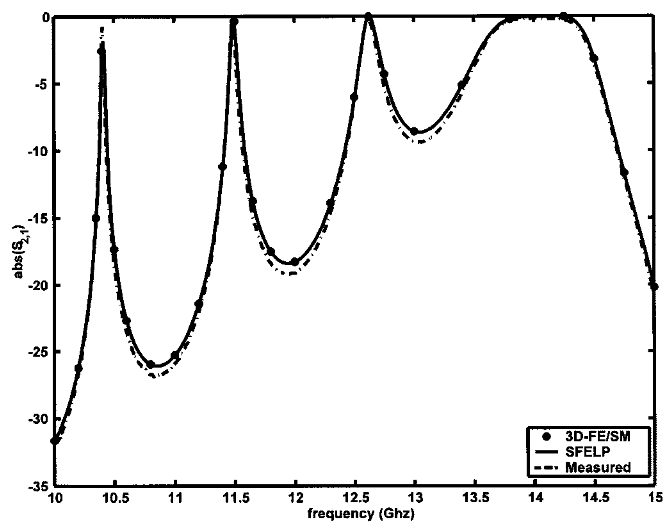

Fig. 13. Magnitude of the S_{21}-parameter for the cylindrical cavity resonator.

is preferable since it allows situating the ports very close to circular-to-iris waveguide discontinuity and, as a consequence, reducing the size of the mesh involved. Besides, the symmetry of the geometry and of the excitations allows the computational volume of the transition to be reduced to a quarter.

The device has been studied in a wide band by applying the SFELP method choosing f_0 equal to the central frequency. For comparison, the 3-D FE/SM has been used to calculate the response of the device at some frequencies of the considered band. Fig. 13 shows the obtained response for the transmission parameter including measurements.

In order to evaluate the effect of choosing other value for f_0, the response was calculated at intervals of 500 MHz for this parameter, extreme to extreme of the band. Differences of less than 0.01 dB between the 11 responses were obtained in the worst case.

The computation of the whole band with the SFELP method takes approximately 3 min on a PC-Pentium II 400 with 384-Mbyte RAM. Direct computation with the 3-D FE/SM requires 1 min per frequency in the same PC.

C. Rectangular-to-Coax Transition

Finally, we have studied a commercial transition between a coaxial connector and a WR-90 rectangular guide with two tuning screws. This problem has already been solved by using a hybrid 2-D FE/MM and 3-D FE/SM for a few frequencies [1]. In this paper, the same device is analyzed by the SFELP method to obtain a continuous broad-band response. Considerations of symmetry allow the reduction of the mesh by one half.

The segmentation used in this case considers only regions where the SFELP method is applied and regions that are analytically included. The screws and coupling between coax and rectangular waveguide belong to the former kind of regions, while the waveguides of connection and short circuit belong to the latter (Fig. 14). Up to 50 modes have been used in the ports between the probe and first screw, six modes in the coax port, and 30 modes in the rest of the ports.

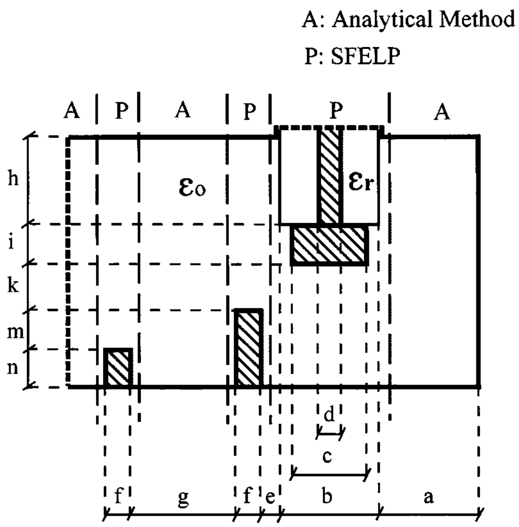

Fig. 14. Segmentation for the analysis of a coax-to-waveguide transition. $a = 3.835$, $b = 4.115$, $c = 2.8$, $d = 1.27$, $e = 0.15$, $f = 1.8$, $g = 4.35$, $h = 3.25$, $i = 2.1$, $k = 1.91$, $m = 1.7$, $n = 1.2$ (all dimensions are expressed in millimeters). $\varepsilon_r = 1.9873$.

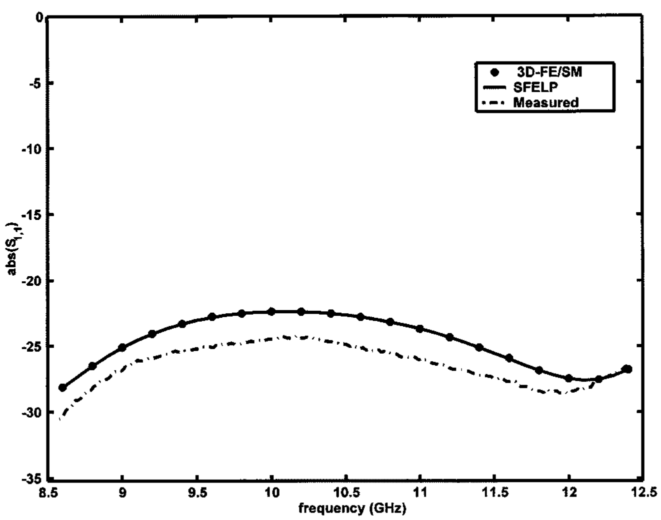

Fig. 15. Magnitude of the reflection coefficient S_{11} in decibels for the coax-to-waveguide transition.

Fig. 15 shows the computed and measured reflection parameter. For comparison, results have also been obtained with the 3-D FE/SM frequency to frequency. For each one of the three regions solved by applying the SFELP method, the value of f_0 has been chosen at random.

The computation of the overall GSM for the whole studied band needed 6 min, while the analysis frequency by frequency required 1 min and 40 s per frequency point in the same PC-Pentium II 400 with 384-Mbyte RAM.

VI. Conclusions

In this paper, the SyMPVL algorithm has been applied to a segmentation method based on a 3-D FE/SM for obtaining the spectral response of microwave circuits (SFELP). The SFELP algorithm allows us to make a fast evaluation of the GAM in a wide band of frequencies. Since we obtain multimode matrices, a close connection between the analyzed regions can be made in a broad band. As a consequence, this method can be used as a powerful tool for designing complex microwave circuits: if we want to change some of the design parameters in the circuit, we only need to repeat the computation of the circuit region modified by this parameter, and this region is efficiently analyzed because its size is reduced and a fast frequency sweep technique is used.

Results show that the method achieves considerable accuracy in the calculation of every one of the elements of the GSM and the computational time is drastically reduced since the two techniques for saving time are used together: the SyMPVL algorithm and segmentation method.

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