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Efficient Analysis of SIW-Based Antenna Geometries Through a Rigorous MoM Mode-Matching Approach

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***Abstract*—An efficient full-wave code handling surface-integrated-waveguide based antennas is presented, implementing a hybrid method-of moments and mode-matching approach. Entire-domain basis functions are chosen to minimize the number of unknowns, and an efficient computation of Green functions for large radial distances is granted by means of a radial-transmission-line representation. The mode matching relies on an efficient cylindrical vector wave function expansion of the field. Both the accuracy and the efficiency are largely superior with respect to general-purpose commercial solvers.**

I. INTRODUCTION

Substrate integrated waveguide (SIW) technology has received an increased interest in the last years especially for millimeter wave applications. The basic idea relies on the use of arrays of metallic posts to realize waveguide channels in a dielectric substrate. The 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. These antenna can be electrically large and often present a large number of elements, such as metallic and dielectric cylinders, and both radiating and coupling slots. Unfortunately, available commercial solvers are ineffective to efficiently analyze structures of greater size and complexity.

In order to overcome these limitations, a rigorous full-wave method is here presented, implementing a hybrid approach based on a method of moments (MoM) to handle coupling and radiating slots, and a mode matching (MM) 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 and an efficient Green function representation particularly attractive for large radial distances. The MM relies on an efficient cylindrical vector wave function expansion of the field. Practical criteria for the necessary number of modes can be established, and the accuracy and efficiency of the code have been demonstrated through the results of the analysis of various structures.

For the sake of simplicity, results related to a sample geometry are here discussed. More complex methods and structures have already been successfully studied, such as stacked configurations, alternative basis functions, asymptotic evaluations of coupling terms, different kinds of feeders.

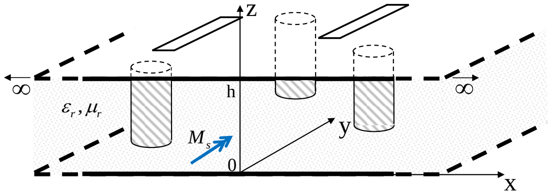


Fig. 1 Geometry of the problem. The posts can be either metallic or dielectric. The slots can be arbitrarily oriented.

II. FORMULATION OF THE PROBLEM

We consider a generic planar SIW structure formed by parallel plate waveguide (PPW) with infinitesimally thin metal plates (Fig. 1). As shown in Fig. 1, there may be dielectric or metallic posts present inside the waveguide and slots may be etched on its top plate. The SIW can be fed either by a rectangular waveguide port or a coaxial probe.

A MoM is implemented by discretizing the equivalent magnetic currents on the slots through entire-domain basis functions; and recurring to a Galerkin testing method.

The generic (*k*,*f*)th entry $Y_{k,f}$ of the admittance matrix is expressed as the "*parallel*" of a free-space admittance $Y_{k,f}^{\mathrm{HS}}$ (involving the free-space Green's function) and a "*guided wave*" admittance $Y_{k,f}^{\mathrm{SIW}}$. The latter requires the field scattered inside the SIW, not known in closed form due to the presence of the posts. In order to overcome this difficulty, we can express the field in the SIW as the sum of a field excited inside the PPW (i.e., in the absence of the posts) and a field scattered by the posts:

$$\begin{aligned} Y_{k,f}^{\mathrm{SIW}} &= \int_S \mathbf{b}_k(\mathbf{r}) \cdot \mathbf{H}^{\mathrm{SIW}}\left[\mathbf{b}_f(\mathbf{r})\right] d\mathbf{r} \\ &+ \int_S \mathbf{b}_k(\mathbf{r}) \cdot \mathbf{H}^{\mathrm{PPW}}\left[\mathbf{b}_f(\mathbf{r})\right] d\mathbf{r} + \int_S \mathbf{b}_k(\mathbf{r}) \cdot \mathbf{H}^{\mathrm{Posts}}\left[\mathbf{b}_f(\mathbf{r})\right] d\mathbf{r} \end{aligned} \tag{1}$$

where $\mathbf{H}^{\mathrm{SIW}}$, $\mathbf{H}^{\mathrm{PPW}}$ and $\mathbf{H}^{\mathrm{Posts}}$ stand for suitable operators acting on the basis function $\mathbf{b}_f$ and giving the magnetic field excited in the SIW, in the PPW, and scattered by the posts, respectively. $\mathbf{H}^{\mathrm{PPW}}$ can be expressed through the PPW Green's function, known in closed form and expressed through a radial-transmission-line expression granting a fast convergence for large radial distances (for small distances a polynomial interpolation is performed).

The field $\mathbf{H}^{\text{Posts}}[\mathbf{b}_f]$ is computed through a MM formulated to enforce the appropriate boundary condition on the posts [1]. This is achieved by expressing the field scattered fields as a sum of vertical TM and TE modes of the PPW, and choosing for each post a given number of azimuthal modes to express the angular variation of fields. The field continuity on the post surfaces can be enforced separately for each vertical mode, due to their orthogonality: this leads to a set of linear problem of reduced size, whose unknowns are coefficients in a cylindrical wave expansion of $\mathbf{H}^{\text{Posts}}[\mathbf{b}_f]$. The remaining integration in (1) can then be performed in closed form by recurring to quantities already computed to set up the MM; the details are for the sake of brevity, and can be found in [2].

III. NUMERICAL RESULTS

A structure is here analyzed for validation of the capabilities of the code presented. It consists of an array of eight slots shielded by lateral metallic pins (see Fig. 2). The structure is fed with a waveguide port at one end of the waveguide. The input matching is granted by three holes, treated here as dielectric posts, placed near the waveguide port (in red in the figure) feeding the structure. The physical and geometrical parameters are given in the caption of Fig. 2. Five azimuthal modes are chosen for each post; three vertical PPW modes are retained in the MM problems; three basis functions are selected for each slot.

The normalized radiation patterns are shown in Fig. 3 in the H plane, for two different frequencies, namely f = 24.15 GHz [Fig. 3 (a)] and f = 25.15 GHz [Fig. 3 (b)].

In Tables I and II we compare our code and HFSS in terms of CPU computation time (an impressive speed up factor of 230 for a single-frequency solution is obtained) and memory usage (the memory requested by HFSS is reduced by 25 due to the small number of unknowns of our code).

TABLE I: CPU SIMULATION TIME

Posts	Slots	HFSS		This paper
		Mesh	Freq. Point	
186	8	1782 s	286 s	**8.7 s**

TABLE II: MEMORY USED

Posts	Slots	HFSS		This paper
		Mesh	Freq. Point	
186	8	1.8 GB	1.8 GB	**70 MB**

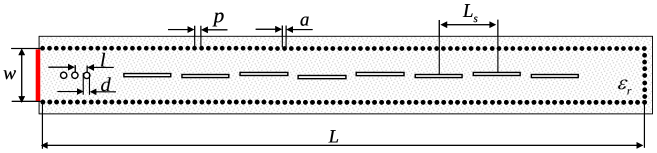
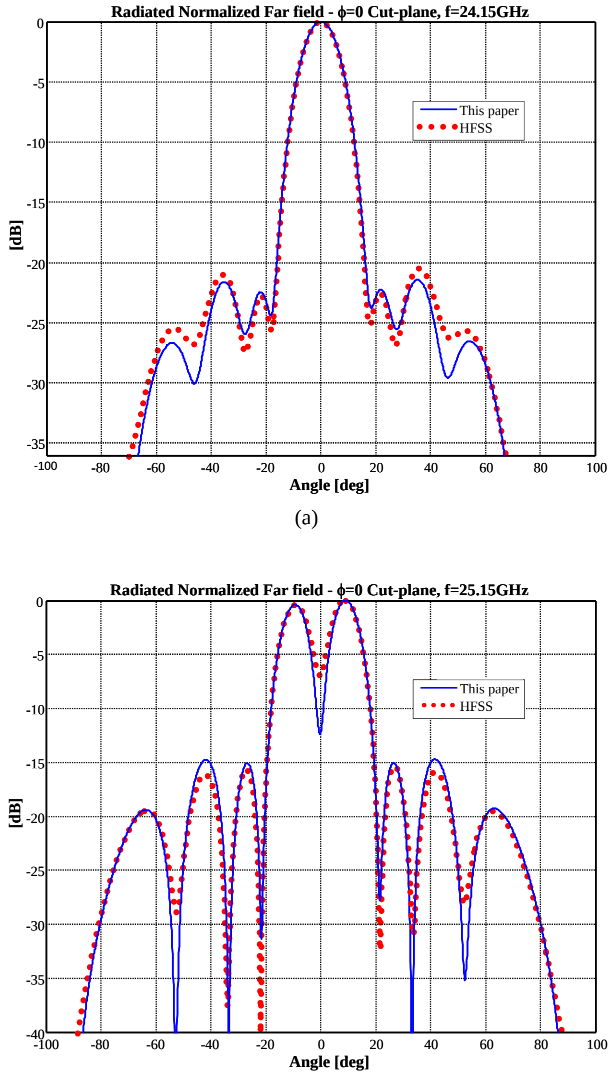


Fig. 2 Top view of the antenna analyzed. The slots are placed on the top plate of a PPW (thickness h = 0.508 mm, ε_r = 2.2). The radius of the each metallic pin is a = 4 mm, their spacing is p = 0.8 mm. The length L = 66.4 mm. Three vacuum holes are present (l = 0.8 mm, d = 0.4 mm, ε_r=μ_r=1).



(a)

(b)

Fig. 3 Normalized radiation pattern of the antenna on the H plane at two different frequencies f. (a) f = 24.15 GHz, (b) f = 25.15 GHz.

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