FAST AND ACCURATE CAD TOOL OF PERIODICALLY LOADED E-PLANE FILTERS

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Abstract

In this paper, a fast and accurate Computer-Aided Design (CAD) tool of periodically loaded E-plane filters is proposed. The tool is based on a very efficient Integral Equation (IE) technique that provides a full-wave modal analysis of discontinuities between arbitrarily shaped waveguides, i.e. ridge waveguides, and rectangular ones. For solving the complete filter, the Boundary Integral - Resonant Mode Expansion (BI-RME) method is also employed. In order to show the advantages of this CAD tool, a periodically loaded E-plane filter with improved stop-band performance is analyzed and compared to standard solutions. For validation purposes, numerical and experimental results are successfully compared.

Index Terms

E-plane Filters, Periodic Structures, Computer-Aided Design (CAD), Integral Equation, Moments Method

I. Introduction

Periodic structures are currently object of great interest in the microwave area for their potential application in the microwave and millimeter-wave domains. In filtering applications, periodic structures have been reported to offer reduced physical size and improved stop-band performance, due to the well-known slow-wave effect caused by periodicity [1]-[3]. The effective wavelength in a periodically loaded structure is significantly reduced relative to the same parameters of a wave propagating in a comparable homogeneous line. Therefore, the half wavelength of a resonator in a periodic structure is considerably reduced. Furthermore, due to the dispersion relation of slow waves, an improved stop-band performance can also be achieved in such a case.

E-plane technology including ridge waveguides offers a very convenient way for realizing periodic structures, through the loading of the waveguide with reactive obstacles in form of ridges. In this high demanding scenario, the usage of flexible CAD tools, based on accurate and efficient electromagnetic simulators, reveals absolutely necessary. This paper revisits a novel hybrid method for the fast and rigorous analysis of periodically loaded E-plane filters composed of cascaded ridge waveguides. For such purposes, an IE-based modal method, originally described in [4] for rectangular waveguides, has been updated to cope with arbitrarily shaped geometries. This method makes use of the modal chart of waveguides with arbitrary cross-section, which is determined following an improved version (see [5] and [6]) of the classical and well-known BI-RME technique [7]. A comprehensive example, which fully validates the right functioning and the efficiency of the new CAD tool developed, is included.

II. Theory

Periodically loaded E-plane filters involve the cascaded connection of ridge and rectangular waveguides. For analysis purposes, it is required to know the complete modal chart of such arbitrary shaped waveguides in a very accurate way. To reach this aim, the well-known BI-RME method (see [7]) is proposed to be used. Following this classical method, the electric field at a generic observation point $\mathbf{r}$ inside the ridge waveguide can be obtained by

$$\mathbf{E}(\mathbf{r}) = -j\eta k \int_{\sigma} \overline{\mathbf{G}}_e(\mathbf{r}, \mathbf{s}', k) \cdot \mathbf{J}_{\sigma}(l')\, dl' \quad (1)$$

where s' indicates a source point on σ (the arbitrary ridge contour), $\eta = \sqrt{\mu/\epsilon}$ is the characteristic impedance and $k = \omega\sqrt{\mu\epsilon}$ is the wavenumber, $\overline{\mathbf{G}}_e$ is the two-dimensional dyadic Green's function of the electric type for the two-dimensional resonator of rectangular cross section and $\mathbf{J}_{\sigma}$ is the current density.

Splitting $\overline{\mathbf{G}}_e$ and $\mathbf{J}_{\sigma}$ into its transversal and longitudinal components, and imposing the corresponding boundary conditions ($\mathbf{E}_t(\mathbf{r}) \cdot \hat{\mathbf{t}}(l) = 0$, and $\mathrm{E}_z(\mathbf{r}) = 0$) on σ, we obtain the integral equations for the transversal electric field $\mathbf{E}_t$ (TE modes) and for the longitudinal electric field E_z (TM modes).

The next step in the BI-RME method is the segmentation of the problem, in order to solve the integral equations via the Galerkin version of the MoM [8], where the basis and testing functions are chosen to be overlapping piece-wise parabolic splines. Following the Galerkin approach, a generalized eigenvalue problem is obtained for the TE case, whereas a standard eigenvalue problem is got for the TM modes (see [5]). The solution of both problems provides as eigenvalues the TE and TM cutoff wavenumbers, and as eigenvectors the modal expansion coefficients and the amplitudes of the transversal and longitudinal components of the unknown current density.

An advantage of the BI-RME technique is that, without hardly additional CPU effort, the coupling coefficients between the arbitrarily-shaped waveguide and the standard rectangular contour enclosing the arbitrary profile can be easily computed (see [9]). The coupling integrals between the modes of the ridge waveguide and those of the rectangular one are defined as follows

$$I_{pq} = \int_S \mathbf{e}_p^{\square} \cdot \mathbf{e}_q^{\diamondsuit} dS \quad (2)$$

where $\mathbf{e}_p^{\square}$ and $\mathbf{e}_q^{\diamondsuit}$ are, respectively, the normalized modal vectors of the rectangular and ridge waveguides.

In order to obtain a full-wave characterization of any planar junction between two waveguides, a very efficient method based on an integral equation technique, originally described in [4] for dealing with rectangular waveguides, has been properly updated. The objective of this technique is the representation of each planar waveguide junction in terms of a Generalized Impedance Matrix (GIM). A remarkable contribution of this method is the distinction made between accessible and localized modes: accessible modes are those used to connect transitions, while localized modes are only used to describe the electromagnetic fields in the junction (the number of localized modes is always greater than the number of accessible ones).

The first step of this technique consists in imposing the boundary condition at the junction, where the total transverse magnetic field in each waveguide region can be expressed in terms of the waveguide modes (see [10]) as follows

$$\mathbf{H}_t^{(\delta)} = \sum_m I_m^{(\delta)} \mathbf{h}_m^{(\delta)} \quad (3)$$

and $(\delta) = (1), (2)$ indicates the suitable region of the junction, $\mathbf{h}_m^{(\delta)}$ is the magnetic vector mode function related to the m-th mode of region (δ). After some mathematical manipulations (see details in [4]), it is possible to obtain the following integral equation

$$\mathbf{h}_n^{(\delta)}(s) = \iint_{CS(2)} \mathbf{M}_n^{(\delta)}(s') K(s, s')\, ds' \quad (4)$$

where s and s' are the observation and source points, respectively, $K(s, s')$ is the kernel of the integral equation, and $\mathbf{M}_n^{(\delta)}(s')$ are unknown vector functions which define the magnetic field at the junction.

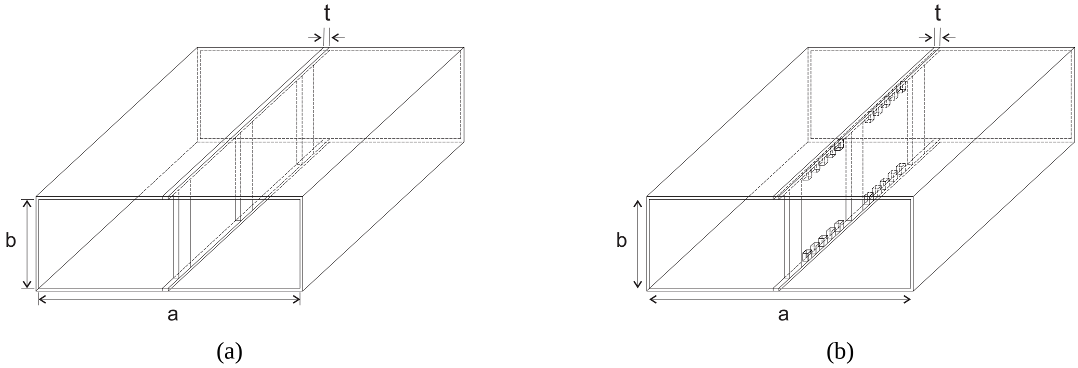

Fig. 1. Three-dimensional layout of the 2 resonator filter: the standard E-plane filter in (a) and the periodically loaded E-plane filter in (b). The common dimensions of the two filters are $a = 22.86$ mm, $b = 10.16$ mm and $t = 0.10$ mm.

Finally, the solution of the integral equation can be carried out using the Galerkin's procedure, where the unknown vector functions are expanded in a set of basis functions used in (δ) region. Proceeding in this way, we can easily compute the impedance parameters of the generalized Z-matrix representation through the following equation

$$Z_{m,n}^{(\delta,\gamma)} = \iint_{cs(2)} \mathbf{M}_n^{(\gamma)}(s') \cdot \mathbf{h}_m^{(\delta)*}(s')\, ds' = \sum_{q=1}^{M^{(\gamma)}} \alpha_q^{(n,\gamma)} \iint_{cs(2)} \mathbf{h}_q^{(2)} \cdot \mathbf{h}_m^{(\delta)*}\, ds' \tag{5}$$

III. Results

In order to demonstrate the improvements introduced by the proposed structure in terms of stop-band performance, the electrical responses of a two-resonator periodic filter (originally proposed in [3]) and of a standard E-plane solution with the same in-band response have been compared. The layout and the dimensions of such two resonator filters are shown on Fig. 1 and Fig. 2. The homogeneous rectangular waveguide sections acting as the resonators of the standard E-plane filter (see Fig. 2 (a)) are replaced with periodic structures consisting of a cascade of ridge waveguides (see Fig. 2 (b)).

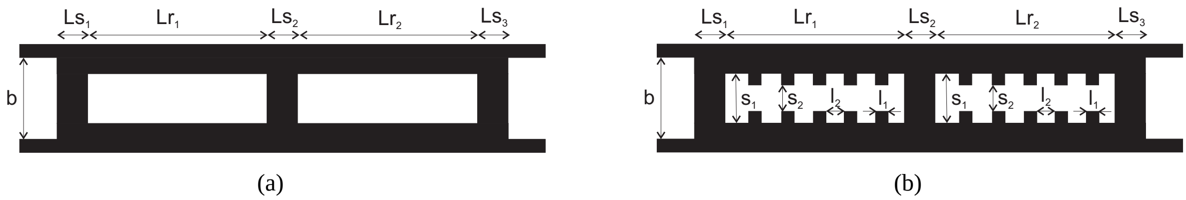

Fig. 2. The dimensions for the standard E-plane filter (a) are: septa lengths $L_{s1} = L_{s3} = 0.31$ mm and $L_{s2} = 1.68$ mm, resonator lengths $L_{r1} = L_{r2} = 20.10$ mm, total length of 42.50 mm. The dimensions for the periodically loaded E-plane filter (b) are: septa lengths $L_{s1} = L_{s3} = 1.20$ mm and $L_{s2} = 4.0$ mm, resonator length $L_{r1} = L_{r2} = 8.0$ mm, ridge dimensions $s_1 = b = 10.16$ mm and $s_2 = 1.0$ mm, ridge lengths $l_1 = 1.0$ mm and $l_2 = 0.5$ mm, total length of 22.40 mm.

In Fig. 3 (a), the E-plane standard filter response obtained with our CAD software package is successfully compared with simulations performed with Ansoft HFSS[1]. Exploiting the symmetry of the structure, our analysis method has required to consider 80 accessible modes, 250 basis functions and 400 kernel terms. In our case, the complete electrical response simulation has only taken a CPU effort of 0.11 sec. per frequency value, whereas HFSS has needed 1.20 sec. per each point. Both software packages have been run in a Pentium IV platform at 3.2 GHz with 1-GB RAM.

In Fig. 3 (b), the periodically loaded E-plane filter response obtained with our CAD software package is well compared with Ansoft HFSS v10.0 simulations, and also with measurements of a filter prototype

[1]HFSS v.10.0, Ansoft Corporation, Pittsburgh, PA, 2005.

fabricated and measured (see [3]). An excellent agreement between all results can be observed. As it is shown in the figures, the periodic loaded filter has better selectivity and wider stop-band response than its standard E-plane counterpart. Furthermore, the overall periodic filter is 47% shorter than the standard filter since the resonator lengths have been widely reduced, as it is expected from the well-known slow wave effect in periodic structures. In the periodic case, by exploitation of the symmetry of the structure, the full-wave analysis method has only required to consider 80 accessible modes, 250 basis functions and 500 kernel terms. Our software tool has only involved a CPU effort of 0.35 sec. per frequency point. On the contrary, the HFSS results have required a CPU effort of 1.20 sec. for each analysis point.

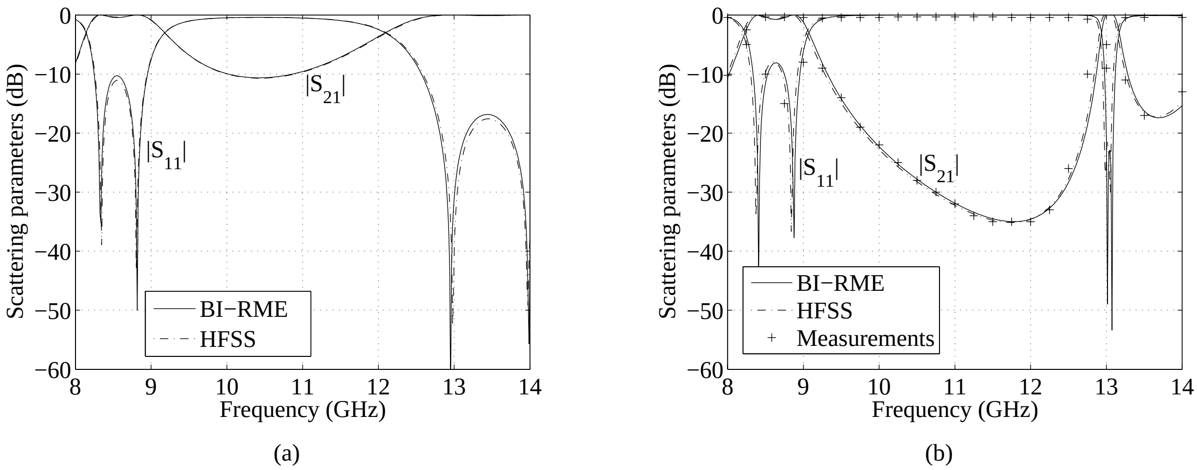

Fig. 3. Electrical responses of the E-plane standard filter in a), and of the periodically loaded E-plane filter in b).

IV. CONCLUSIONS

A very efficient and accurate CAD tool of periodically loaded E-plane filters has been described. For the fast and rigorous analysis of such filters, an advanced hybrid method combining the BI-RME and the IE techniques has been proposed. This novel CAD tool has been successfully applied to the analysis of a compact E-plane filter, composed of periodic ridge waveguides, with an improved stop-band response. Numerical and experimental results are presented to fully validate these arguments.

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