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VERY FAST SIMULATION STRATEGY (VFSS) DEVELOPED WITHIN CODESTAR PROJECT

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Abstract*—An efficient methodology to extract compact models for microstrip lines on lossy silicon substrate and other on-chip passive structures is presented. The VFSS consists in a series of techniques aiming the speed-up of the compact model extraction process. The electromagnetic field equations are solved by the "dual Finite Integration Technique" (dFIT), a numerical method which allows the accuracy control of the computed frequency dependent parameters. Several techniques are used to accelerate the extraction process, such as minimal virtual boundary, minimal mesh and minimal frequency samples set. In the interconnect case, the solution of the transmission line equations with frequency dependent parameters is then approximated by a rational function of appropriate degree in order to extract the compact model and its SPICE equivalent circuit. The behavior of the compact models shows good agreement with respect to the measured data.*

1. INTRODUCTION

. With the increase of the operating frequency, the behavior of on-chip interconnects becomes a dominant factor in the overall integrated circuit performance. The literature reflects much interest in the computation of frequency-dependent characteristics of on-chip interconnects and passive components [1]. Generally, the electromagnetic simulation by numerical methods are considered too time consuming to be a viable solution for computer aided design of integrated systems. However, the validity of any new approach is checked by comparison with them.

The goal of the present paper is to present techniques that speed-up the numerical electromagnetic simulation in order to make it suitable for the CAD environment.

2. TLTM MODELS FOR INTERCONECT LINES

The combination of *ALLROM technique* [2] with the *Very Fast Simulation (VFS)* strategy proposed here leads to the following algorithm to extract models of the interconnect lines by *Transmission Lines Transversal Magnetic Field (TLTM)* technique :

A) *Grid calibration* – the grid is successively refined, until the static p.u.l. capacitance $\mathbf{C}_l$ is accurate enough;

B) *Virtual boundary calibration* – the computational domain is successively extended until the static p.u.l. inductance $\mathbf{L}_l$ is accurate enough;

C) *Frequency analysis* – the frequency dependent p.u.l. parameters $\mathbf{Z}_l(\omega) = \mathbf{R}_l(\omega) + j\,\omega\,\mathbf{L}_l(\omega)$, $\mathbf{Y}_l(\omega) = \mathbf{G}_l(\omega) + j\,\omega\,\mathbf{C}_l(\omega)$ are computed in a minimal set of frequency samples;

D) *Length extension* – the frequency characteristic $\mathbf{Y}(\omega)$ of the real length line is computed by transmission line equations in an extended set of adaptive frequency samples, using an appropriate interpolation of p.u.l. parameters;

E) *Optimal order of the compact model* – compact models of increasing orders and their SPICE equivalent circuits are extracted and simulated, until the result is close to $\mathbf{Y}(\omega)$;

F) *Validation* – based on the results of the SPICE simulation in frequency domain, the scattering parameters $\mathbf{S}(\omega)$ are computed and compared with the measurements.

3. GRID CALIBRATION BY DFIT

he matrix of p.u.l. line capacitance $\mathbf{C}_l$ is extracted from the solution of the 2D-transversal electrostatic field problem. The *dual Finite Integration Technique* (*dFIT*) used to solve it provides lower and upper bounds of the exact solution [3]. These bounds are used to control the accuracy of the numerical solution by means of a multigrid approach (fig.1). In the case of passive structures, the dFIT is used to solve 3D electromagnetic field equations.

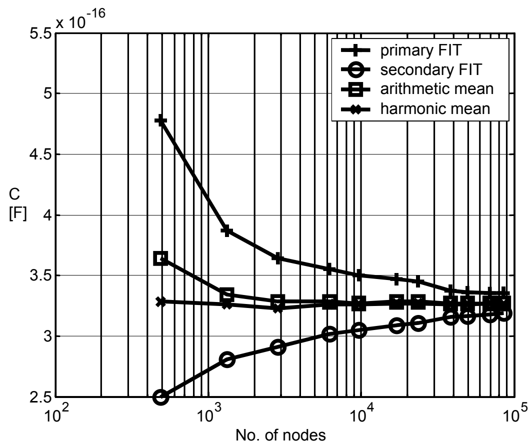

Fig. 1. Bounds of the static capacity vs. the multigrid level.

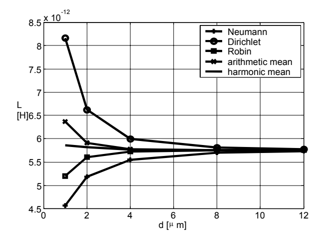

Fig. 2. Bounds of the inductance vs. the boundary position.

4. VIRTUAL BOUNDARYCALIBRATION BY ADB

The matrix of p.u.l. line inductance $\mathbf{L}_l$ is extracted from the solution of the magnetostatic field 2D-transversal problem. The dual boundary conditions (Neumann and Dirichlet) provide lower and upper bounds for the solution in the unbounded domain. They are used to control the accuracy of the solution in the truncated computational domain and to find the position of the minimal virtual boundary (fig.2). The *average of* solutions in dual *boundary* (*ADB*) conditions is adopted as the numerical solution.

5. FREQUENCY ANALYSIS

The frequency dependent p.u.l. line parameters (fig.3) are extracted from the solution of electromagnetic field problem solved in a short section (5 % of the wave length) of the interconnect. The model is discretized by only one layer of "electric cells", without "magnetic" branches along the longitudinal direction. The numerical solution is computed by *dFIT* combined with *ADB* and *FredHo* [4]. The used recurrent algorithm generates only 3 up to 7 frequency samples. Thus the frequency analysis step, which otherwise would be the most expensive one, is carried out with a minimum CPU time.

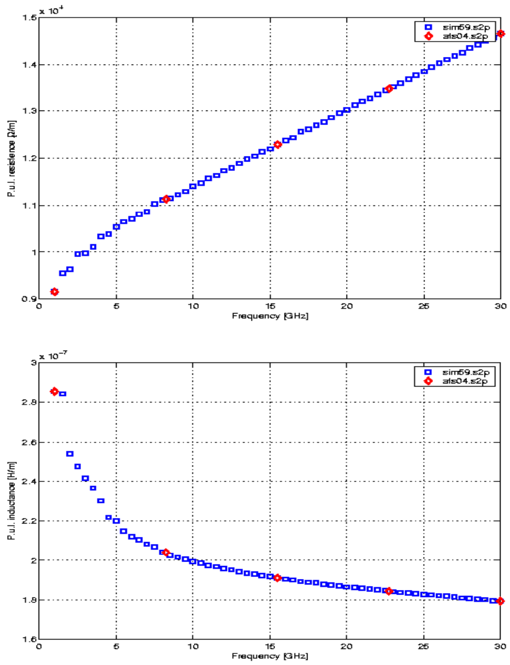

Fig. 3. R(f) and L(f) in linear scales

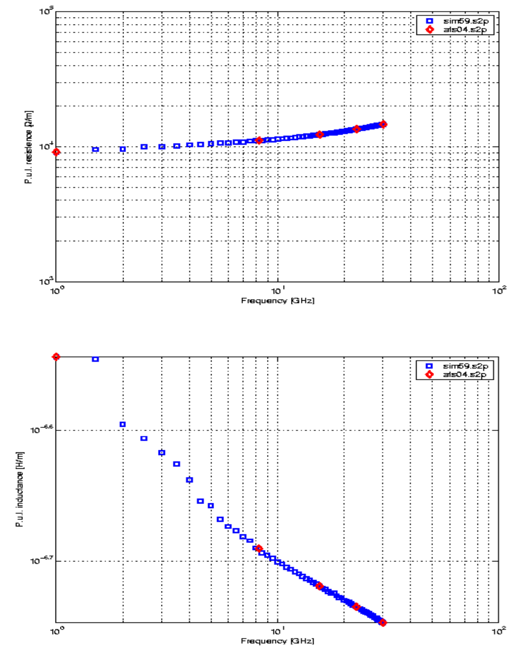

Fig. 4. R(f) and L(f) in log-log scales

6. ADAPTIVE FRQUENCY SAMPLING (AFS)

Unlike **Y**(ω) for the "long" line, the p.u.l. parameters $\mathbf{R}_l(\omega)$, $\mathbf{L}_l(\omega)$, $\mathbf{C}_l(\omega)$, $\mathbf{G}_l(\omega)$ have smooth and monotonic frequency dependence, requiring a reduced number of frequency samples to describe them, especially in the log-log scale (fig 3, 4). Therefore, the *piece-wise-linear* (*PWL*) interpolation is less appropriate than the *piece-wise-polytropic* (*PWP*) interpolation (which is *PWL* in log-log scale) as shows the results given in table 1.

An *Adaptive Frequency Sampling* (*AFS*) algorithm automatically selects the interpolation points. The frequency response **Y**(ω) is sampled more densely where needed (fig. 5). The speed-up provided by AFS was up to 5.5 (fig. 6).

Table 1 - Interpolation errors

No. of frequency samples	2	3	5	7
PWL error [%]	30.2	15.4	6.9	2.3
PWP error [%]	9.93	4.40	2.7	1.8

7. MODEL EXTRACTION AND SPICE SYNTHESIS

The frequency characteristic **Y**(ω) of interconnects is approximated by rational functions using the *Vector Fitting* procedure [5] and then a SPICE equivalent circuit is synthesized by the *Differential Equation Macromodel* [6].

In figure 7 is depicted how the relative errors between electromagnetic simulation results and Spice simulation results for the extracted compact model depends of the order of compact model.

Based in this dependence, an automatic procedure selected as the suitable compact model that of order q = 10.

8. VALIDATION FOR CODESTAR BENCHMARKS

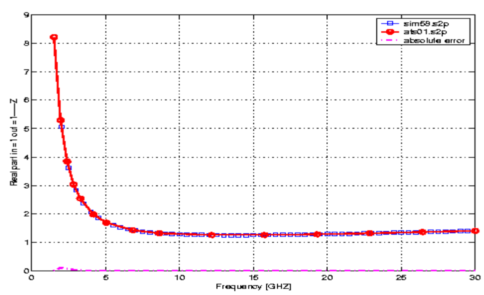

Fig 5. Example of AFS grid

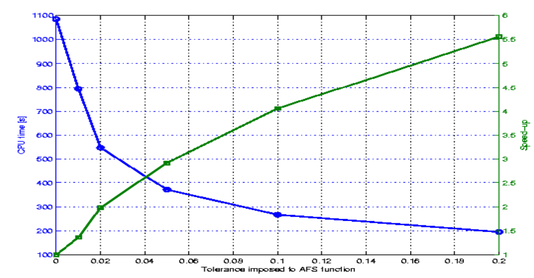

Fig 6. ATS speed-up

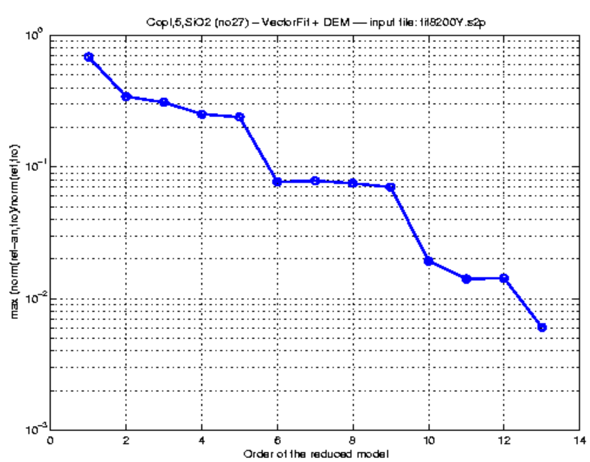

Fig. 7 Relative error of the compact model

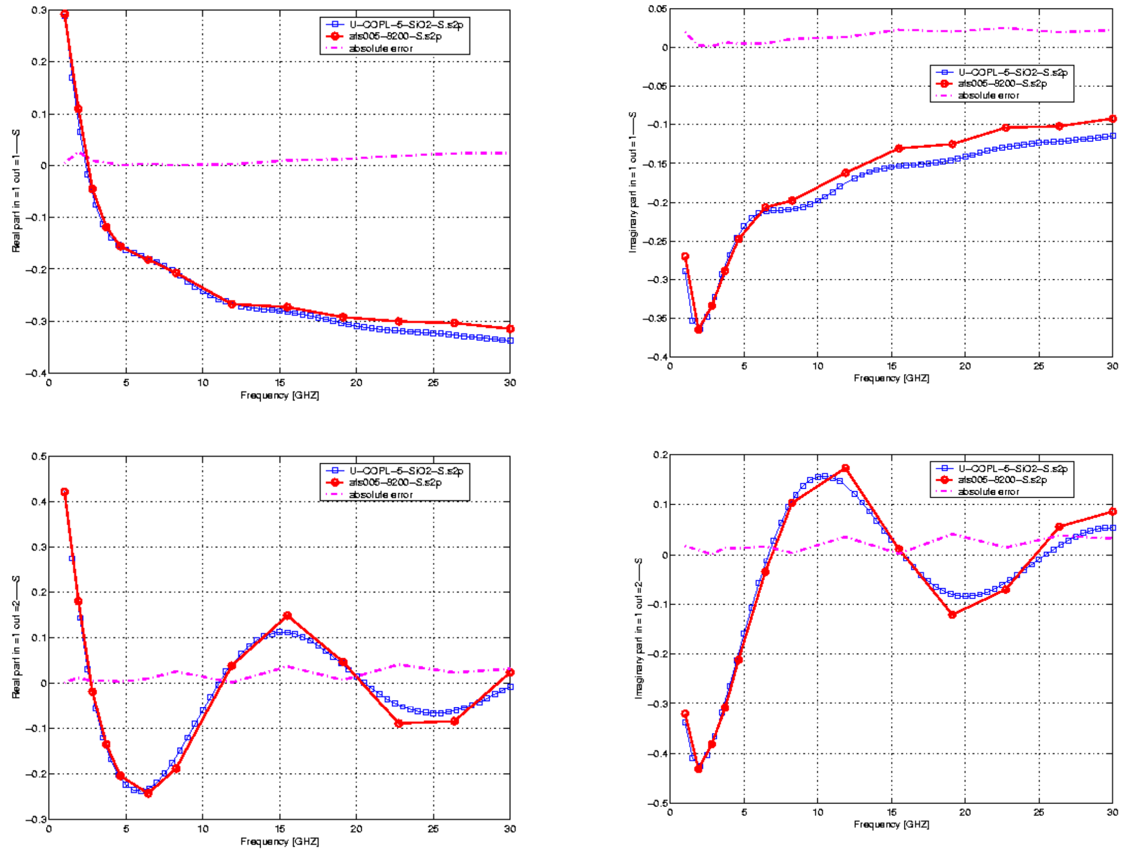

Fig 8. Comparison between measurement and simulation results - scattering parameters vs frequency

The described procedure was validated by comparing simulation results with measured data for a series of 16 benchmarks developed within FP5/IST/CODESTAR European project that addressed the issue of compact model extraction for passive on-chip components (www.imec.be/codestar).

Fig.8 shows the good agreement between measurement and simulation for the benchmark no.27 (coplanar line of Al on SiO2, 8200 μm length, 5 μm wide). Errors less than 5% are obtained for all the analyzed test structures.

9. PARALLEL AND DISTRIBUTED SIMULATION

One of the techniques to accelerate the simulation is to use parallel or distributed architectures for the computing systems and to develop appropriate algorithms for them. Running the distributed version of dFIT code developed within Codestar project on a hybrid LAN with 24 PCs the simulation time decreased more than 12 times(fig. 9, 10). The best PC in the LAN was an Intel P3Celeron@2GHz w. 256MB RAM and the weakest one was an Intel P3MMX@450Mhz w. 256MB RAM.

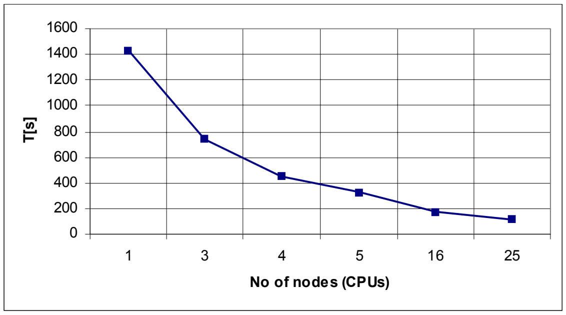

Fig 9. Simulation time on a distributed LAN

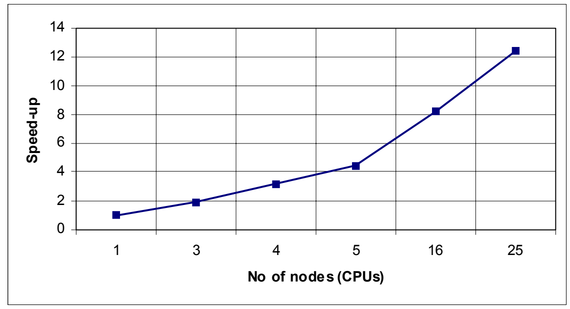

Fig 10. Distributed simulation speed-up

10. CONCLUSIONS

The *Very Fast Simulation* (*VFS*) is a new and efficient methodology for the compact models extraction. It comprises besides *ALPROM* (smaller models are obviously simulated faster than large ones) the following acceleration techniques:

- ***AFS*** **- Adaptive Frequency Sampling;**
- ***TLTM*** **- Transmission Line model based on Transversal Magnetic field;**
- ***FTS*** **- Frequency versus Time domain Simulation or Space State approach;**
- ***PDS*** **- Parallel or Distributed Simulation.**

The efficiency and the modeling aspects covered by these techniques is presented in the table 2.

Table 2 - The efficiency of VFS techniques

VFS techniques	Modeling aspect	Simulation speed-up
AFS	Frequency analysis	5.5
TLTM	2D geometrical structure with transversal magnetic field	41
PDS	Available platforms	12

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