Efficient FDTD Modeling of Irises/Slots in Microwave Structures

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Abstract — **A new methodology is proposed for the computationally efficient, numerically stable, and accurate FDTD simulation of microwave structures with electrically thin irises and slots. The proposed method is based on the hybridization of Yee's standard FDTD scheme with Padé approximations of the electromagnetic properties of the irises/slots. Using rigorous modal expansions for the description of the fields in the waveguide sections formed by the irises/slots, highly accurate rational function approximations of their transmission and reflection properties are obtained. These transfer functions are then incorporated directly in the FDTD algorithm through their corresponding z-transform expressions. Results from the analysis of typical building blocks in combine filters and multiplexes for the satellite and wireless communications are used to demonstrate the validity and accuracy of the proposed methodology.**

I. INTRODUCTION

Combline filters and multiplexes used in satellite and wireless communications systems, often involve irises or slots to realize the electromagnetic couplings between adjacent or non-adjacent cavities. In printed antennas, patches are usually slot–coupled with feed lines. The MMIC compatible microstrip-to-waveguide transition is another example of slot-couplings. In 3D MCM interconnects, traces on different layers are often connected to each other by vias through perforated ground planes. In all the aforementioned applications, the irises or slots are electrically small in one or more dimensions. Thus, for their modeling techniques such as the FDTD method requires special refinement techniques to be used in the neighborhood of the irises/slots. These techniques include: sub-gridding (either global or locally conformal), specialized equations derived through finite-volume integrations, etc. In addition to the increase in modeling complexity, use of sub-gridding requires smaller time integration step and proper synchronization of the field updates at grid interfaces to avoid numerical instabilities.

An alternative methodology to handle such irises and slots is presented in this paper. The coupling irises and/or slots are modeled as sections of uniform waveguides. Thus, their electromagnetic fields are expressed in terms of a finite set of eigenmodes. At the interface between irises/slots and their adjacent regions, continuity of the tangential electric and magnetic fields are enforced through impedance relations that involve the waveguide modal impedances. Since the modal impedances are available in closed form, their higher-order derivatives with respect to the complex frequency $s=j\omega$ can be obtained analytically. This way, Padé approximation techniques can be used to cast the aforementioned impedance relations in terms of rational functions of s. Subsequently, application of the z-transform leads to FDTD-compatible expressions for the impedance relationships between the transverse electric and magnetic fields at the interfaces between the iris/slot and the adjacent domains.

The mathematical details of the development of the proposed model are presented first. This is followed by the application of the generated models to the FDTD analysis of typical building blocks in combline filters and multiplexers. Comparisons with experimental data are used to demonstrate the validity of the new models.

II.FORMULATION

For the sake of clarity, the slot-coupled rectangular combline resonators shown in Fig.1, used as a typical building block in high-Q filters and multiplexes in wireless communications, are to demonstrate the development of the proposed models. However, the methodology is general and can be extended easily to a variety of other practical applications.

With reference to Fig.1(b), the coupling slot is modeled as a section of a homogeneous, uniform waveguide. Thus, the transverse (to z) electromagnetic fields in the slot can be written as

$$\mathbf{E}_t = \sum_m V_m^h(z)\mathbf{e}_m^h(x,y) + \sum_n V_n^e(z)\mathbf{e}_n^e(x,y) \qquad (1a)$$

$$\mathbf{H}_t = \sum_m I_m^h(z)\mathbf{h}_m^h(x,y) + \sum_n I_n^e(z)\mathbf{h}_n^e(x,y) \qquad (1b)$$

where $\mathbf{e}_i(x,y)$ and $\mathbf{h}_i(x,y)$ satisfy the relation,

$$\mathbf{h}_i(x,y) = \mathbf{u}_z \times \mathbf{e}_i(x,y)$$

When the symmetry is used, the transverse electromagnetic fields at the interface between the slot and the combline resonator can be related to each other with

$$\mathbf{E}_t = \sum_m Z_m^h(s)\mathbf{e}_m^h(x,y)\iint_{slot} \mathbf{H}_t \bullet \mathbf{h}_m^h(x,y)ds + \sum_n Z_n^e(s)\mathbf{e}_n^e(x,y)\iint_{slot} \mathbf{H}_t \bullet \mathbf{h}_n^e(x,y)ds \qquad (2)$$

Where $Z_m^h(s)$ and $Z_n^e(s)$ have analytical expressions in s-domain as follows:

$$Z_m^h(s) = \frac{s\mu}{\sqrt{\varepsilon\mu s^2 + K_{cm}^2}} \tanh\left(\frac{t}{2}\sqrt{\varepsilon\mu s^2 + K_{cm}^2}\right)$$

$$Z_n^e(s) = \frac{\sqrt{\varepsilon\mu s^2 + K_{cn}^2}}{s\varepsilon} \tanh\left(\frac{t}{2}\sqrt{\varepsilon\mu s^2 + K_{cn}^2}\right) \qquad \text{for E.W.(3a)}$$

$$Z_m^h(s) = \frac{s\mu}{\sqrt{\varepsilon\mu s^2 + K_{cm}^2}} \coth\left(\frac{t}{2}\sqrt{\varepsilon\mu s^2 + K_{cm}^2}\right)$$

$$Z_n^e(s) = \frac{\sqrt{\varepsilon\mu s^2 + K_{cn}^2}}{s\varepsilon} \coth\left(\frac{t}{2}\sqrt{\varepsilon\mu s^2 + K_{cn}^2}\right) \qquad \text{for M.W.(3b)}$$

It should be mentioned that for asymmetrical structures, $\mathbf{E}_t$ and $\mathbf{H}_t$ on either sides of the coupling slot are related to each other with a block-diagonal modal impedance matrix, the non-zero elements of which are available in closed form.

To create the update scheme for $\mathbf{E}_t$ at the interface, it is necessary for eqn.(2) to be deduced. $Z_m^h(s)$ and $Z_n^e(s)$ are expanded in terms of Taylor series as follows

$$Z(s) = z_0 + z_1 s + z_2 s^2 + z_3 s^3 + \cdots\cdots \qquad (4)$$

where the expansion coefficients z_i' are easily generated, due to the available analytical expressions for $Z_m^h(s)$ and $Z_n^e(s)$ (see (3)). The rational function for $Z_m^h(s)$ and $Z_n^e(s)$ is introduced as

$$Z(s) = \frac{a_0 + a_1 s + a_2 s^2 + \cdots + a_L s^L}{b_0 + b_1 s + b_2 s^2 + \cdots + b_M s^M} \qquad (5)$$

With b_0=1 and following the standard procedure of the Padé approximation [1], the denominator is derived from the expansion coefficients above as follows,

$$\begin{bmatrix} z_{L-M+1} & z_{L-M+2} & \cdots & z_L \\ z_{L-M+2} & z_{L-M+3} & \cdots & z_{L+1} \\ \vdots & \vdots & \vdots & \vdots \\ z_L & z_{L+1} & \cdots & z_{L+M-1} \end{bmatrix} \begin{bmatrix} b_M \\ b_{M-1} \\ \vdots \\ b_1 \end{bmatrix} = -\begin{bmatrix} z_{L+1} \\ z_{L+2} \\ \vdots \\ z_{L+M} \end{bmatrix} \qquad (6)$$

The z-domain expression for $Z_m^h(s)$ and $Z_n^e(s)$ are written as

$$Z(z) = \frac{c_0 + c_1 z^{-1} + c_2 z^{-2} + \cdots + c_m z^{-m}}{d_0 + d_1 z^{-1} + d_2 z^{-2} + \cdots + d_n z^{-n}} \qquad (7)$$

where the bilinear transform

$$s = \frac{2}{\Delta t} \times \frac{1 - z^{-1}}{1 + z^{-1}} \qquad (8)$$

has been used. In (8) Δt is equal to the time step in FDTD scheme. When the z-domain expressions for $Z_m^h(s)$ and $Z_n^e(s)$ are substituted in (2), the update algorithm for $\mathbf{E}_t$ at the interface is obtained. Taking into account that $\mathbf{E}_t$ and $\mathbf{H}_t$ have half a time step shift from each other in time domain, the actual update value for $\mathbf{E}_t$ is modified by an average over one time step as

$$\mathbf{E}_t = \mathbf{E}_t\left(\frac{1 + z^{-1}}{2}\right) \qquad (9)$$

It is interesting to note that when considering the electromagnetic couplings of the slots, the update algorithm for $\mathbf{E}_t$ and $\mathbf{H}_t$ developed above keeps the same scheme as Yee's FDTD does in the regions connected with the slots, without introducing any additional subgrids. The significant advantage of the present algorithm is its stability, accuracy and efficiency.

III. RESULTS AND DISCUSIONS

The FDTD algorithm developed above is used to simulate the electromagnetic coupling through the slots in the rectangular combline resonators shown in Fig. 1 and in the cylindrical combline resonators shown in Fig. 2.

Fig. 3 shows a function of the electromagnetic coupling as the relative slot height (b-d)/b with the slot thickness t as a parameter. It is observed that the slot height changes the electromagnetic property of the couplings. When the slot height is large, the magnetic coupling becomes dominant. In the opposite case, the electric coupling becomes strong. However, the electric coupling is not a monotone function of the height. On the other hand, both electric and magnetic couplings decrease with the thickness of the slot.

The convergence of FDTD is checked for the slot-coupled cylindrical combline resonators shown in Fig.2. The dependences of the coupling coefficients on both the number of the axial grid points and the number of grid points along the circumference are shown in Fig.4 (a) and (b).

Fig.5 depicts the effects of the slot height on the couplings for the slot-coupled cylindrical combline resonators, with the slot thickness as a parameter. Also shown in this figure are experimental data available in reference [3]. The consistency between the experimental data and simulated results supports the accuracy of the proposed methodology.

IV. CONCLUSIONS

A novel methodology for the efficient and accurate FDTD simulation of slot-coupled microwave structures has been presented. The present implementation is a hybridization of FDTD and the Padé approximation technique. It eliminates the need for subgridding, thus facilitating modeling versatility, avoiding numerical stability problems and improving computational efficiency. The proposed methodology is also applicable to the FDTD-based modeling of multi-layered, slot-coupled printed antennas and 3D MCM interconnects with perforated ground planes.

REFERENCES

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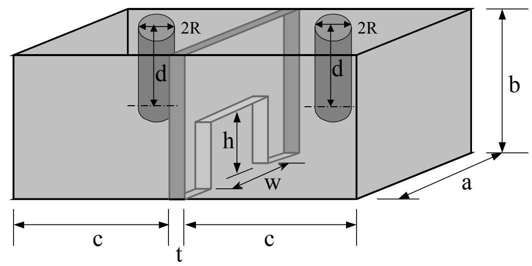
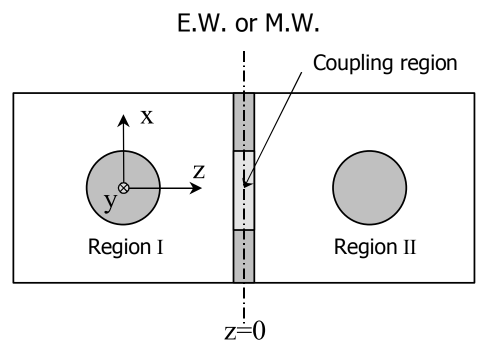


(a) Sketch of the structure



(b) Top view with coordinates

Fig.1 Slot-coupled rectangular combline resonators

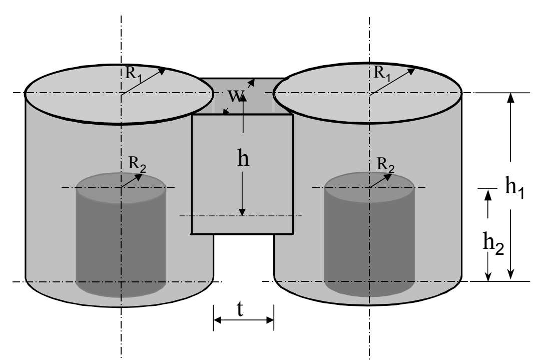


Fig.2 Slot-coupled cylindrical combline resonators

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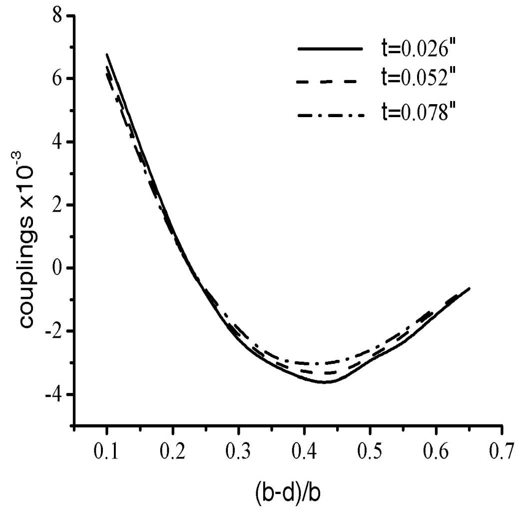
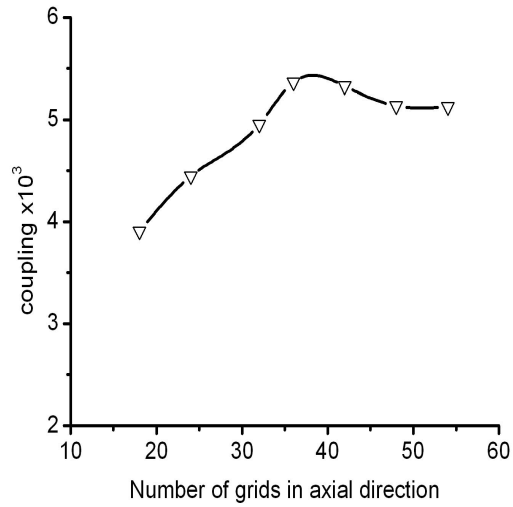
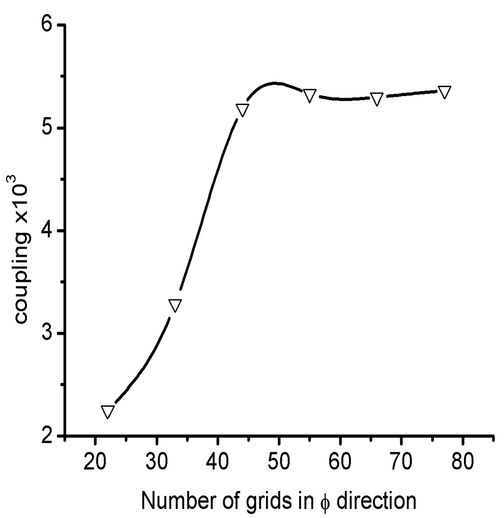


Fig.3 Electromagnetic coupling for the slot-coupled rectangular Resonators versus the relative slot height (b-d)/b, with the slot thickness t as a parameter.
a=0.872”, b=1.872”, c=1.0”, R=0.13”, d=1.084”, w=0.872”



(b) axial

Fig.4 Convergence check of FDTD for the slot-coupled cylindrical combline resonators



(a) circumferential

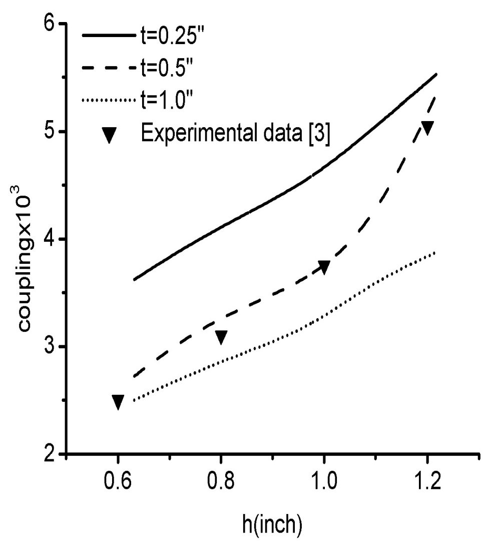


Fig.5 Effects of the slot height h on the couplings for the slot-coupled cylindrical combline resonators, with the slot thickness t as a parameter.
R_1=0.7485”, R_2=0.219”, h_1=1.826”, h_2=1.728”, w=0.8”