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Optimized Analysis of Slotted Substrate Integrated Waveguides by a Method-of-Moments Mode-Matching Hybrid Approach

Guido Valerio[1], Massimiliano Casaletti[1], Josip Seljan[1],
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***Abstract* – A full-wave hybrid formulation is proposed for the efficient and accurate modeling of substrate integrated waveguides by rigorously accounting for all possible interactions among elements such as vertical metallic or dielectric posts and coupling or radiating slots. The method is specifically accelerated in order to maximize the efficiency of the analysis of common structures. Its flexibility allows for the study of a large class of devices, possibly in stacked-waveguide configurations, and for the characterization of radiated fields and input port parameters.**

1 INTRODUCTION

Substrate integrated waveguide (SIW) technology has received an increased interest in the last years especially for millimeter wave applications [1]. The basic idea relies on the use of arrays of metallic posts to realize waveguide channels in a dielectric substrate. The fabrication process is low-cost and suitable for standard printed circuit board fabrication. A number of novel antenna designs have been proposed during the years like multi-layer pillbox antennas, Rotman lenses with integrated phase shifters, etc [2], [3]. These antennas are electrically large and often consist of a large number of elements, such as metallic and dielectric cylinders, and both radiating and coupling slots. Unfortunately, available commercial solvers are incapable of efficiently analysing structures of greater size and complexity.

To this aim, a rigorous full-wave method has been developed, implementing a hybrid approach based on the method of moments (MoM) to handle coupling and radiating slots, and mode matching (MM) [4] for analyzing the scattering effects of metallic and dielectric posts inside parallel plate waveguides (PPWs). The MoM uses entire-domain basis functions to minimize the number of unknowns in large structures. An efficient Green’s function representation is chosen, based on a radial transmission-line expression. It is particularly attractive since it leads to a fast (exponentially) converging series at large radial distances [5]. On the other hand, the MM relies on an efficient cylindrical vector wave function expansion of the field. The coupling between post and slot is rigorously computed by solving a small number of small-sized linear systems. The solutions of these problems are stored and used several times in the code, thus minimizing the required computational effort.

Several optimizations can be performed in order to speed up the analysis of large SIW structures. For instance, practical criteria for the necessary number of vertical PPW modes can be established in order to obtain the desired accuracy with a minimal number of unknown. Furthermore, the number of azimuthal PPW modes on each post can be related to the radius of the post. Finally, common symmetries of slot arrays can be suitably taken into account to reduce the computation of slot-slot and slot-post coupling.

In this paper, the capabilities of the code, in terms of its accuracy and efficiency, are demonstrated through the analysis of a radiating structure.

2 HYBRID METHOD

The typical structure under analysis is shown in Fig. 1, where vertical cylindrical posts are placed inside a PPW, and radiating slots are etched on the PPW upper metal plate. The method can easily be applied also when different PPWs are stacked along the vertical direction, coupled through slots etched in their common plates. However, for the sake of brevity, only the single PPW of Fig. 1 will be explicitly discussed in this paper.

2.1 Method of Moments

The analysis is performed by replacing the slots by equivalent magnetic currents and substituting them with metallic conductors [see Fig. 2(a)]. In such a way, two problems are obtained: a half-space problem and a closed problem [see Fig. 2(b)].

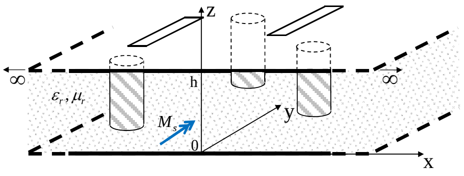

Figure 1: Geometry of the problem.

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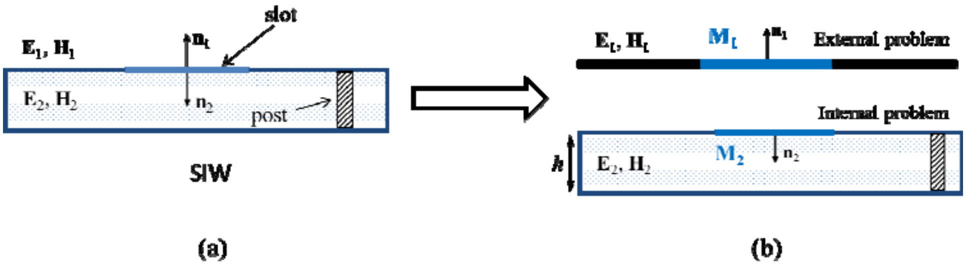


Figure 2: Application of the MoM. (a) Original structure. (b) Separation into an "external problem", and an "internal problem," including the PPW and the vertical posts.

The continuity of the electric field across the slots requires that the same set of magnetic currents should be considered in the two problems [i.e., $\mathbf{M}_1 = \mathbf{M}_2$ in Fig. 2(b)]. The continuity of the magnetic field across the slots leads to an integral equation coupling the outer and the inner regions through appropriate Green's functions. The integral equation is discretized through a MoM, by expressing the unknown magnetic currents as a sum of basis functions. A Galerkin scheme is chosen, so that basis functions are chosen as test functions. In particular, in the most common case of narrow rectangular slots, entire-domain basis functions are here implemented of the kind:

$$\mathbf{b}_{q,n}(u,v) = \hat{\mathbf{u}} b_{q,n}(u) = \hat{\mathbf{u}} \frac{1}{W_q} \sin\left[\frac{n\pi}{L_q}\left(u + \frac{L_q}{2}\right)\right] \quad (1)$$

for $-L_q/2 < u < L_q/2$, and $-W_q/2 < v < W_q/2$, where a local u-axis is associated to the qth slot along its length L_q, and orthogonal to its width W_q, with the origin at the slot center.

A uniform current along the transverse direction of each slot, as in to (1), is justified for narrow slots [5]. For wider or arbitrarily shaped slots different kind of basis functions could be implemented (e.g., edge-singular [6], subdomain functions [7], etc.) since the hybrid approach described in this paper is general and independent on the choice of the basis function.

The general entry $Y_{i,j}$ of the MoM matrix element is expressed as the sum of two contribution:

$$Y_{i,j} = Y_{i,j}^{\mathrm{HS}} + Y_{i,j}^{\mathrm{SIW}} \quad (2)$$

The term $Y_{i,j}^{\mathrm{HS}}$ is computed through the Green function $\underline{\mathbf{G}}^{\mathrm{HS}}$ of the half-space, easily found through the image theorem:

$$Y_{i,j}^{\mathrm{HS}} = \int_S \mathbf{b}_j(\mathbf{r}) \cdot \left[-j\omega\varepsilon \int_{S'} \underline{\mathbf{G}}^{\mathrm{HS}}(\mathbf{r},\mathbf{r}') \cdot \mathbf{b}_i(\mathbf{r}') d\mathbf{r}'\right] d\mathbf{r} \quad (3)$$

The computation of $Y_{i,j}^{\mathrm{HS}}$ is not described here since it can be performed by standard integration techniques. On the other hand, the term $Y_{i,j}^{\mathrm{SIW}}$ requires the knowledge of the magnetic field excited by the *i*th basis function *inside* the SIW, denoted as $\mathbf{H}^{\mathrm{SIW},i}$:

$$Y_{i,j}^{\mathrm{SIW}} = \int_{\mathrm{S}} \mathbf{b}_j(\mathbf{r}) \cdot \mathbf{H}^{\mathrm{SIW},i}(\mathbf{r}) d\mathbf{r} \quad (4)$$

2.2 Mode Matching

Unfortunately, this field $\mathbf{H}^{\mathrm{SIW},i}$ is not available in closed form due to the presence of the vertical posts. To overcome this limitation, $\mathbf{H}^{\mathrm{SIW},i}$ is expressed as the sum of a PPW contribution (in the absence of posts) and a post-scattered contribution $\mathbf{H}^{\mathrm{Posts},i}$. The former is computed by the PPW Green function, which is known in closed form. The latter is expressed as a superposition of cylindrical waves with any possible azimuthal and vertical dependency [8], [9]:

$$\begin{aligned}\mathbf{H}^{\mathrm{Posts},i}(\mathbf{r}) = &\sum_{p=1}^{N_{post}} \sum_{m=0}^{+\infty} \sum_{n=-\infty}^{+\infty} A_{m,n,p}^{\mathrm{TM},i} \mathbf{M}_n\left(k_{\rho_m}, k_{z_m}, \boldsymbol{\rho}-\boldsymbol{\rho}_p, z\right) \\ &+ \sum_{p=1}^{N_{\mathrm{post}}} \sum_{m=1}^{+\infty} \sum_{n=-\infty}^{+\infty} A_{m,n,p}^{\mathrm{TE},i} \mathbf{N}_n\left(k_{\rho_m}, k_{z_m}, \boldsymbol{\rho}-\boldsymbol{\rho}_p, z\right)\end{aligned} \quad (5)$$

(ρ, ϕ, z) being a cylindrical reference system, $\boldsymbol{\rho}_p$ the radial position of the pth post, the vertical and radial wave numbers are respectively $k_{z_m} = m\pi/h$ and $k_{z_m} = \sqrt{k^2 - (m\pi/h)^2}$. The cylindrical vector wave functions $\mathbf{M}$ and $\mathbf{N}$ are defined as:

$$\begin{aligned}\mathbf{M}_n &= \nabla \times \left[\hat{\mathbf{z}} H_n^{(2)}\left(k_{\rho_m}\rho\right) e^{-jn\phi} \cos\left(k_{z_m} z\right)\right] \\ \mathbf{N}_n &= \frac{1}{k} \nabla \times \nabla \times \left[\hat{\mathbf{z}} H_n^{(2)}\left(k_{\rho_m}\rho\right) e^{-jn\phi} \sin\left(k_{z_m} z\right)\right].\end{aligned} \quad (6)$$

The integer index m describes the vertical variation of the PPW TM and TE modes; the integer index n is related to the azimuthal variation of each mode around the cylinder axis; the p sum is performed over all the N_{post} posts.

A MM is then enforced on the surface of each vertical posts in order to determine the unknown complex amplitudes A in (5) [4]. Finally, once these coefficients are calculated for any basis function, the field $\mathbf{H}^{\text{SIW},i}$ can be used in the matrix entry (4).

Indeed, the computation of the matrix element (4) can be dramatically accelerated if we resort to suitable integral identities. Closed-form expressions of the spatial integral can be obtained, not shown here for the sake of brevity: the matrix element can thus be expressed as a sum over vertical modes, azimuthal modes, and posts.

Furthermore, several acceleration procedures can be employed in order to adapt the method to the specific symmetries of the structure (translational invariance of some slot, of some posts, etc.) and avoid the computation of duplicated elements in the MoM matrix or in the MM matrix. They have been implemented in the code and used in the simulations discussed in next section.

3 NUMERICAL RESULTS

The approach presented in the previous section is here applied to a realistic SIW antenna in order to validate its accuracy and flexibility. The structure selected is shown in Fig. 3. It consists in an array of five slotted waveguides, whose walls are realized through metallic posts. Each waveguide contains eight slots, and it is fed through a waveguide port. An extra post is used for input-matching purposes. A total of 674 posts is present.

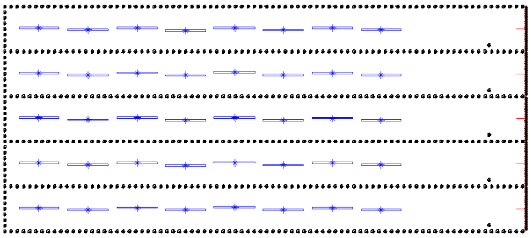
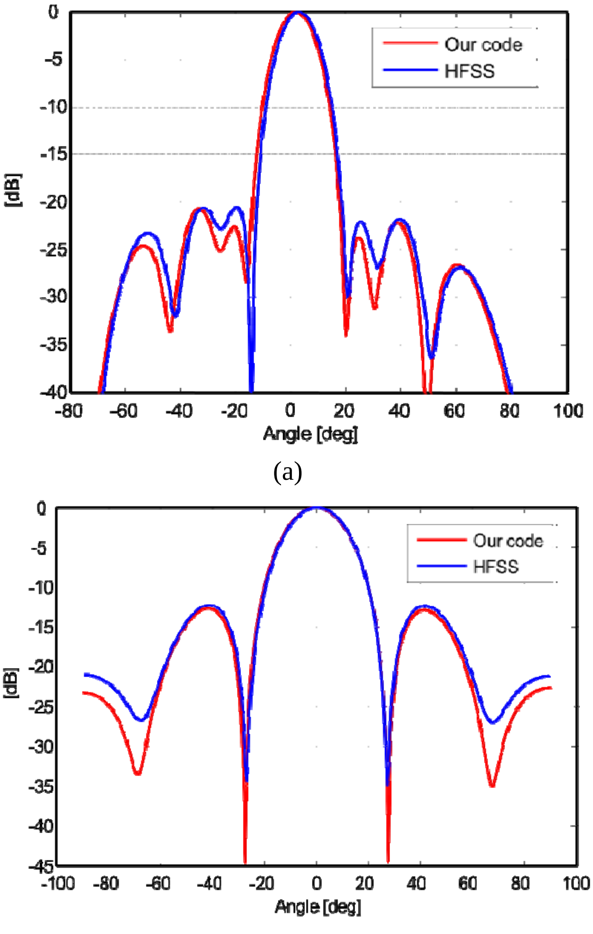


Figure 3: Top view of the structure analyzed in this paper. The slots are placed on the top plate of a PPW (thickness h = 0.508 mm, ε_r = 2.2). The radius of the each metallic pin is 0.2 mm, their spacing is p = 0.8 mm. The length of the structure is 66.4 mm. One metallic post in each waveguide (radius 0.2 mm) is used for matching purposes.

In Fig. 4 the radiated field at the frequency f = 24.15 GHz is shown on the two principal planes, when all the five waveguides are excited with the same phase. The result of our hybrid code (red line) is compared with an analysis performed with the finite-element commercial code HFSS [10] (blue line). An excellent agreement is achieved between the methods, thus fully validating our code.

While the results of the two approaches are comparable, the CPU computation time of our analyses was reduced of a factor 200 for a single-frequency analysis (e.g., as required by an optimization procedure).

The considerable advantages of our code can be even more remarkable for larger and more complex structures, implementing stacked geometries and complex, multilayered PPW, or strong post-slot interactions through higher order modes of the PPW.



(a)

(b)

Figure 4: Normalized radiation pattern of the structure in Fig. 3 at f = 24.15 GHz. (a) H plane, (b) E plane.

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