EFFICIENT ANALYSIS OF LOSSY SIW STRUCTURES BASED ON THE PARALLEL PLATES WAVEGUIDE GREEN'S FUNCTION AND FAST FREQUENCY SWEEP

Giandomenico Amendola,[1] Giovanni Angiulli,[2] Emilio Arnieri,[1] and Luigi Boccia[1]
[1] DIMES, University. della Calabria, via Pietro Bucci, 87036, Rende, Italy
[2] DIIES, University "Mediterranea", via Graziella, Loc. Feo di Vito, 89121, Reggio, Calabria, Italy; Corresponding author: giovanni.angiulli@unirc.it

ABSTRACT: *A fast frequency analysis of lossy substrate-integrated waveguides based on the asymptotic waveform evaluation (AWE) and Padè approximant technique in conjunction with the dyadic Green's function technique, is presented. The derivatives needed to evaluate moments in the AWE method are computed in a simple way thanks to an efficient method that reduces their computational cost. Numerical results demonstrate the efficiency and the accuracy of the proposed approach.*
 Microwave Opt Technol Lett 57:2435–2437, 2015; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29341

Key words: *substrate-integrated waveguide; Green's function; asymptotic waveform evaluation -Padè method*

1. INTRODUCTION

During the years, the number of papers on scientific and technical journals having the design of devices based on the substrate-integrated waveguide (SIW) technology as a subject, is noticeably increased (see [1–3] and references within) clearly showing that SIW is to be considered a well-consolidated technology. Even if for design purposes commercial codes based on finite difference time-domain method (FDTD) or finite element method (FEM) are used, there is a growing interest in the development of more effective methods that can significantly shorten the design and optimization process of these devices. Recently, in a series of papers [4–9], the authors have presented effective methods to analyze SIW structures, based on the dyadic Green's function of the parallel plates waveguide. With respect to commercial codes, the proposed method significantly reduced both CPU time and memory storage [4]. It has been successfully applied to analyze array of slots [5] and resonators [6], and later, it has been extended to handle lossy SIW structures [7,8]. To further reduce the computational time, in [9], a fast frequency sweep technique based on asymptotic waveform evaluation (AWE) and Padè approximant has been applied to the analysis of lossless SIW structures [9]. In this letter, the method presented in [9] has been tailored to treat the case of lossy SIWs. Since the presence of losses hugely complicates the expressions of the elements of the matrix relevant to the scattering from vias, making unpractical the analytical approach adopted in [9] for evaluating the derivatives needed to implement the fast frequency sweep, in this letter, the derivatives are efficiently computed exploiting the approach proposed in [10]. In what follows, after a brief presentation of the theoretical framework of the Green's function technique as applied to SIW lossy structures, the proposed AWE–Padè fast frequency sweep method will be discussed. Numerical results will show that a significant reduction of CPU time is achieved by the method without reducing the overall accuracy.

2. THE LOSSY PARALLEL PLATES WAVEGUIDE

The detailed derivation of the dyadic Green's function of the lossy parallel plates waveguide $\bar{\bar{G}}_{\mathrm{PPW}}(\boldsymbol{r},\boldsymbol{r}')$ has been presented in [8]. Thanks to its knowledge, the total magnetic field $\boldsymbol{H}(\boldsymbol{r})$ inside a lossy SIW structure can be written as

$$\boldsymbol{H}(\boldsymbol{r}) = -j\omega\epsilon_r\epsilon_0 \int \boldsymbol{d\rho}'\,\bar{\bar{G}}_{\mathrm{PPW}}\left(\boldsymbol{r},\boldsymbol{r}'\right)\boldsymbol{J_M}\left(\boldsymbol{r}'\right)+\boldsymbol{H}_{sCyl}(\boldsymbol{r}) \quad (1)$$

where $\boldsymbol{J_M}(\boldsymbol{r})$ is the magnetic current source and $\boldsymbol{H}_{sCyl}(\boldsymbol{r})$ is the scattering contribution from metallic vias. As demonstrated in [4,8] $\boldsymbol{H}_{sCyl}(\boldsymbol{r})$ can be written as series of outgoing TM and TE cylindrical vector wave functions $\boldsymbol{M}_n\left(k_{\rho m}, k_{zm}, \rho_{<>},\ z, \Delta z\right)$ and $\boldsymbol{N_n}\left(k_{\rho m}, k_{zm}, \rho_{<>},\ z, \Delta z\right)$ (in what follows the apex M and M are used for TE and TM modes, respectively), having coefficients $A^M_{m,n,l}$ $A^N_{m,n,l}$ [8] which can be evaluated by solving the following linear matrix system

$$\boldsymbol{L}^{M,N}\boldsymbol{A}^{M,N} = \boldsymbol{\Gamma}^{M,N} \quad (2)$$

arising from the discretization via method of moments of the relevant scattering operator [8]. Once that the terms $A^M_{m,n,l}$ $A^N_{m,n,l}$ in (2) are computed, the admittance $Y^{(p_i,p_j)}$ between ports p_i and p_j of the SIW structure at hand can be evaluated as

$$Y^{(p_i,p_j)} = -\frac{\int_{S_{p_j}} \boldsymbol{dr}\boldsymbol{H}^{p_i}(\boldsymbol{r})\cdot\boldsymbol{J}_M^{p_j}(\boldsymbol{r})}{|V|^2} \quad (3)$$

where S_{p_j} is the surface of port p_j, V is the voltage between the inner and the outer conductor of the coaxial port, $\boldsymbol{H}^{p_j}(\boldsymbol{r})$ is the total magnetic field due to the magnetic current density $\boldsymbol{J}_M^{p_j}(\boldsymbol{r})$ on port p_j and density $\boldsymbol{J}_M^{p_i}(\boldsymbol{r})$ is the magnetic current density impressed on port p_i [8].

3. FAST FREQUENCY SWEEP

AWE is a well-established technique to implement the fast frequency sweep analysis of electromagnetic problems [9,11]. The method synthesizes a model of reduced order that gives a good approximation of the frequency response of the system under analysis. Customarily, the AWE technique is used to find the Padè approximation of the frequency response by directly operating on the output parameters, like **Z** or **S** matrix. However, as demonstrated in [9], when applied to SIW devices this implementation does not produce a significant speed up. Following the approach exploited in [9], AWE is applied expanding the term $\boldsymbol{A}(\omega)^{M,N}$ in (2) a Taylor series around ω_0 as

$$\boldsymbol{A}(\omega)^{M,N} = \sum_{n=0}^{\infty} \boldsymbol{U}_{\boldsymbol{n}}^{\boldsymbol{M},\boldsymbol{N}}(\omega-\omega_0)^n \quad (4)$$

where the moments $\boldsymbol{U}_{\boldsymbol{n}}^{\boldsymbol{M},\boldsymbol{N}}$ are recursively calculated as

$$\boldsymbol{U}_{\boldsymbol{n}}^{\boldsymbol{M},\boldsymbol{N}} = \boldsymbol{L}^{\boldsymbol{M},\boldsymbol{N}}(\omega_0)^{-1}\left[\frac{\boldsymbol{\Gamma}^{M,\ N(n)}(\omega_0)}{n!} - \sum_{r=0}^{n}\left(\frac{(1-\delta_{r0})\boldsymbol{L}^{\boldsymbol{M},\ N}(\omega_0)^{(r)}\boldsymbol{U}^{M,\ N}_{n-r}}{r!}\right)\right] \quad (5)$$

Next, the expansion (4) is used to find a rational Padè expansion of $\boldsymbol{A}(\omega)^{M,\ N}$

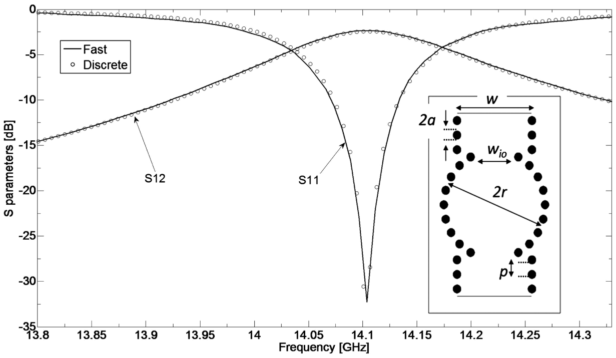

Figure 1 Scattering parameters of a single cavity circular filter, as in [13], $h = 0.380$ mm, $w = 3.8$ mm, $w_{io} = 1.683$ mm, $a = 0.2$ mm, $r = 2.4$ mm $p = 0.7$ mm, $\Sigma = 9.9$, $\tan\delta = 0.001$, $\sigma = 5.8*107$ S/m.

$$\boldsymbol{A}(\omega)^{M,\ N} = \frac{\sum_{n=0}^{N} \boldsymbol{a}_n^{M,\ N} (\omega-\omega_0)^n}{\sum_{n=0}^{N} \boldsymbol{b}_n^{M,\ N} (\omega-\omega_0)^n} \tag{6}$$

where the unknown coefficients $\boldsymbol{a}_n^{M,N}$, $\boldsymbol{b}_n^{M,N}$ are obtained equating between them expansions (4) and (6). In [9], where lossless circuits were considered, moments $\boldsymbol{U}_{\boldsymbol{n}}^{\boldsymbol{M},\ N}$ were determined using the analytical expressions of derivatives of the elements $l_{m,n}^{M,N}$ of $\boldsymbol{L}^{M,N}$. Here the expressions of these coefficients are complicated by the presence of losses (in particular, the $l_{m,n}^{M,N}$, defined in [8], includes both Bessel functions and their first derivatives) and the analytical approach results very cumbersome to apply. To avoid to recur to numerical differentiation, which would result to be very inefficient, the approach proposed in [10] has been exploited. It allows to approximate the derivative needed to compute the moments $\boldsymbol{U}_{\boldsymbol{n}}^{\boldsymbol{M},\ N}$ around ω_0 of the terms $l_{m,n}^{M,N}$ in a simple recursive way at a very small computational cost. The point of departure is the following approximation for $l_{m,n}^{M,N}$ [10].

$$l_{m,n}^{M,N}(\omega) = \left[G_{nm}^{(0)} + C_{nm}^{(0)}(\omega\text{-}\omega_0)\right] \mathrm{e}^{j\,(H_{mn}+D_{mn}(\omega\text{-}\omega_0))} \tag{7}$$

where

$$G_{nm}^{(0)} = |z_{nm}(\omega)| \;\; C_{nm}^{(0)} = \frac{d|z_{nm}(\omega_0)|}{d\omega} \tag{8}$$

$$H_{nm} = \arg(z_{nm}(\omega_0)) \;\; D_{mn} = \frac{d}{d\omega}(\arg(z_{nm}(\omega_0))) \tag{9}$$

Exploiting the above relations, derivatives of order n are well approximated by

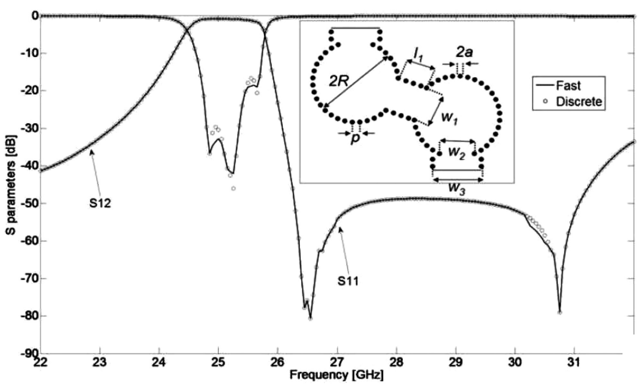

Figure 2 Scattering parameters of a dual-cavity filter as in [10], $h = 0.5$ mm, $w_1 = 4.08$ mm, $w_2 = 3.93$ mm, $w_3 = 5.50$ mm, $a = 0.2$ mm, $p = 0.851$ mm, $l_1 = 3.404$ mm, $R = 4.83$ mm, $a = 2.55$ mm, $\Sigma = 2.2$, $\tan\delta = 0.001$, $\sigma = 5.8*107$ S/m.

TABLE 1 MAE and CPU Time for the Post Filter [14]

Method	Np	MAE of s_{12}	CPU Time (s)
Discrete simulations	112	0	134.2
Proposed method	4	0.0181	12.8

$$\frac{d^n}{dz^n} z_{nm}(\omega) = \left[G_{mn}^{(n)} + C_{mn}^{(n)}(\omega-\omega_0)\right] e^{j(H_{nm}+D_{nm}(\omega-\omega_0))} \tag{10}$$

with

$$G_{mn}^{(n)} = C_{nm}^{(n-1)} + jD_{nm}G_{nm}^{(n-1)} \;\; C_{nm}^{(n)} = jD_{nm}C_{nm}^{(n-1)} \tag{11}$$

Once the $\boldsymbol{U}_{\boldsymbol{n}}^{\boldsymbol{M},\boldsymbol{N}}$ are known, the Padè rational expansion combined with the Complex Frequency Hopping (CFH) technique [12] is applied to compute the port admittance (3) and the scattering parameters of the SIW device at hand.

4. NUMERICAL RESULTS

To test the effectiveness and the speed up of the proposed method, a single SIW circular cavity filter [13] and a SIW post filter [14] have been simulated using a MATLAB code implementing the fast frequency sweep method above described. Being characterized by increasing number of poles, these structures have been allowed to validate the method at an increasing level of complexity. All simulation have been carried out on a machine mounting an AMD Athlon IIX2 250 3.00 GHz CPU and equipped with 4 GB RAM. As it can be seen from computational results reported in Figures 1 and 2, there is a very good agreement between fast sweep and discrete (or point-to-point) simulations. In particular, when only a single resonance is considered, as in the first case, the discrete and fast sweep results are very close each other. Conversely, when the presence of multiple resonances is considered, as in the second case, approximation obtained is less accurate but still satisfactory. In Table 1 is reported both the mean absolute error (MAE) of s_{12} defined as

$$\mathrm{MAE} = \frac{1}{N\mathrm{p}} \sum_{n}^{N\mathrm{p}} |s_{12,n} - \check{s}_{12,n}| \tag{12}$$

and the CPU time comparison between discrete and the fast sweep simulations for the case of the SIW post filter. In (12), $s_{12,n}$ and $\check{s}_{12,n}$ are the values of s_{12} computed by the discrete and by fast frequency sweep simulation, respectively, and N_p is the number of calculation points. It can be noticed an error limit of $\epsilon = 0.2$ at midpoint gives a very accurate result for $\check{s}_{12,n}$, providing a reduction in time of an order of magnitude if compared with the discrete simulation.

5. CONCLUSION

In this letter, a method for the analysis of lossy SIW structures based on the method of moments and the fast frequency sweep has been presented. The fast sweep is based on a combined AWE–Padè technique with CFH technique. The derivatives needed to the moments' expansions have been determined using the analytical approximation proposed in [10], which allows the recursive calculation for higher order without recurring to numerical differentiation. Numerical results show a considerable reduction of the CPU time without compromising the overall accuracy of the method.

REFERENCES

1. M. Bozzi, A. Georgiadis, and K. Wu, Review of substrate-integrated waveguide circuits and antennas, IET Microwave Antennas Propag 5 (2011), 909–920.

2. S. Kurudere and V.B. Ertürk, SIW-based interdigital bandpass filter with harmonic suppression, Microwave Opt Technol Lett 57 (2015), 66–69.
3. J. Lacik, Circularly polarized SIW square ring-slot antenna for X-band applications, Microwave Opt Technol Lett, 54 (2012), 2590–2594.
4. E. Arnieri and G. Amendola, Analysis of substrate integrated waveguide structures based on the parallel plate waveguide Green's function, IEEE Trans Microwave Theory Tech 56 (2008), 1615–1623.
5. E. Arnieri and G. Amendola, Method of moments analysis of slotted substrate integrated waveguide arrays,", IEEE Trans Antennas Propag 59 (2011), 1148–1154.
6. G. Amendola, G. Angiulli, E. Arnieri, and L. Boccia, Resonant frequencies of circular substrate integrated resonators, IEEE Microwave Wireless Compon Lett 18 (2008), 239–241.
7. G. Amendola, G. Angiulli, E. Arnieri, and L. Boccia, Computation of the resonant frequency and quality factor of lossy substrate integrated waveguide resonators by method of moments, Prog Electromagn Res Lett 40 (2013), 107–117.
8. G. Amendola, E. Arnieri, and L. Boccia, Analysis of lossy SIW structures based on the parallel plates waveguide Green's function, Prog Electromagn Res C 33 (2012), 157–169.
9. E. Abaei, G. Amendola, E. Arnieri, S. Costanzo, and E. Mehrshahi, A fast frequency sweep Green's function analysis of substrate integrated waveguides, Radioengineering 21 (2013), 1025–1030.
10. A. Belenguer, H. Esteban, E. Diaz, C. Bachiller, J. Cascon, V.E. Boria, Hybrid technique plus fast frequency sweep for the efficient and accurate analysis of substrate integrated waveguide devices, IEEE Trans Microwave Theory Tech 59 (2011), 552–560.
11. L.T. Pillage and R.A. Rohrer, Asymptotic waveform evaluation for timing analysis, IEEE Trans Comput-Aided Des Integr Cir Syst 9 (1990), 352–366.
12. E. Chiprout and M.S. Nakhla, Analysis of interconnect networks using complex frequency hopping (CFH), IEEE Trans Comput-Aided Des Integr Cir Syst 14 (1995), 186–200.
13. J.C. Potelon, J.F. Bohorquez, C. Favennec, E. Rius, and C. Person, Design of Ku-band filter based on substrate integrated circular cavities (SICCs), IEEE MTT-S Int Microwave Symp, (2006), 1237–1240.
14. M. Bozzi and L. Perregrini, and W. Ke, Modeling of conductor, dielectric, and radiation losses in substrate integrated waveguide by the boundary integral-resonant mode expansion method, IEEE Trans Microwave Theory Tech 56 (2008), 3153–3161.