MoM/BI–RME Analysis of Boxed MMICs with Arbitrarily Shaped Metallizations

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Abstract— **In this paper, we propose a novel approach for the analysis of shielded microstrip circuits, composed of a number of thin metallic areas with arbitrary shapes and finite conductivity, embedded in a multilayered lossy medium. The analysis is based on the solution of an Integral Equation (IE) obtained by enforcing the proper boundary condition to the electric field on the metallic areas. The solution of the IE is obtained by the Method of Moments (MoM) with entire domain basis functions, which are numerically determined by the Boundary Integral–Resonant Mode Expansion (BI–RME) method. The use of the BI–RME method allows for the efficient calculation of the basis functions independently on the shape of the domain, thus permitting the analysis of a wide class of circuits. Two examples demonstrate the accuracy, rapidity, and flexibility of the proposed method.**

Keywords— **MMICs, Integral Equations, Moment Method, Entire Domain Basis Functions, Microstrip Filters.**

I. Introduction

In the last years, a considerable interest has been directed to the design of boxed multilayered circuits (Fig. 1). This configuration is typically considered in the design of many actual Monolithic Microwave Integrated Circuits (MMICs), both in single–layer [1] and in multilayered configuration [2,3].

Among the possible numerical methods applied to the analysis of this type of structures, the Integral Equation (IE) method is by far one of the most efficient. The IE method can be formulated either in the spectral [4] or in the spatial domain [5]. The resulting integral equation is solved by the Method of Moments (MoM), usually considering sub–domain basis functions (*e.g.*, roof–tops [6,7] or basis functions on triangular domains [8,9]).

Recently, the IE/MoM method in the spectral domain was applied with entire domain basis functions [10]. The main advantage of using the vector modal functions derived in that work is the dramatic reduction in the order of the MoM matrix, since few entire domain basis functions are usually sufficient to represent the unknown currents. Moreover, the calculation of the MoM matrix is enhanced because of the rapid decrease of the spectral components to be added subsequently for the calculation of the matrix elements. It is noted, however, that the original work derived in [10] is limited to areas with a rectangular shape, where the entire domain basis functions are known analytically.

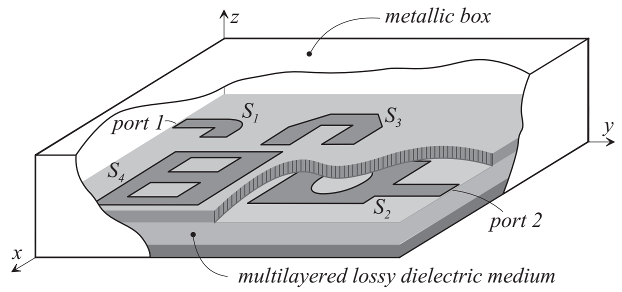

Fig. 1. A shielded MMIC with arbitrarily shaped metallic areas in a multilayered lossy medium. The patches can be placed at different height and they may overlap.

In this paper, we present the extension of the method proposed in [10] to the case of metallic areas with an arbitrary shape (Fig. 1). The entire domain basis functions are determined numerically by the Boundary Integral–Resonant Mode Expansion (BI–RME) method [11]. The use of the BI–RME method has two main advantages. The first is the possibility of obtaining entire domain basis functions for arbitrary shapes in a short time, and the second is that the entries of the MoM matrix are practically obtained as a by–product of the method itself. In fact, the surface integrals involved in the calculations of the MoM matrix can be converted into line integrals on the boundary of the metallic areas, and the quantities required on the boundary are the basic output of the BI–RME calculation.

A preliminary discussion of the proposed algorithm was presented in [12]. This paper gives a comprehensive explanation of the MoM/BI–RME method, adding two novel capabilities: metallic areas including a port may have an arbitrary shape, and multiply connected metallizations can be considered.

II. IE/MoM Approach

Let us consider the structure shown in Fig. 2, consisting of a multilayered medium and P metallic areas with arbitrary shapes $S_1, \ldots, S_P$, possibly located at different interfaces. The circuit is fed at the frequency ω at K ports, ($K \leq P$) conventionally defined on the first K areas $S_1, \ldots, S_K$.

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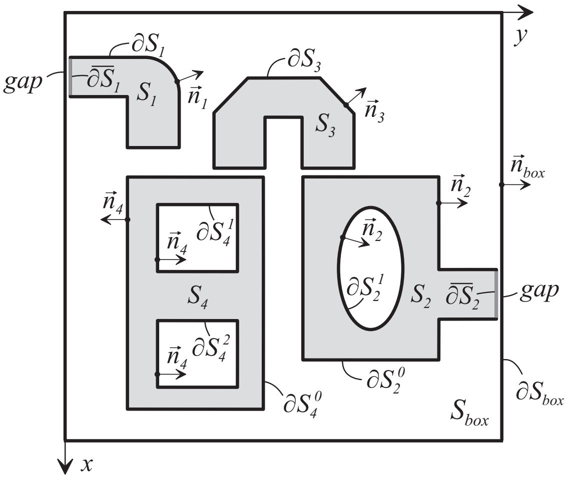


Fig. 2. Different metallic areas considered in the analysis: simply (S_1) or multiply connected patches attached to a port (S_2), simply (S_3) or multiply connected internal patches (S_4). ∂S_p represents the boundary of the area S_p except the possible part corresponding to a port (denoted by $\overline{\partial S}_p$). In case of multiply connected areas, ∂S_p consists of many lines $\partial S_p^0, \partial S_p^1, \ldots$.

As usual [5,13,14], the ports are represented as small gaps between the metallization and the wall of the box (delta–gap excitations).

In [10] the analysis is based on the solution of a system of P integral equations, which are obtained by enforcing the boundary condition to the transverse–to–z electric field at all the metallic areas:

$$Z\vec{J}_p(\vec{r}) - \sum_{q=1}^{P} \int_{S_q} \overleftrightarrow{G}(\vec{r},\vec{r}\,'|\omega)\cdot \vec{J}_q(\vec{r}\,')\,dS' = \begin{cases} -\vec{n}_p\, v_p \delta(\vec{r},\vec{r}_p)|_{\vec{r}_p\in\overline{\partial S}_p} & (p=1,\ldots,K) \\ 0 & (p=K+1,\ldots,P) \end{cases} \quad (1)$$

where: the points $\vec{r}$, $\vec{r}\,'$ belongs to S_p and S_q, respectively; $\overline{\partial S}_p$ denotes the part of the boundary of S_p that belongs to the p-th port; $\vec{n}_p$ is the outward normal; v_p is the voltage applied to the p–th port; Z is the "sheet impedance" of the metallizations. The choice of Z is problem–dependent. For instance: in the case of a single–layer microstrip circuit with a metallization thickness t much larger than the skin depth δ, we can use the surface impedance of the conductors $Z = Z_s = (1+j)\rho/\delta$ (ρ is the resistivity of the metal); in the case of low frequency calculations ($t \ll \delta$), we can use $Z = \rho/t$. Moreover, $\vec{J}_q$ is the (unknown) current density on S_q, and the Green's function $\overleftrightarrow{G}$ is given by [15]

$$\overleftrightarrow{G}(\vec{r},\vec{r}'|\omega) = \sum_m V_m(z,z'|\omega)\,\vec{\mathcal{E}}_m(x,y)\,\vec{\mathcal{E}}_m(x',y') \qquad (2)$$

where $\vec{\mathcal{E}}_m$ are the transverse electric modal vectors of the TE and TM modes of the box, with the normalization $\int_{S_{box}} |\vec{\mathcal{E}}_m|^2 dS = 1$. The expressions of $\vec{\mathcal{E}}_m$ are

$$\vec{\mathcal{E}}'_m = -\frac{\nabla_T \chi'_m}{k'_m} \qquad \text{(TM modes)} \qquad (3)$$

$$\vec{\mathcal{E}}''_m = -\vec{u}_z \times \frac{\nabla_T \chi''_m}{k''_m} \qquad \text{(TE modes)} \qquad (4)$$

where χ'_m and χ''_m are the eigenfunctions of the Helmholtz equation with the Dirichlet or Neumann boundary conditions on ∂S_{box} (see Fig. 2), and k'_m, k''_m are the corresponding eigenvectors. Finally, functions V_m are determined by considering the equivalent modal transmission lines for the layered box [10,16].

Equation (1) is solved by applying the MoM in the Galerkin version. The unknown current density $\vec{J}_p$ is represented through a suitable set of N_p basis functions $\vec{e}_r^{\,(p)}$ defined on the p–th patch

$$\vec{J}_p = \sum_{r=1}^{N_p} \xi_r^{(p)} \vec{e}_r^{\,(p)} \qquad (p=1,\ldots,P) \qquad (5)$$

where $\xi_r^{(p)}$ are unknown coefficients.

As discussed in [10], the calculation of the MoM matrices involves frequency–independent coefficients of two types. The former represents the *coupling integral* between the r–th basis function on the p–th metallic area and the m–th modal vector of the box, and is given by

$$\mathcal{C}_{rm}^{(p)} = \int_{S_p} \vec{e}_r^{\,(p)}(\vec{r}) \cdot \vec{\mathcal{E}}_m(\vec{r})\,dS \qquad (6)$$

The latter is the projection of the delta–gap excitation of the p–th port on the r–th basis function (*port integral*), and is given by

$$\mathcal{P}_r^{(p)} = \int_{\overline{\partial S}_p} \vec{e}_r^{\,(p)}(\vec{r}) \cdot (-\vec{n}_p)\,d\ell \qquad (7)$$

For any frequency, the scattering parameters are calculated straightforwardly from the coefficients $\xi_r^{(p)}$ obtained by the solution of the MoM system [10].

III. Entire Domain Basis Functions

A key feature of the present approach is the use of a set of entire domain basis functions, *i.e.*, functions $\vec{e}_r^{\,(p)}$ which span the entire domain S_p.

The advantage of using such functions has been demonstrated in [10], with reference to the case where all surfaces S_p are rectangular. More specifically, the electric modal vectors of rectangular waveguides bounded by magnetic or mixed–type walls have been used as basis functions. In this paper the same concept is applied to metallization of arbitrary shapes, with no restriction on the geometry of the surfaces S_p. In this case, the basis functions must be determined numerically and the efficiency of the numerical method used for their calculation is a vital issue. The BI–RME method discussed in Sec. V permits to determine very efficiently a lot of basis functions.

In the case of simply connected surfaces, we have to calculate two classes of basis functions expressed by

$$\vec{e}_r^{\,\prime(p)} = -\vec{u}_z \times \frac{\nabla_T \psi_r^{\prime(p)}}{\kappa_r^{\prime(p)}} \tag{8}$$

$$\vec{e}_r^{\,\prime\prime(p)} = -\frac{\nabla_T \psi_r^{\prime\prime(p)}}{\kappa_r^{\prime\prime(p)}} \tag{9}$$

where the pairs $\{\psi_r^{\prime(p)}, \kappa_r^{\prime(p)}\}$ and $\{\psi_r^{\prime\prime(p)}, \kappa_r^{\prime\prime(p)}\}$ are the eigensolutions of the homogeneous Helmholtz equation in the domain S_p, i.e.,

$$\nabla_T^2 \psi_r^{\prime(p)} + {\kappa_r^{\prime(p)}}^2 \psi_r^{\prime(p)} = 0 \quad \text{in } S_p \tag{10}$$

$$\nabla_T^2 \psi_r^{\prime\prime(p)} + {\kappa_r^{\prime\prime(p)}}^2 \psi_r^{\prime\prime(p)} = 0 \quad \text{in } S_p \tag{11}$$

In the case of N–times connected surfaces, the set of basis functions must be supplemented with $N-1$ additional functions

$$\vec{e}_r^{\,0(p)} = -\vec{u}_z \times \nabla_T \psi_r^{0(p)} \tag{12}$$

where $\psi_r^{0(p)}$ satisfy the Laplace equation in the domain S_p, i.e.,

$$\nabla_T^2 \psi_r^{0(p)} = 0 \quad \text{in } S_p \tag{13}$$

The boundary conditions are different for metallizations connected or not connected to ports.

In the case of metallizations not connected to ports (*e.g.*, S_3 and S_4 in Fig. 2), $\vec{J}_p$ is tangent to the whole boundary of S_p. The same boundary condition on the basis functions is satisfied provided that

$$\psi_r^{\prime(p)} = 0 \quad \text{on } \partial S_p \tag{14}$$

$$\partial \psi_r^{\prime\prime(p)} / \partial n_p = 0 \quad \text{on } \partial S_p \tag{15}$$

$$\psi_r^{0(p)} = \begin{cases} 1 & \text{on the inner contour } \partial S_p^i \\ 0 & \text{on } \partial S_p - \partial S_p^i \end{cases} \tag{16}$$

In the case of metallizations connected to ports (*e.g.*, S_1 and S_2 in Fig. 2), $\vec{J}_q$ is perpendicular to the port segment $\overline{\partial S}_p$. In this case, $\psi_r^{\prime(p)}$, $\psi_r^{\prime\prime(p)}$, and $\psi_r^{0(p)}$ must satisfy the mixed boundary conditions

$$\begin{cases} \psi_r^{\prime(p)} = 0 & \text{on } \partial S_p \\ \partial \psi_r^{\prime(p)} / \partial n_p = 0 & \text{on } \overline{\partial S}_p \end{cases} \tag{17}$$

$$\begin{cases} \partial \psi_r^{\prime\prime(p)} / \partial n_p = 0 & \text{on } \partial S_p \\ \psi_r^{\prime\prime(p)} = 0 & \text{on } \overline{\partial S}_p \end{cases} \tag{18}$$

$$\begin{cases} \psi_r^{0(p)} = \begin{cases} 1 & \text{on the inner contour } \partial S_p^i \\ 0 & \text{on } \partial S_p - \partial S_p^i \end{cases} \\ \partial \psi_r^{0(p)} / \partial n_p = 0 \quad \text{on } \overline{\partial S}_p \end{cases} \tag{19}$$

It is worthy noting that, in the case of metallizations connected to ports, ∂S_p denotes the boundary of S_p but the port segment $\overline{\partial S}_p$.

IV. Coupling and Port Integrals

When considering metallic areas with a rectangular shape the coupling integrals (6) and the port integrals (7) can be calculated analytically by using the analytical expressions of the basis functions (see [10], for instance). This possibility is precluded in the case of arbitrary shapes, because the basis functions are determined numerically. In this case, the surface integration (6) is a time consuming task, especially in cases of basis functions determined by a boundary integral method, since it requires the numerical evaluation of the basis functions in many points within the integration domain S_p. However, the coupling integrals (6) can be transformed from surface to line integrals, thus reducing dramatically the computing time. As shown in the Appendix, we have

$$\int_{S_p} \vec{e}_r^{\,\prime(p)} \cdot \vec{\mathcal{E}}_m^{\prime} \, dS = 0 \tag{20}$$

$$\int_{S_p} \vec{e}_r^{\,\prime\prime(p)} \cdot \vec{\mathcal{E}}_m^{\prime} \, dS = \frac{\kappa_r^{\prime\prime(p)}}{k_m^{\prime}\left({\kappa_r^{\prime\prime(p)}}^2 - {k^{\prime}_m}^2\right)} \int_{\partial S_p} \psi_r^{\prime\prime(p)} \frac{\partial \chi_m^{\prime}}{\partial n_p} \, d\ell \tag{21}$$

$$\int_{S_p} \vec{e}_r^{\,0(p)} \cdot \vec{\mathcal{E}}_m^{\prime} \, dS = 0 \tag{22}$$

$$\int_{S_p} \vec{e}_r^{\,\prime(p)} \cdot \vec{\mathcal{E}}_m^{\prime\prime} \, dS = \frac{k_m^{\prime\prime}}{\kappa_r^{\prime(p)}\left({\kappa_r^{\prime(p)}}^2 - {k^{\prime\prime}_m}^2\right)} \int_{\partial S_p} \chi_m^{\prime\prime} \frac{\partial \psi_r^{\prime(p)}}{\partial n_p} \, d\ell \tag{23}$$

$$\int_{S_p} \vec{e}_r^{\,\prime\prime(p)} \cdot \vec{\mathcal{E}}_m^{\prime\prime} \, dS = \frac{1}{\kappa_r^{\prime\prime(p)} k_m^{\prime\prime}} \int_{\partial S_p} \psi_r^{\prime\prime(p)} \frac{\partial \chi_m^{\prime\prime}}{\partial t_p} \, d\ell \tag{24}$$

$$\int_{S_p} \vec{e}_r^{\,0(p)} \cdot \vec{\mathcal{E}}_m^{\prime\prime} \, dS = -\frac{1}{k_m^{\prime\prime}} \int_{\partial S_p} \chi_m^{\prime\prime} \frac{\partial \psi_r^{0(p)}}{\partial n_p} d\ell \tag{25}$$

where $\partial / \partial t_p$ is the derivative along the boundary, namely in the direction of $\vec{t_p} = \vec{u}_z \times \vec{n}_p$.

It is noted that these formulas hold true in both cases of metallizations connected or not connected to ports.

For the port integrals (7), we easily obtain

$$\int_{\overline{\partial S}_p} \vec{e}_r^{\,\prime(p)}(\vec{r}) \cdot (-\vec{n}_p) \, d\ell = 0 \tag{26}$$

$$\int_{\overline{\partial S}_p} \vec{e}_r^{\,\prime\prime(p)}(\vec{r}) \cdot (-\vec{n}_p) \, d\ell = \frac{1}{\kappa_r^{\prime\prime(p)}} \int_{\overline{\partial S}_p} \frac{\partial \psi_r^{\prime\prime(p)}}{\partial n_p} \, d\ell \tag{27}$$

$$\int_{\overline{\partial S}_p} \vec{e}_r^{\,0(p)}(\vec{r}) \cdot (-\vec{n}_p) \, d\ell = 0 \tag{28}$$

V. Application of the BI–RME method

In the analysis of circuits of practical interest some tens of basis functions (8) and (9) are usually needed for each metallic area. This, in turn, requires the calculation of some tens of eigensolutions of the Helmoltz equations (10), (11).

In the past years, some of the authors developed a novel method (the BI–RME method) for the solution of the Helmoltz equation in arbitrary domains [17,18,19]. A comprehensive description of the BI–RME method is reported in

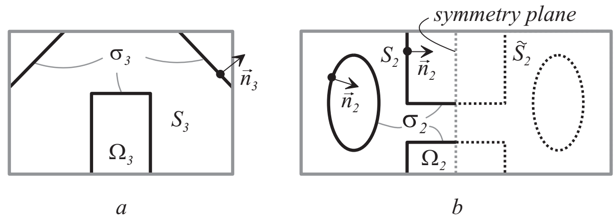


Fig. 3. Geometry for the application of the BI–RME method: *a*) an internal metallic area, *b*) a metallic area connected to a port.

a book [11]. In this section, we limit ourselves to a brief outline of the BI–RME method, to higlight its advantages in the calculation of entire domain basis functions.

The BI–RME method is a modified boundary integral approach for the evaluation of eigenfunctions. The surface S_p (either simply or multiply connected) is considered as a part of a fictitious enlarged domain Ω_p with a rectangular shape (Fig. 3*a*). The eigenfunctions to be determined are defined in Ω_p, and are assumed to vanish outside S_p. They are expressed as combinations of Boundary Integrals (BI) and a Resonant Mode Expansion (RME), involving the modal potentials of the region Ω_p. The boundary integrals involve $\partial\psi_r^{\prime(p)}/\partial n_p$ and $\psi_r^{\prime\prime(p)}$ over the line σ_p (see Fig. 3*a*), which corresponds to the part of ∂S_p not coincident with the rectangular boundary. Using the BI-RME representation of the eigenfunctions and imposing the proper boundary conditions on σ_p, the eigenvalue problems (10) and (11) are converted into integral–differential equations. As in the case of the conventional Boundary Element Method (BEM), the discretized problem resulting from the application of the BI–RME method is much smaller than in conventional approaches based on differential equations (FEM, FDFD, ...). Differently from the conventional BEM, the BI–RME method leads to the determination of the eigenfunctions by the solution of a linear matrix eigenvalue problem. In particular, it provides as eigenvalues $\kappa_r^{\prime(p)}$ and $\kappa_r^{\prime\prime(p)}$ up to a prescribed value κ_{max}, and as eigenfunctions $\partial\psi_r^{\prime(p)}/\partial n_p$ and $\psi_r^{\prime\prime(p)}$ over the line σ_p and the modal amplitudes of the RME.

The method is very efficient and reliable, also in cases where a large number of eigenfunctions have to be determined. Moreover, no spurious modes are found. Furthermore, it is worth noting that the order of the matrix eigenvalue problem to be solved depends on the extension of the line σ_p and the surface of the resonator Ω_p. For this reason, the efficiency of the BI–RME method highly improves when a large part of the boundary of S_p fits with the rectangular boundary as in the example in Fig. 3*a*.

The evaluation of coupling integrals (21), (23), and (24) requires $\partial\psi_r^{\prime(p)}/\partial n_p$ and $\psi_r^{\prime\prime(p)}$ on ∂S_p. On the portion σ_p, these quantities are directly the solutions of the BI–RME method. On tho other part of ∂S_p, they are obtained from the BI-RME representation of the eigenfunctions (see (5.44) and (5.94) in [11].) Even if a post–processing is required for obtaining the boundary values on $\partial S_p - \sigma_p$, it is convenient to let ∂S_p coincide with $\partial\Omega_p$ as much as possible. In fact, this reduces the dimensions of the eigenvalue problems to be solved, thus increasing the rapidity and accuracy of the solution.

To solve the Helmoltz equation in the case of a metallization connected to a port, the exterior domain Ω_p includes not only S_p, but also its mirror image $\widetilde{S}_p$, as shown in Fig. 3*b*. The problem is solved by imposing an even or an odd symmetry condition with respect to the symmetry plane shown in Fig. 3*b*. The details on the implementation of the BI–RME method taking into account the symmetries are discussed in [11], Sec. 5.2.3.

Finally, for multiply connected surfaces, all the possible basis functions (12) must be considered, requiring the determination of all the solutions $\psi_r^{0(p)}$ of the Laplace equation (13). These basis functions are obtained by solving (13) through the conventional BEM [17]. Even in this case, when the patch is connected to a port it is possible to solve the Laplace equation by creating a mirror image $\widetilde{S}_p$ of S_p, and considering an even symmetry condition on the symmetry plane.

VI. Numerical Results

We used the code for the analysis of printed circuits involving resonators with complex shapes, which fully exploit the capabilities of the method.

The first example refers to the analysis of a narrow–band microstrip filter composed of two T–shaped port elements and two square–loop resonators (Fig. 4), firstly proposed in [20]. The results obtained by the MoM/BI–RME approach are reported in Fig. 5 and compared with experimental data and simulations given in [20], showing a good agreement. The convergence was obtained with 4000 modes of the box and 62 basis functions (8 on each T–shaped line and 23 on each loop resonator), corresponding to $\kappa_{max} = 1.153\ mm^{-1}$.

For this example, we report in Fig. 6 the study of the convergence properties of the MoM/BI–RME method. In particular, we verified the convergence when varying the number of basis functions (Fig. 4*a*), and when varying the number of modes of the box (Fig. 4*b*). These graphs show that the frequency response does not change when considering more than 62 basis functions or more than 4000 modes of the box.

The calculation of the frequency response of Fig. 4 takes 22 *sec* for the determination of the basis functions and the evaluation of the coupling and port integrals, and 0.135 *sec* for the MoM solution in each frequency point (on a Pentium III at 1 *GHz*). Thus, the total computing time for the analysis in 100 frequency points is 35.5 *sec*. It is worthy observing that taking advantage of the symmetries of the geometry (which were not exploited in our analysis) should lead to a dramatic reduction of the total computing time.

The second example refers to the analysis of a narrow–band microstrip filter composed of two open–loop resonators (Fig. 7) [20]. The analysis of this structure (already presented in [12]) is particularly challenging, since the lines and the loops are separated by very narrow capacitive gaps, and the surface current must be accurately represented near these gaps. Consequently, in this case, the analysis requires more basis functions than in the previous example. Fig. 8 shows the frequency response of the filter considering 4000 modes of the box and 158 basis functions (12 on each port line, 22 on the middle line, and 56 on each open–loop) corresponding to $\kappa_{max} = 3.144\ mm^{-1}$. The results are a good agreement with the theoretical and experimental data taken from [20]. The computing time (without exploiting the symmetries) is 48 *sec* for the calculation of the basis functions and of the coupling and port integrals, and 0.63 *sec* for the MoM solution in each frequency point (on a Pentium III at 1 GHz). Thus, the total computing time for the analysis in 100 frequency points is 111 *sec*.

As a final remark, we can observe that the selection of the basis functions in our approach is performed by a spectral criterion, including all the entire domain basis functions up to a prescribed κ_{max}. Especially in cases of metallizations where one of the dimensions is much larger than the other (*e.g.*, narrow strips), this criterion leads to the adoption of very large values of κ_{max}, in order to include in the set of basis functions a sufficient number of elements with significant variation along the narrow dimension. Of course, it can happen that many basis functions with uselessly rapid variation in the larger direction can be included in the basis. These functions could be discarded, but the procedure for their recognition is too complicate to be conveniently implemented in a general purpose computer code. Anyway, the numerical experiments presented above permit not to dramatize the problem, because we noted that it is sufficient to consider basis functions whose variation in the narrow dimension correspond to one or two sinusoidal oscillations. In spite of the roughness of the current representation the results are very good: this is, probably, dependent on the variational properties of the admittance parameters obtained by the Galerkin procedure.

VII. Conclusion

We have presented an efficient technique for the accurate analysis of multilayered shielded printed circuits composed of arbitrary shaped metallic areas. This technique is based on an Integral Equation solved by using the Method of Moments with entire domain basis functions. The basis functions are efficiently evaluated by the Boundary Integral–Resonant Mode Expansion method. This leads to MoM matrices of small size, even in the case of complex circuits. Moreover, the transformation of the coupling integrals from surface to line integrals permits to use the basic outputs of the BI–RME method for calculating the MoM matrix .

The analyses of circuits of practical interest have been reported and compared with both theoretical and experimental data, showing that the approach is indeed feasible and leads to a software code which is efficient an accurate.

Appendix

Following a procedure similar to the one presented in [21,22], the transformation of the coupling integrals from surface to line integrals is based on the application of

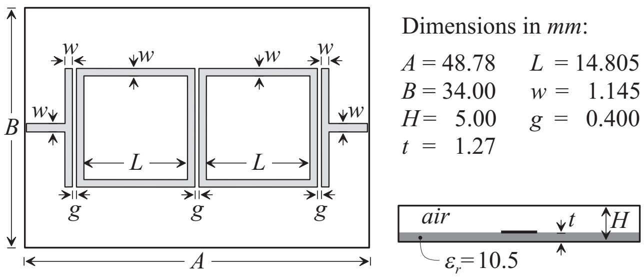


Fig. 4. Printed microstrip filter composed of T–shaped port elements and loop resonators.

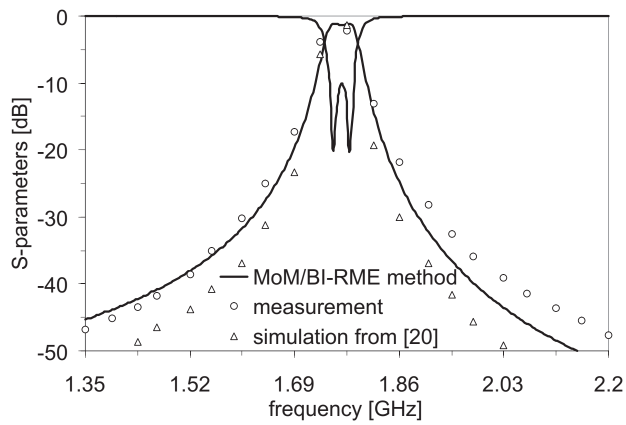


Fig. 5. Comparison between simulated and measured results presented in [20], and results obtained with the present approach, for the filter shown in Fig. 4.

Green's identity (see, for instance, [23], Appendix 2, Eq. 45)

$$\int_{S_p} \vec{\mathcal{A}} \cdot \nabla_T \mathcal{B}\, dS = \int_{\partial S_p} \mathcal{B}\, \vec{n} \cdot \vec{\mathcal{A}}\, d\ell + + \int_{\overline{\partial S}_p} \mathcal{B}\, \vec{n} \cdot \vec{\mathcal{A}}\, d\ell - \int_{S_p} \mathcal{B}\, \nabla_T \cdot \vec{\mathcal{A}}\, dS \qquad \text{(A.1)}$$

In the case of internal patches, obviously, the port segment $\overline{\partial S}_p$ is not defined and the line integral on $\overline{\partial S}_p$ vanishes.

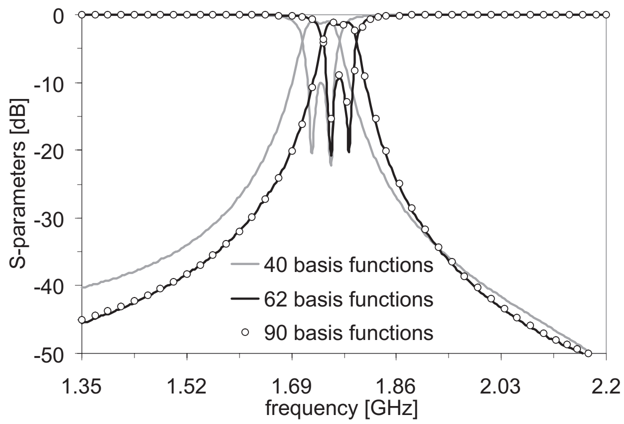
Derivation of (20)

The electric modal fields are related to scalar potentials through (8) and (3), thus resulting

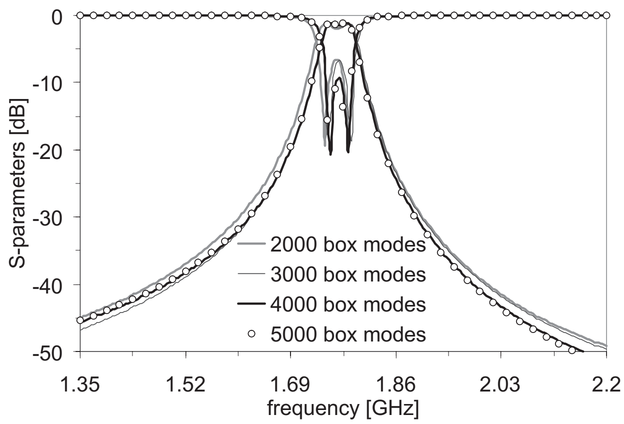
$$\int_{S_p} \vec{e}_r^{\,\prime(p)} \cdot \vec{\mathcal{E}}_m'\, dS = \int_{S_p} \vec{u}_z \times \frac{\nabla_T \psi_r^{\prime(p)}}{\kappa_r^{\prime(p)}} \cdot \frac{\nabla_T \chi_m'}{k_m'}\, dS = -\frac{1}{\kappa_r^{\prime(p)} k_m'} \int_{S_p} \nabla_T \psi_r^{\prime(p)} \cdot \vec{u}_z \times \nabla_T \chi_m'\, dS \qquad \text{(A.2)}$$

By applying (A.1) to (A.2) with $\vec{\mathcal{A}} = \vec{u}_z \times \nabla_T \chi_m'$ and $\mathcal{B} = \psi_r^{\prime(p)}$, we have

$$\int_{S_p} \vec{e}_r^{\,\prime(p)} \cdot \vec{\mathcal{E}}_m'\, dS = -\frac{1}{\kappa_r^{\prime(p)} k_m'} \int_{\partial S} \psi_q^{\prime(p)}\, \vec{n}_p \cdot \vec{u}_z \times \nabla_T \chi_m'\, d\ell - \frac{1}{\kappa_r^{\prime(p)} k_m'} \int_{\overline{\partial S}_p} \psi_q^{\prime(p)}\, \vec{n}_p \cdot \vec{u}_z \times \nabla_T \chi_m'\, d\ell + \frac{1}{\kappa_r^{\prime(p)} k_m'} \int_{S_p} \psi_r^{\prime(p)}\, \nabla_T \cdot (\vec{u}_z \times \nabla_T \chi_m')\, dS \qquad \text{(A.3)}$$



a



b

Fig. 6. Convergence behavior of the MoM/BI–RME method in the analysis of the circuit shown in Fig. 4: *a*) as a function of the total number of basis functions, when considering 4000 modes of the box; *b*) as a function of the number of modes of the box, when considering 62 basis functions.

In the r.h.s. of (A.3) the surface integral vanishes because of

$$\nabla_T \cdot (\vec{u}_z \times \nabla_T \mathcal{F}) = 0 \qquad \text{(A.4)}$$

for any scalar function $\mathcal{F}$ (see, for instance, [23], Appendix 2, Eq. 38), whereas the line integral on ∂S_p vanishes since $\psi_r^{\prime(p)} = 0$ on ∂S_p. Moreover, the line integral on $\overline{\partial S}_p$ is not defined for internal patches and, in the case of patches attached to ports, vanishes since $\vec{n}_p \cdot \vec{u}_z \times \nabla_T \chi'_m = -\partial \chi'_m / \partial t_p = 0$ on $\overline{\partial S}_p$. This proves (20).

Derivation of (21)

From (9) and (3) we have

$$\int_{S_p} \vec{e}_r^{\prime\prime(p)} \cdot \vec{\mathcal{E}}'_m \, dS = \int_{S_p} \frac{\nabla_T \psi_r^{\prime\prime(p)}}{\kappa_r^{\prime\prime(p)}} \cdot \frac{\nabla_T \chi'_m}{k'_m} \, dS$$
$$= \frac{1}{\kappa_r^{\prime\prime(p)} k'_m} \int_{S_p} \nabla_T \psi_r^{\prime\prime(p)} \cdot \nabla_T \chi'_m \, dS \qquad \text{(A.5)}$$

By applying (A.1) to (A.5) with $\vec{\mathcal{A}} = \nabla_T \chi'_m$ and $\mathcal{B} = \psi_r^{\prime\prime(p)}$, and using the Helmoltz equation $\nabla_T^2 \chi'_m = -k'^2_m \chi'_m$, we have

$$\int_{S_p} \vec{e}_r^{\prime\prime(p)} \cdot \vec{\mathcal{E}}'_m \, dS = \frac{1}{\kappa_r^{\prime\prime(p)} k'_m} \int_{\partial S_p} \psi_r^{\prime\prime(p)} \, \vec{n}_p \cdot \nabla_T \chi'_m \, d\ell$$
$$+ \frac{1}{\kappa_r^{\prime\prime(p)} k'_m} \int_{\overline{\partial S}_p} \psi_r^{\prime\prime(p)} \, \vec{n}_p \cdot \nabla_T \chi'_m \, d\ell$$
$$+ \frac{k'_m}{\kappa_r^{\prime\prime(p)}} \int_{S_p} \psi_r^{\prime\prime(p)} \, \chi'_m \, dS \qquad \text{(A.6)}$$

By remembering that $\psi_r^{\prime\prime(p)} = 0$ on $\overline{\partial S}_p$, the line integral on $\overline{\partial S}_p$ in (A.6) vanishes.

Moreover, by applying (A.1) to (A.5) with $\vec{\mathcal{A}} = \nabla_T \psi_r^{\prime\prime(p)}$ and $\mathcal{B} = \chi'_m$, and taking into account that $\nabla_T^2 \psi_r^{\prime\prime(p)} = -\kappa_r^{\prime\prime(p)2} \psi_r^{\prime\prime(p)}$, we have

$$\int_{S_p} \vec{e}_r^{\prime\prime(p)} \cdot \vec{\mathcal{E}}'_m \, dS = \frac{1}{\kappa_r^{\prime\prime(p)} k'_m} \int_{\partial S_p} \chi'_m \, \vec{n}_p \cdot \nabla_T \psi_r^{\prime\prime(p)} \, d\ell$$
$$+ \frac{1}{\kappa_r^{\prime\prime(p)} k'_m} \int_{\overline{\partial S}_p} \chi'_m \, \vec{n}_p \cdot \nabla_T \psi_r^{\prime\prime(p)} \, d\ell$$
$$+ \frac{\kappa_r^{\prime\prime(p)}}{k'_m} \int_{S_p} \psi_r^{\prime\prime(p)} \, \chi'_m \, dS \qquad \text{(A.7)}$$

By remembering that $\partial \psi_r^{\prime\prime(p)} / \partial n_p = 0$ on ∂S_p and that $\chi'_m = 0$ on $\overline{\partial S}_p$, the line integrals in (A.7) vanish. Therefore, by substituting the surface integral in the r.h.s. of (A.6) into (A.7), and considering $\kappa_r^{\prime\prime(p)2} \neq k'^2_m$, we finally obtain (21).

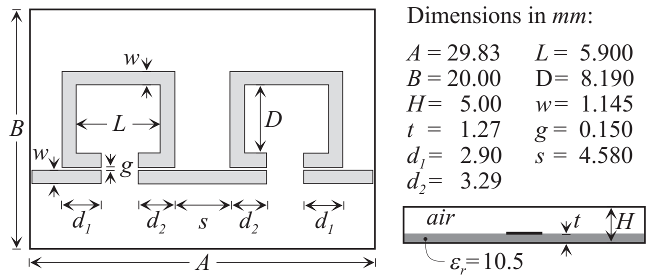


Fig. 7. Printed microstrip filter composed of two open–loop resonators.

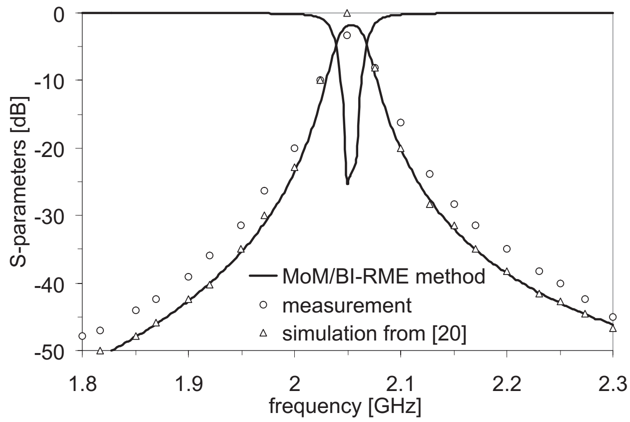


Fig. 8. Comparison between simulated and measured results presented in [21], and results obtained with the present approach, for the filter shown in Fig. 7.

Derivation of (22)

From (12) and (3) we have

$$\int_{S_p} \vec{e}_r^{\,0(p)} \cdot \vec{\mathcal{E}}'_m \, dS = \int_{S_p} \vec{u}_z \times \nabla_T \psi_r^{0(p)} \cdot \frac{\nabla_T \chi'_m}{k'_m} \, dS = \frac{1}{k'_m} \int_{S_p} \nabla_T \psi_r^{0(p)} \cdot \nabla_T \chi'_m \times \vec{u}_z \, dS \quad (A.8)$$

By applying (A.1) to (A.8) with $\vec{\mathcal{A}} = \nabla_T \chi'_m \times \vec{u}_z$ and $\mathcal{B} = \psi_r^{0(p)}$, we have

$$\int_{S_p} \vec{e}_r^{\,0(p)} \cdot \vec{\mathcal{E}}'_m \, dS = \frac{1}{k'_m} \int_{\partial S_p} \psi_r^{0(p)} \, \vec{n}_p \cdot \nabla_T \chi'_m \times \vec{u}_z \, d\ell + \frac{1}{k'_m} \int_{\overline{\partial S}_p} \psi_r^{0(p)} \, \vec{n}_p \cdot \nabla_T \chi'_m \times \vec{u}_z \, d\ell - \frac{1}{k'_m} \int_{S_p} \psi_r^{0(p)} \, \nabla_T \cdot (\nabla_T \chi'_m \times \vec{u}_z) \, dS \quad (A.9)$$

In the r.h.s. of (A.9), the surface integral vanishes due to (A.4). With regards to the line integral on ∂S_p, $\psi_r^{0(p)} = cost$ on each contour ∂S_p^i. In the case of a closed contour ∂S_p^i

$$\int_{\partial S_p^i} \vec{n}_p \cdot \nabla_T \chi'_m \times \vec{u}_z \, d\ell = \int_{\partial S_p^i} \nabla_T \chi'_m \cdot \vec{t}_p \, d\ell = 0 \quad (A.10)$$

(see [23], Appendix 2, Eq. 55). In the case of an open line ∂S_p^i (only for patches attached to ports),

$$\int_{\partial S_p^i} \vec{n}_p \cdot \nabla_T \chi'_m \times \vec{u}_z \, d\ell = \int_{\partial S_p^i} \nabla_T \chi'_m \cdot \vec{t}_p \, d\ell = \chi'_m(P) - \chi'_m(Q) \quad (A.11)$$

where P and Q are extreme points of the line ∂S_p^i, which are located on the box wall ∂S_{box}, where $\chi'_m = 0$. Finally, the line integral on $\overline{\partial S}_p$ vanishes since $\vec{n}_p \cdot \nabla_T \chi'_m \times \vec{u}_z = \partial \chi'_m / \partial t_p = 0$ on $\overline{\partial S}_p$. This proves (22).

Derivation of (23)

From (8) and (4) we have

$$\int_{S_p} \vec{e}_r^{\,\prime(p)} \cdot \vec{\mathcal{E}}''_m \, dS = \int_{S_p} \left(\vec{u}_z \times \frac{\nabla_T \psi_r^{\prime(p)}}{\kappa_r^{\prime(p)}} \right) \cdot \left(\frac{\nabla_T \chi''_m}{k''_m} \times \vec{u}_z \right) dS = -\frac{1}{\kappa_r^{\prime(p)} k''_m} \int_{S_p} \nabla_T \psi_r^{\prime(p)} \cdot \nabla_T \chi''_m \, dS \quad (A.12)$$

Therefore, the derivation of (23) is similar to the one of (21), only taking into account the different boundary condition of the scalar potential $\psi_r^{\prime(p)}$.

Derivation of (24)

From (9) and (4) we have

$$\int_{S_p} \vec{e}_r^{\,\prime\prime(p)} \cdot \vec{\mathcal{E}}''_m \, dS = \int_{S_p} \frac{\nabla_T \psi_r^{\prime\prime(p)}}{\kappa_r^{\prime\prime(p)}} \cdot \left(\frac{\nabla_T \chi''_m}{k''_m} \times \vec{u}_z \right) dS = \frac{1}{\kappa_r^{\prime\prime(p)} k''_m} \int_{S_p} \nabla_T \psi_r^{\prime\prime(p)} \cdot \nabla_T \chi''_m \times \vec{u}_z \, dS \quad (A.13)$$

By applying (A.1) to (A.13) with $\vec{\mathcal{A}} = \nabla_T \chi''_m \times \vec{u}_z$ and $\mathcal{B} = \psi_r^{\prime\prime(p)}$, we have

$$\int_{S_p} \vec{e}_r^{\,\prime\prime(p)} \cdot \vec{\mathcal{E}}''_m \, dS = \frac{1}{\kappa_r^{\prime\prime(p)} k''_m} \int_{\partial S_p} \psi_r^{\prime\prime(p)} \, \vec{n}_p \cdot \nabla_T \chi''_m \times \vec{u}_z \, d\ell + \frac{1}{\kappa_r^{\prime\prime(p)} k''_m} \int_{\overline{\partial S}_p} \psi_r^{\prime\prime(p)} \, \vec{n}_p \cdot \nabla_T \chi''_m \times \vec{u}_z \, d\ell - \frac{1}{\kappa_r^{\prime\prime(p)} k''_m} \int_{S_p} \psi_r^{\prime\prime(p)} \, \nabla_T \cdot (\nabla_T \chi''_m \times \vec{u}_z) \, dS \quad (A.14)$$

In the r.h.s. of (A.14), the surface integral vanishes due to (A.4). In the case of patches connected to ports, the line integral on $\overline{\partial S}_p$ vanishes since $\psi_r^{\prime\prime(p)} = 0$ on $\overline{\partial S}_p$. Moreover, in the line integral ∂S_p, $\vec{n}_p \cdot \nabla_T \chi''_m \times \vec{u}_z = \nabla_T \chi''_m \cdot \vec{t}_p$. This proves (24).

Derivation of (25)

From (12) and (4) we have

$$\int_{S_p} \vec{e}_r^{\,0(p)} \cdot \vec{\mathcal{E}}''_m \, dS = \int_{S_p} \left(\vec{u}_z \times \nabla_T \psi_r^{0(p)} \right) \cdot \left(\frac{\nabla_T \chi''_m}{k''_m} \times \vec{u}_z \right) dS = -\frac{1}{k''_m} \int_{S_p} \nabla_T \psi_r^{0(p)} \cdot \nabla_T \chi''_m \, dS \quad (A.15)$$

By applying (A.1) to (A.15) with $\vec{\mathcal{A}} = \nabla_T \psi_r^{0(p)}$ and $\mathcal{B} = \chi''_m$, we have

$$\int_{S_p} \vec{e}_r^{\,0(p)} \cdot \vec{\mathcal{E}}''_m \, dS = \frac{1}{k''_m} \int_{\partial S_p} \chi''_m \, \vec{n}_p \cdot \nabla_T \psi_r^{0(p)} \, d\ell + \frac{1}{k''_m} \int_{\overline{\partial S}_p} \chi''_m \, \vec{n}_p \cdot \nabla_T \psi_r^{0(p)} \, d\ell - \frac{1}{k''_m} \int_{S_p} \chi''_m \, \nabla_T^2 \psi_r^{0(p)} \, dS \quad (A.16)$$

In the r.h.s. of (A.16), the surface integral vanishes because $\nabla_T^2 \psi_r^{0(p)} = 0$, whereas the line integral on $\overline{\partial S}_p$ vanishes since $\partial \psi_r^{0(p)} / \partial n_p = 0$ on $\overline{\partial S}_p$. This proves (25).

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