Parameterized surrogate/behavioral models for analysis of RF circuits in frequency or time-domain

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Abstract

Surrogate models of distributed components embedded in circuit simulators are often not accurate enough for modern applications. The accuracy can be increased if a model is constructed based on data obtained from e.m. simulation. Even then, however, parameterized, closed-form surrogate models can not be directly used for non-linear analysis involving time domain simulations. It is hence essential to create models that are accurate enough for frequency domain analysis and at the same time are stable and passive.

1. Introduction

The increase in the operational frequency along with a growing integration of high frequency devices makes a system design an enormous challenge for engineers. Currently, one of the hot topics is the development of fast and versatile modelling and simulation tools for high-complexity and/or highly-integrated devices. Additionally, tightening time-to-market constraints enforce the adaptation of new design methodologies. During the design process of the basic building blocks of the system the main steps that involve RF and microwave engineering are the pre-layout and post-layout stages.

The result of the pre-layout stage is an electric scheme of the circuit composed of lumped elements that represent passive and active (linear and non-linear) components. At this stage parasitic effects are often not taken into account. Traditional pre-layout design of analog microwave components and systems is carried out using circuit simulators. The simulator uses lumped elements, transmission lines and relies on S,Y, or Z parameters of individual components making up the circuit. The advantage of such approach is a speed of the simulation which allows optimization.

There are few circuit simulators on the market that are dedicated to microwave components design. The software, besides lumped elements and ideal transmission lines, has a built-in library of surrogate models of simple discontinuities made in the most popular microwave technologies. The library consists of the models developed for the most popular elements, but one has to note that each model has limited accuracy. For example, commercial simulators commonly represent the 90-degree microstrip bend with the Kirchning, Jansen and Koster model that has the following limitations [1]: $0.2 \leq \frac{w}{H} < 6$, $2.36 \leq \epsilon_r \leq 10.4$, $f_{max} \leq \frac{12GHz}{H[mm]}$, where w is the width of the strip, H is the height of the substrate and f_{max} is maximum model frequency. The versatility of the model is then a strongly restricted. If one compares the contents of the libraries with current and emerging technologies, it is obvious that there is a need for novel libraries of surrogate models.

Post-layout simulation is a much longer process. In microwave frequencies the passive electronic circuits are distributed, so the response depends on the structure dimensions and topology. Several parasitic effects, that could be neglected at lower frequencies, must be included in simulation on microwave frequencies due to their influence on device's operation. For example, the effects that should not be neglected at high frequencies include dispersion, skin effect, frequency dependent losses and parasitic radiation.

The parasitic effects of passive components and new technologies can be accounted for in high-accuracy electromagnetic simulators. There are several full-wave solvers capable of analysis of microwave devices. Each technique is better or worse suited for a given technology, but a common factor of electromagnetic approach is a high numeric cost of problem solution which leads to very long time of computation, especially in the case of complex structures. Additionally, an effort to provide the input data (like geometry) and to ensure the correct conditions of simulation can be substantial.

2. Surrogate/behavioral modeling

A solution to overcome this problem is to create new libraries of parameterized, surrogate models based on the results of EM simulations. The basic idea behind surrogate/behavioral modelling is a construction of a "black-box" representation of the circuit that closely approximates the response of the original structure within the range of its input parameters (Fig. 1). In most cases the inputs of the model $x_1, x_2, \ldots, x_N$ are the frequency and/or structure dimensions, while the outputs describe the device's response. The advantage of surrogate models is that once the model has been created it can be used in many different designs, thus the gain of its construction is high.

In this paper the surrogate models are created using the interpolation scheme [2]. The main idea is to represent the transfer function of the device being modelled with a multivariate complex-valued rational function. In this approach, the scattering parameters of the device being modelled are expressed in the following form:

$$S(x_1, x_2, ..., x_N) = \frac{A(\underline{X})}{B(\underline{X})} = \frac{A(x_1, x_2, ..., x_N)}{B(x_1, x_2, ..., x_N)} \tag{1}$$

where both numerator $A(\underline{X})$ and denominator $B(\underline{X})$ are multinomials (sum of monomials multiplied by scalar coefficients). In general, the problem (1) is non-linear and the unknown coefficients a_i and b_i corresponding to the multinomials of numerator and denominator of 1 can be found enforcing its linearization and requiring that equation:

$$A(\underline{X}) - \widehat{S}(\underline{X})B(\underline{X}) = 0 \tag{2}$$

is fulfilled on at least $L \geq M_1 + M_2$ support points, where M_1 and M_2 are the numbers of unknown coefficients a_i and b_i. The linear problem is solved applying the total least squares technique (TLS) [4]

The algorithm employs an adaptive sampling technique called also *reflective exploration* [3, 2]. The procedure leads to an improvement of model quality and assures the points are selected at optimal locations, which minimizes the total number of samples used. It is especially advisable if the models are based on results of computationally expensive calculations, such as electromagnetic simulations.

3. Time domain model

Combining surrogate models in frequency domain with technique of passivity enforcement, like the one presented in [6], one obtains a parameterized SPICE network with guaranteed passivity. Such circuits can be useful in many applications, such as analysis and tuning of RFIC devices on post-layout stage of design in time-domain.

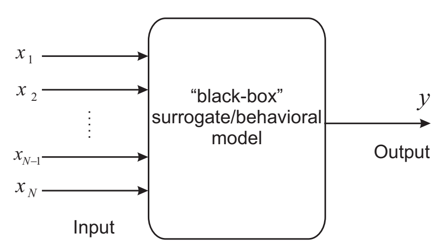

Fig. 1: Basic idea of surrogate/behavioral modelling

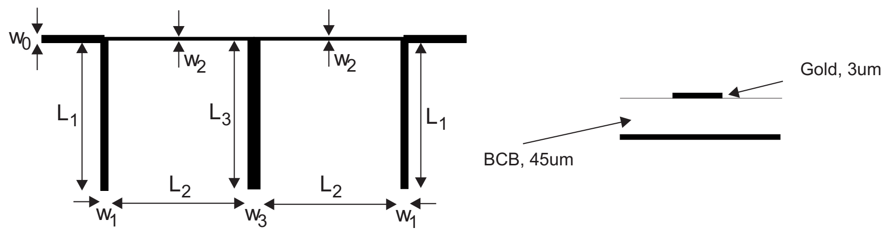

Fig. 2: Structure layout with details of MCM-D substrate.

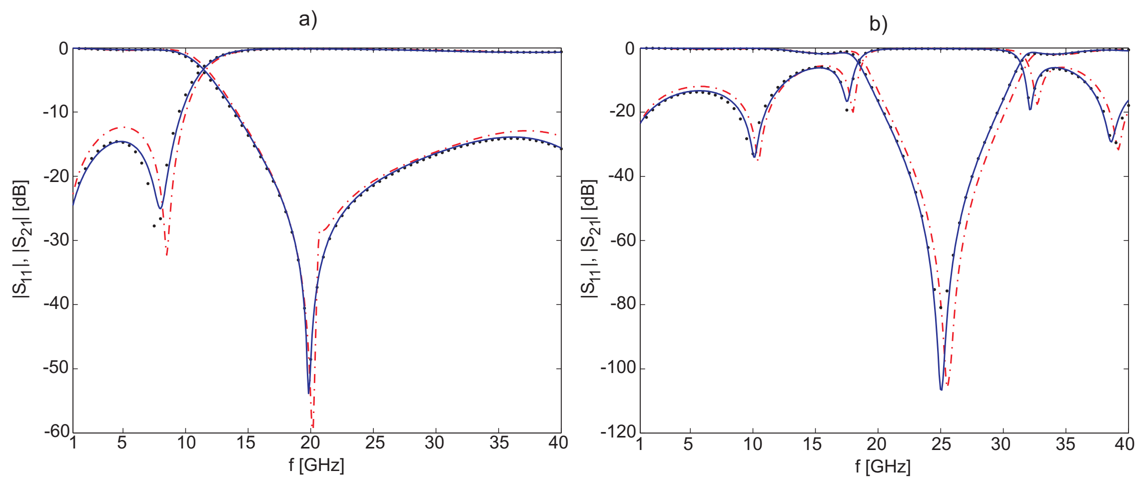

Fig. 3: Accuracy comparison of structure response computed with the application of created rational models and built-in models from commercial circuit simulator: $(\cdots)$ electromagnetic response, (—) response obtained from created models, (-.-.-) response of models from commercial software. Structure dimensions: a) $w_0 = 0.157$mm, $w_1 = 0.157$mm, $w_2 = 0.05$mm, $w_3 = 0.2$mm, $L_1 = 2.5$mm, $L_2 = 1.3$mm, $L_3 = 1$mm, b) $w_0 = 0.157$mm, $w_1 = 0.1$mm, $w_2 = 0.1$mm, $w_3 = 0.1$mm, $L_1 = 2$mm, $L_2 = 2$mm, $L_3 = 2$mm

4. Application example

To show the advantage of surrogate models based on the results of the electromagnetic simulations two microstrip elements were modelled: a section of microstrip line and an open-end stub. The parameters assumed for the microstrip line were as follows: frequency $f \in (1GHz - 40GHz)$, line width $w \in (50\mu m - 2mm)$ and line length $L \in (0.5mm - 2mm)$. The stub has five parameters: frequency $f \in (1GHz - 40GHz)$, width of the input line $w_1 \in (0.5mm - 2mm)$, width of the output line $w_2 \in (0.5mm - 2mm)$, width of the stub $w_3 \in (0.5mm - 2mm)$ and length of the stub $D \in (1mm - 2.5mm)$. The cascade connection of the scattering parameters of this basic elements allows one to obtain a fully parameterized model of the structure presented in Fig.2.

Figure 3 shows a comparison of accuracy of the evaluation of structure response for different structure dimensions. The reference are the characteristics computed with a full-wave tool using the method of moments (Agilent's Momentum). In the same figure a response of the structure calculated with the commercial circuit simulator is presented. It can be seen that the models used in the simulator have a limited accuracy and in some frequency ranges the error of the response is high. On the other hand, the response computed with application of the models developed with the technique described here is very close to electromagnetic response. It has to be noticed, that the computation of structure response using electromagnetic solver (Momentum) takes about 7s for a single frequency point. The application of surrogate models reduces this time to 0,05s (Matlab implementation).

Since the response of surrogate model is not passive, to restore the passivity of the model the technique

Table 1: Accuracy of the developed parameterized equivalent circuit of filtering structure compared to models response from leading circuit simulator (all errors in decibels).

Structure dimensions [mm]							Non-passive		Passive		Commercial sim.	
w_0	w_1	w_2	w_3	L_1	L_2	L_3	$E_{RMS}^{S_{11}}$	$E_{RMS}^{S_{21}}$	$E_{RMS}^{S_{11}}$	$E_{RMS}^{S_{21}}$	$E_{RMS}^{S_{11}}$	$E_{RMS}^{S_{21}}$
0.13	0.1	0.15	0.1	1.5	2	2	-55.7	-50.8	-53.0	-48.8	-40.8	-42.2
0.18	0.1	0.15	0.2	1.5	1.5	1.8	-52.9	-51.4	-52.7	-48.6	-37.3	-36.7
0.1	0.05	0.05	0.1	2.5	2	2	-47.6	-47.0	-46.7	-47.5	-35.8	-37.1
0.157	0.1	0.1	0.1	2	2	2	-53.1	-49.7	-53.0	-50.0	-37.3	-35.7
0.157	0.157	0.05	0.2	2.5	1.3	1	-53.1	-49.0	-51.8	-49.9	-37.1	-44.2

presented in [6] was used. In Table 1 the comparison of errors of the non-passive, passive and built-in commercial circuit simulator model responses for different structure dimensions are presented. It can be seen, that in each case the proposed scheme gives one passive models with accuracy higher than models included in commercial circuit simulator.

5. Conclusions

The need for new libraries of distributed, passive elements made in various modern technologies was shown in this paper. It was shown that commonly used coarse models are often too inaccurate to perform a successful design. It is recommended that models should be based on the results of electromagnetic simulator, which ensures the accuracy of the model. Finally, the surrogate/behavioral model from frequency domain can be transformed into a passive equivalent circuit for time-domain analysis.

6. Acknowledgment

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