SCALABLE CIRCUIT MODELS FOR PASSIVE HIGH-SPEED INTERCONNECTION STRUCTURES

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ABSTRACT

An automated circuit-modeling tool is presented for arbitrary planar transmission lines. The tool builds compact, parameterized, analytical models based on multiple full-wave 2D electro-magnetic (EM) simulations. The transmission line parameters are stored as a multidimensional function of frequency and geometrical parameters. The modeling algorithm combines adaptive data selecting and modeling techniques. The circuit models combine EM-accuracy and generality, and circuit simulation speed and flexibility.

1. INTRODUCTION

Multiconductor transmission line structures form a basic building block of microwave and RF integrated circuits. The modeling of their behavior at microwave and millimeter wave frequencies is essential to the correct functioning of these devices (Dhaene and De Zutter 1992; Dhaene et al. 1994). Their presence is certainly not restricted to MIC's (microwave Integrated Circuits) and MMIC's (Monolithic MIC's). Due to the increasing bitrates in digital broadband systems and in computers, the behavior of multiconductor busses on boards and backplanes becomes increasingly important.

Accurate parameterized circuit models for arbitrary transmission line structures are required for the design and optimization of high-speed electronic circuits. Several numerical 2D EM techniques (such as the method of moments (Momentum 1995-2006)) can be used to accurately model transmission lines. However, most numerical EM techniques require a significant amount of expertise and computer resources, so that they are often only used for verification purposes. On the other hand circuit simulators are very fast, and offer a lot of different analysis possibilities. However, the number of available analytical transmission line models is limited, and the accuracy is not always guaranteed up to RF or microwave frequencies.

We developed a new automated tool for building parameterized circuit models of general passive transmission line structures with user-defined accuracy. The analytical models represent the transmission line parameters as a multidimensional function of frequency and geometrical parameters.

The models are based on full-wave 2D EM simulations, and can easily be incorporated in circuit simulators. This brings EM-accuracy and generality in the circuit simulator, without sacrificing speed. The model generation process is fully automated. Data points are selected efficiently and model complexity is automatically adapted. The algorithm consists of an adaptive modeling loop (section 2) and an adaptive sample selection loop (section 3). An example is given to illustrate the technique (section 4).

2. ADAPTIVE MODEL BUILDING ALGORITHM

Manuscripts Coupled transmission lines are 2D structures, and they are fully characterized by their length l, and by their impedance matrix Z_{cir} (= $R_{cir} + j\,\omega L_{cir}$) and the admittance matrix Y_{cir} (= $G_{cir} + j\,\omega C_{cir}$) per unit length (Dhaene and De Zutter 1992)-(Dhaene et al. 1994). The circuit parameters are generated using the 2D solver of the commercially available full-wave electro-magnetic simulator ADS Momentum (Momentum 1995-2006).

The transmission line parameters R, L, G and C are approximated by a weighted sum of multidimensional orthonormal polynomials (*multinomials*) P_m. The multinomials only depend on the coordinate $\bar{x}$ in the multidimensional parameter space R, while the weights C_m only depend on the frequency f:

$$RLGC(f,\bar{x}) \approx A(f,\bar{x}) = \sum_{m=1}^{M} C_m(f) P_m(\bar{x}) \qquad (1)$$

The weights C_m are calculated by fitting equation (1) on a set of D data points $\{\bar{x}_d, S(f,\bar{x}_d)\}$ (with d = 1, …, D). The number of multinomials M is adaptively increased until the error function $E(f,\bar{x}) = |\,RLGC(f,\bar{x}) - A(f,\bar{x})|$ is lower than a user-defined accuracy level in all the data points. For numerical stability and efficiency reasons orthonormal multinomials are used (De Geest et al. 1999; Dhaene et al. 2001).

3. ADAPTIVE DATA SELECTION ALGORITHM

The modeling process starts with an initial set of data points in the multidimensional parameter space. New data points are added adaptively until the user-defined accuracy level is guaranteed.

The process of selecting data points and building models in an adaptive way is called *reflective exploration* (Beyer and Smieja 1996). Reflective exploration is useful when the process that provides the data is very costly, which is the case for full-wave EM simulators. Reflective exploration requires *reflective functions* that are used to select a new data point.

The difference between 2 consecutive approximate models (with different order *M* in (1)) is used as a reflective function. A new data point is selected near the maximum of the reflective function. No new data points are added if the magnitude of the reflective function is smaller than the user-defined accuracy level (over the whole parameter space).

Physical rules are also checked. If the approximate modeling function $A(f,\bar{x})$ violates certain physical rules, a new data point is chosen where the criteria are violated the most.

Furthermore, at least one data point is chosen in the close vicinity of local minima and maxima of the modeling function $A(f,\bar{x})$ over the parameter space of interest.

The complete flowchart of the adaptive modeling algorithm is given in Fig. 1.

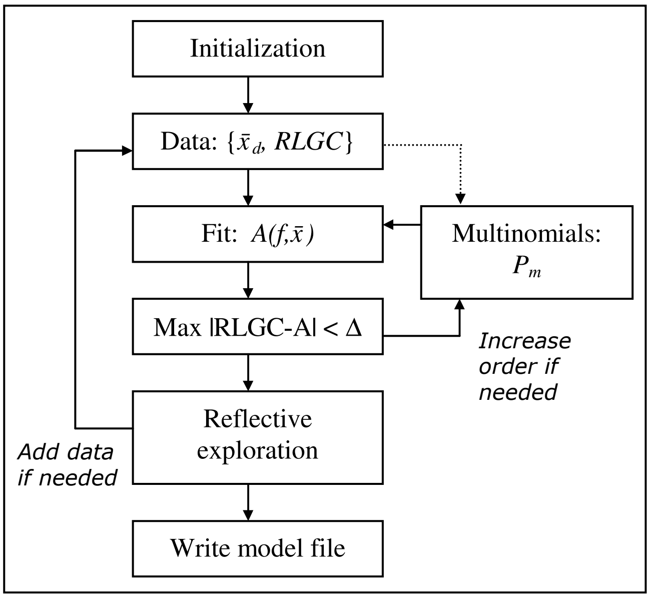

Figure 1. Adaptive modeling and sampling flowchart

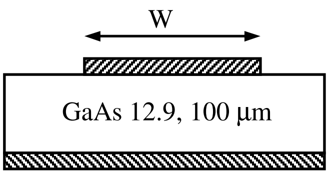

Figure 2. Single transmission line: cross section.

Table 1. Single transmission line: parameter ranges

variable	min	max
Width	20 µm	100 µm
f	0 GHz	60 GHz

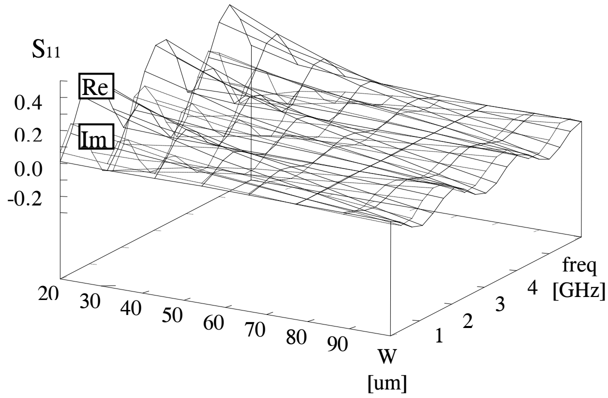

Figure 3. Single transmission line (1 mm): S_{11}(W,,f).

4. EXAMPLE: MICROSTRIP TRANSMISSION LINES

The automated modeling tool was used to generate analytical circuit models for a *single transmission line*, and *2 coupled transmission lines*. A GaAs microstrip substrate was used (h = 100 µm, ε_r = 12.9).

The parameter ranges of the *single transmission line* (Fig. 2) circuit are shown in Table 1. The new adaptive modeling tool selected 5 data points (= discrete 2D layouts) over the parameter range in an adaptive way, and grouped all *RLGC*-parameter data all in one global, compact, analytical model. In Fig. 3, the reflection coefficient S_{11} (reference impedance 50Ω) is shown as a function of *Width* and *frequency* for a line of 1 mm long. Note the wave behavior along the frequency axis, and the (almost) zero reflection if Width = 73µm (corresponding with a characteristic impedance of 50Ω).

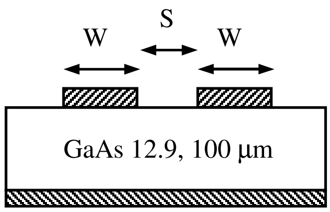

Figure 4. Coupled transmission lines: cross section.

Table 2. Coupled transmission lines: parameter ranges

variable	min	max
Width	40 µm	100 µm
Spacing	5 µm	50 µm
f	0 GHz	60 GHz

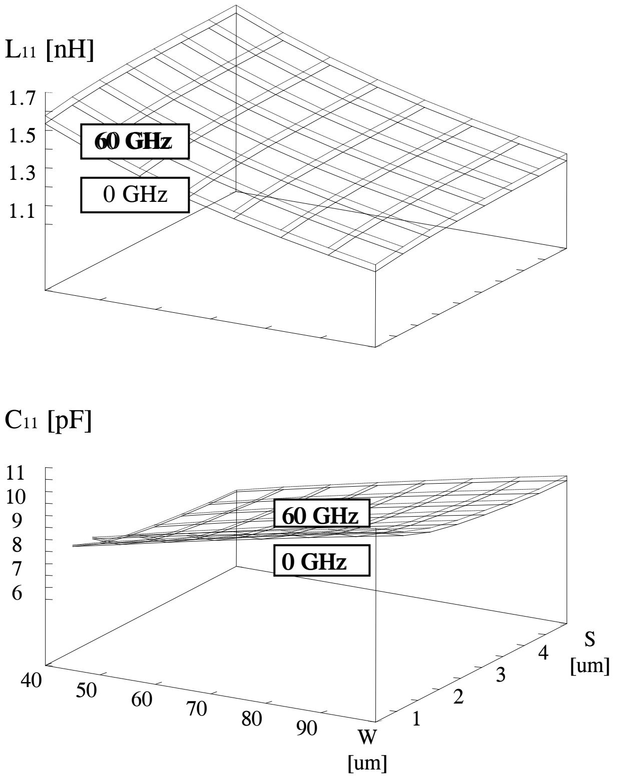

Figure 5. Coupled transmission lines : $L_{11}(W,S,f)$ & $C_{11}(W,S,f)$.

The parameter ranges of the *coupled transmission lines* (Fig. 4) circuit are shown in Table 2. The automated modeling tool selected 35 data points (corresponding with 35 transmission line configurations) over the parameter range of interest in an adaptive way, and grouped all RLGC-parameter data in one global, compact, analytical matrix model. In Figure 5, the inductance per unit length L_{11}, and the capacitance per unit length C_{11} are shown as a function *Width*, *Spacing* and *frequency*. As expected, the capacitance increases if *Width* and *frequency* increase, and *Spacing* decreases.

5. CONCLUSIONS

A new adaptive technique was presented for building parameterized models for general passive planar interconnection structures. The models are based on full-wave EM simulations, and have a user-defined accuracy. Once generated, the analytical models can be grouped in a library, and incorporated in a circuit simulator where they can be used for simulation, design and optimization purposes. Two microstrip examples were given to illustrate the new technique.

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