Efficient Full-Wave CAD Tool of Passive Components based on Coaxial Waveguide Junctions

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***Abstract* — An efficient full-wave CAD tool dedicated to coaxial waveguide junctions is presented. The tool is well suited to treat both standard coaxial lines and rectangular-circular coaxial waveguides. The case of offset internal conductors and dielectric filling are contemplated as well. The tool is very efficient and accurate, which allows to be used by iterative optimization procedures for the design of coaxial waveguide components such as low-pass and band-pass filters, and impedance transformers among other structures. Direct coaxial excitations in rectangular waveguides can be characterized as well.**

***Index Terms* — Design automation, coaxial waveguide junctions, low-pass and band-pass filters, Moment methods.**

I. Introduction

Coaxial waveguides have been extensively used to design microwave components as interconnections, filters, impedance transformers, couplers, etc. [1]. This particular technology is usually selected for ground and space applications due to its easy handling of high power signals. Classic coaxial lines made of two concentric circular conductors can be easily characterized, while Rectangular-Circular (R-C) coaxial lines (composed of a circular conductor enclosed in a metallic rectangular housing) are not so easy to analyze. The latter geometry is of particular interest in reason of its geometrical and electrical properties, since it features a rectangular housing (easy to manufacture and compatible with rectangular waveguide geometries) and a circular internal conductor (no sharp edges, hence exhibiting low-losses).

Several approaches have been developed in the past to study such structures including mode matching [2], spectral-domain techniques [3], finite-elements and finite-differences in time domain. Most of these techniques drive to a single-mode representation of waveguide junctions; the effect of the higher order modes excited at the discontinuities is lumped into a reactance. The use of hybrid techniques [4] has also been proposed to solve a wide range of waveguide problems and could be also used to treat coaxial structures, but not very efficiently.

Nevertheless, to the authors' knowledge, efficient CAD tools especially dedicated to the analysis of general coaxial junctions are still missing, in particular those providing a multi-modal characterization needed for accurate component design procedures, such as for instance the one presented in [5] for standard coaxial waveguides.

In this paper, we describe a full-wave CAD tool dedicated to these particular geometries, resulting in a very efficient and accurate multi-modal characterization of several coaxial waveguide junctions. The high efficiency of the presented tool permits its use within iterative optimization procedures in a very short time. The tool presented in this paper overcomes the limitation of dealing only with symmetrical geometries, limitation common to nearly all the best performing methods developed in the past. A comprehensive example fully validates the right functioning and the efficiency of the CAD tool developed.

II. Theoretical Background

The analysis approach used is based on the segmentation of a structure made of standard coaxial waveguides, R-C waveguides and rectangular waveguides in a cascade of guiding sections and waveguide junctions. Each building block is then characterized by means of its multimode generalized impedance matrix (GIM) [6]. The S-parameter description of the entire structure is obtained by using the Integral Equation formulation described in [6], chapter 7.

The first step consists on computing the full-wave modal spectrum of each waveguide. The Boundary-Integral Resonant Mode Expansion (BI-RME) method [7] has been recently particularized to the efficient and accurate consideration of circular arcs [8], and has therefore been selected for integration in the CAD tool developed. The BI-RME method allows the determination of the modal spectrum of an arbitrarily shaped waveguide by enclosing the waveguide itself in a rectangular (or circular) frame $\mathcal{F}$. The modes of the waveguide under investigation are expressed in terms of a number ($N_{\mathcal{F}}$) of modes of the frame used. As side products of the modal characterization, the modal coupling coefficients between the modes of the arbitrarily shaped waveguide and the modes of the frame are obtained with a minor computational effort (see [6], chapter 9).

Said respectively $\mathbf{e}_i^{(AW)}$ and $\mathbf{e}_j^{(\mathcal{F})}$ the normalized electric modal vectors of the i-th mode of the arbitrarily shaped waveguide (AW) and of the j-th mode of the frame ($\mathcal{F}$), the

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modal coupling coefficient between these two modes is denoted by $\langle \mathbf{e}_i^{(AW)}, \mathbf{e}_j^{(\mathcal{F})}\rangle$. If the same frame $\mathcal{F}$ is used to compute the modes of two AWs connected in a junction, the modal coupling coefficients between the modes of the two AWs are given by the expression [9]:

$$\left\langle \mathbf{e}_i^{(AW_1)}, \mathbf{e}_j^{(AW_2)} \right\rangle = \sum_{n=1}^{N_{\mathcal{F}}} \left\langle \mathbf{e}_i^{(AW_1)}, \mathbf{e}_n^{(F)} \right\rangle \left\langle \mathbf{e}_n^{(F)}, \mathbf{e}_j^{(AW_2)} \right\rangle \qquad (1)$$

The terms included in the series (1) are already given once the modes of the AWs are computed by the BI-RME method, thus resulting into an efficient implementation.

III. Application to Coaxial Waveguide Components

The approach described in the previous section has been applied to the study of the guiding structures depicted in Fig. 1. The number of modes of the rectangular frame used (coinciding with the rectangular housing of the R-Cs) is always the same for all the waveguides, which allows the exploitation of (1).

Every R-C is identified by the radius of its internal conductor (R_i) and by its location within the frame, while the circular coaxial waveguides are defined in terms of the radii of the concentric circular conductors (R_{in}, R_{out}) and their location. For simplicity in Fig. 1 the circular conductors are placed at the center of the rectangular frame, but it is important to stress that analyzing eccentric conductors is also possible; which allows simulating mechanical misalignments due to manufacturing processes.

The possibility of having a dielectric medium filling the regions where the waves propagate (the gray regions in Fig. 1) has also been implemented by rescaling the cutoff frequencies of the modes obtained by the BI-RME method. In case of having in the i-th WG a medium with $\varepsilon_r=\varepsilon_i$, the cutoff frequency of the j-th mode will be:

$$f_j^{(i)} = f_{j,0}^{(i)} / \sqrt{\varepsilon_i} \qquad (2)$$

where $f_{j,0}^{(i)}$ is the cutoff frequency of the same mode propagating in the same region in case of $\varepsilon_r=1$.

This capability enables the analysis of WGs having dielectric supports (typically Teflon) to keep the internal conductor in the right position inside the rectangular housing.

The above approach has been used to derive the GIM of the junctions generated connecting circular coaxial waveguides, R-C coaxial waveguides and rectangular waveguides to each other. Every waveguide belonging to one of these three families can be connected to a waveguide belonging to one of the three families. All the configurations are possible keeping in mind that:

- Two waveguides involved in a junction must have the same rectangular frame $\mathcal{F}$;
- The circular contours of the conductors do not have to intersect each other.

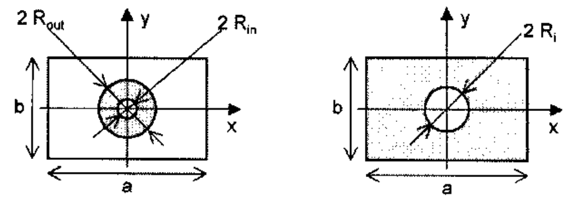

Fig. 1. Waveguides under analysis: i. circular coaxial waveguide, ii. rectangular-circular coaxial waveguide.

Since in general equivalent circuits of microwave structures are given in terms of transmission lines with a certain characteristic impedance level, a key point in the design of structures obtained by cascading different coaxial waveguides is to establish a unique relation between the physical dimensions of each R-C and the impedance level associated to the fundamental mode (TEM) propagating through it (for standard coaxial waveguides an exact analytical expression exists [6], chapter 1). For this purpose a very efficient and accurate integral formulation has been developed.

The electrostatic potential $\Phi(\mathbf{r})$ in an arbitrary observation point (defined by the vector $\mathbf{r}$) located in the cross-section of the R-C, is given by [10]:

$$\Phi(\mathbf{r}) = \int_{\sigma} g(\mathbf{r}, \mathbf{s}) \rho_s(l)\, dl \qquad (3)$$

where $\rho_s(l)$ represents the surface charge density at a certain source point $\mathbf{s}$ located at the curvilinear coordinate l on the contour σ of the internal conductor, and $g(\mathbf{r},\mathbf{s})$ is the scalar two-dimensional Green's function for the two-dimensional Poisson's equation. Equation (3) is solved by using a Galerkin's Method of Moment (MoM) approach making use of entire domain basis functions to represent the surface charge density distribution along σ.

The MoM approach drives to a matrix equation whose details are given in [7]. Once the matrix equation is solved the surface charge density distribution along the contour of the internal conductor is known. The current flowing through the internal conductor is computed as the circulation of the magnetic field around σ, hence in terms of ρ_s as (see Appendix):

$$I = \frac{1}{\sqrt{\mu\varepsilon}} \oint_{\sigma} \rho_s(l)\, dl = \frac{1}{\sqrt{\mu\varepsilon}} \sum_{n=1}^{N} b_n f_n \tag{4}$$

The voltage between the internal and the external conductor of the R-C is simply obtained by evaluating (3) for an arbitrary observation point $\mathbf{r}$ located in σ. In fact the integral has not to be evaluated since for the electrostatic case (TEM propagation through the R-C) σ is an equipotential region and there $\Phi = \Phi_{ic}$, constant and arbitrarily fixed to 1. The characteristic impedance is then computed as the ratio between the voltage and the current.

The use of entire domain basis functions (we selected stretched harmonic functions) makes the computation of the f_n analytical, hence virtually instantaneous (see (A4)). The reduced number of required basis functions makes the MoM matrix equation very small in size and the computation of the characteristic impedance very efficient. The algorithm for the characteristic impedance computation has been validated by several comparisons with published data [11] and numerical simulations performed with CST Microwave Studio® 4.2 (CST GmbH, Darmstadt, Germany). By using four basis functions to describe ρ_s and 400 integration points along σ (driving to a very short computation time) the accuracy is in any case better than 0.1 %, even in case of strongly offset conductors. Further details of this method and verification results will be given during the talk.

IV. Example

The structure in Fig. 2 has been selected as an example of the analysis capabilities of the tool developed. The presence of different dielectric materials and offset conductors is contemplated. A common frame (10 mm×13 mm) has been used for all the waveguides. Referred to the center of the frame the first circular coaxial waveguide from the right has a y-offset of 1 mm and the first R-C from the right has also a y-offset of 1 mm, whereas the remaining circular conductors are centered. The dielectric medium filling the input/output circular coaxial waveguides has $\varepsilon_r = 2$, the remaining WGs are filled with $\varepsilon_r = 1$.

The structure has been also analyzed with the CST Microwave Studio® 4.2 and with our tool by using two different parameters settings, named *Fast* and *Accurate*, the difference being the number of interacting modes used to connect the different waveguide junctions and the number of frame modes N_F used in the BI-RME algorithm.

The simulated results are displayed in Fig. 3. The computation time on an Intel Pentium4 (@ 1.5 GHz) PC for 2000 frequency points is of about 50 sec. for the *Fast* setting (10 accessible modes at any junction, $N_F = 500$), of about 40 min. for the *Accurate* setting (80 accessible modes at any junction, $N_F = 2000$) and of about 1 hour and 47 min. for CST Microwave Studio® 4.2 while using a mesh of 30 grid lines per wavelength.

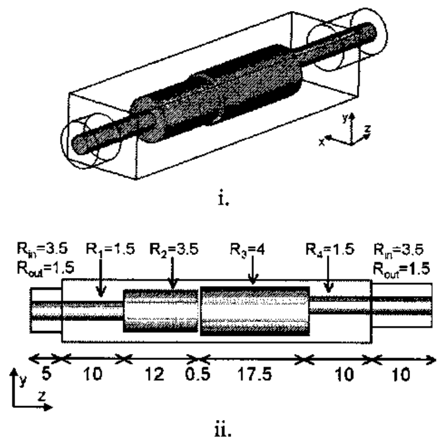

Fig. 2. Geometry under investigation: i. perspective view (propagation along z direction), ii. side view (dimensions in mm).

As we can see (Fig. 3), the *Fast* computation is better than a rough estimation of the response obtained by the *Accurate* simulation. In case of iterative optimization procedures, the *Fast* analysis could be used for nearly all the repeated runs, keeping the *Accurate* analysis for the final fine tuning. This would dramatically reduce the time required for a complex design.

V. Conclusion

In this paper a CAD tool for passive components based on coaxial waveguide junctions has been presented. The tool is able to treat standard circular coaxial waveguides as well as rectangular-circular waveguides, including dielectric filling and offset internal conductors. The tool is very efficient and accurate, thus making possible advanced design even using iterative optimization procedures.

The theoretical background and its application to the specific structure have been presented. An efficient formulation for the numerical evaluation of the characteristic impedance associated to the TEM mode propagating through a rectangular-circular waveguide has been described in detail. This formulation enables a direct correspondence with transmission line models.

The analysis results of a complex example have been compared with the ones obtained by using a well-established commercial tool showing very good agreement and a dramatic reduction of the computation time. Further examples will be presented during the talk.

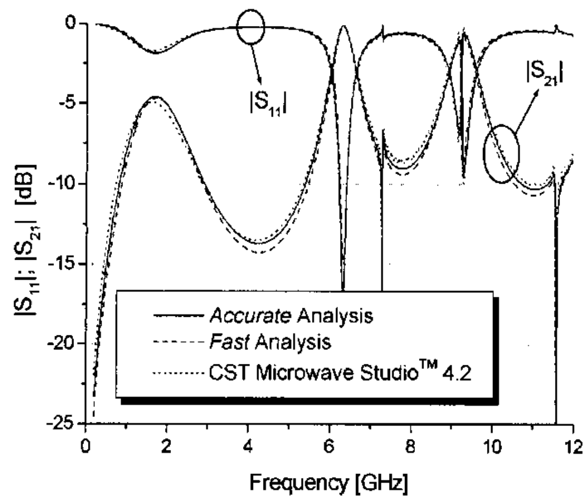

Fig. 3. Simulation results.

VI. Appendix – Demonstration of Eq. (4)

To solve (3) by applying a Galerkin's MoM the surface charge density ρ_s is expressed as series expansion of a set of N basis functions w_n:

$$\rho_s(l)=\sum_{n=1}^{N} b_n\, w_n(l) \tag{A1}$$

Once the MoM matrix equation is solved the coefficients b_n are known. The current in the internal conductor of an R-C can be computed as follows:

$$I=\oint_\sigma \boldsymbol{H}\cdot d\boldsymbol{l}=\frac{1}{\eta}\oint_\sigma E_n(l)\,dl \tag{A2}$$

E_n is the component of the electric field orthogonal to σ and $\eta=\sqrt{\mu/\varepsilon}$ is the wave impedance.

Since the internal conductor is assumed to be perfectly conductive, $E_n = \rho_s/\varepsilon$, then we have:

$$I=\frac{1}{\eta}\oint_\sigma \frac{\rho_s(l)}{\varepsilon}dl=\frac{1}{\sqrt{\mu\varepsilon}}\oint_\sigma\left(\sum_{n=1}^{N} b_n w_n(l)\right)dl=\frac{1}{\sqrt{\mu\varepsilon}}\sum_{n=1}^{N} b_n f_n \tag{A3}$$

where the f_n are given by:

$$f_n=\oint_\sigma w_n(l)\,dl=\int_0^{2\pi} w_n(\theta)\,\mathrm{R}_{ic}\,d\theta=\mathrm{R}_{ic}\int_0^{2\pi} w_n(\theta)\,d\theta \tag{A4}$$

being R_{ic} the inner conductor radius and θ the angular coordinate along σ.

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