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ALLROM STRATEGY FOR ORDER REDUCTION OF ON-CHIP PASSIVE STRUCTURES AT HIGH FREQUENCIES

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Abstract - *In order to solve a complex problem such as the electromagnetic field analysis in integrated circuits, a series of idealizations have to be considered. Their main goal is to reduce the number of internal state variables at minimum, while the input-output behavior of the device is essentially kept unchanged. This paper describes the strategy we adopted for the full-wave analysis of passive on-chip components, taking into account the non-homogeneous dielectrics and semiconductor substrate effects, besides proximity and skin effects in conductors The final goal is to obtain a reduced compact model, described as a net-list, that accurately describes the input-output relationship of the device considered.*

1. INTRODUCTION

In order to solve a complex problem such as the electromagnetic field analysis in integrated circuits, a series of idealizations have to be considered. Their main goal is to reduce the number of internal state variables at minimum, while the input-output behavior of the device is essentially kept unchanged. The reduced order modeling (ROM) for VLSI physical verification became an important problem in the design of optimal semiconductor devices.

According to [1], order reduction can be applied in three phases. *A-priori ROM* comprises the numerical methods used to approximate the distributed parameters model with a lumped parameters one, called also *macro-modeling* or *discretization process*. *On the fly ROM* is applied during the model extraction, while *a-posteriori ROM* is the classical reduced order model procedure, applied to the extracted model [2], and requiring sometimes large computational efforts.

2. ALLROM STRATEGY

Our view to CODESTAR model building process for on-chip passive and interconnect components is shown in fig 1. The input consists of information extracted from the layout and technology files The ALLROM strategy consists of four important phases: *macromodeling, a-priori ROM*, *on the fly ROM* and *a-posteriory ROM.*

A. Macromodeling

The *macromodeling phase* is the first step of model building and it requires decisions related to the computational domain clipping, geometric and material idealizations, and phenomenon idealization. A problem specific to the VLSI modeling is the geometrical and material modeling of via microstructures, non-Manhattan geometries (cylinders and polygonal paths), pins. In this case, our approach uses cell homogenization (CellHo), as shown in fig.2 This will have a very important influence on the reduction of the number of degrees of freedom (dofs) in the a-priory ROM stage.

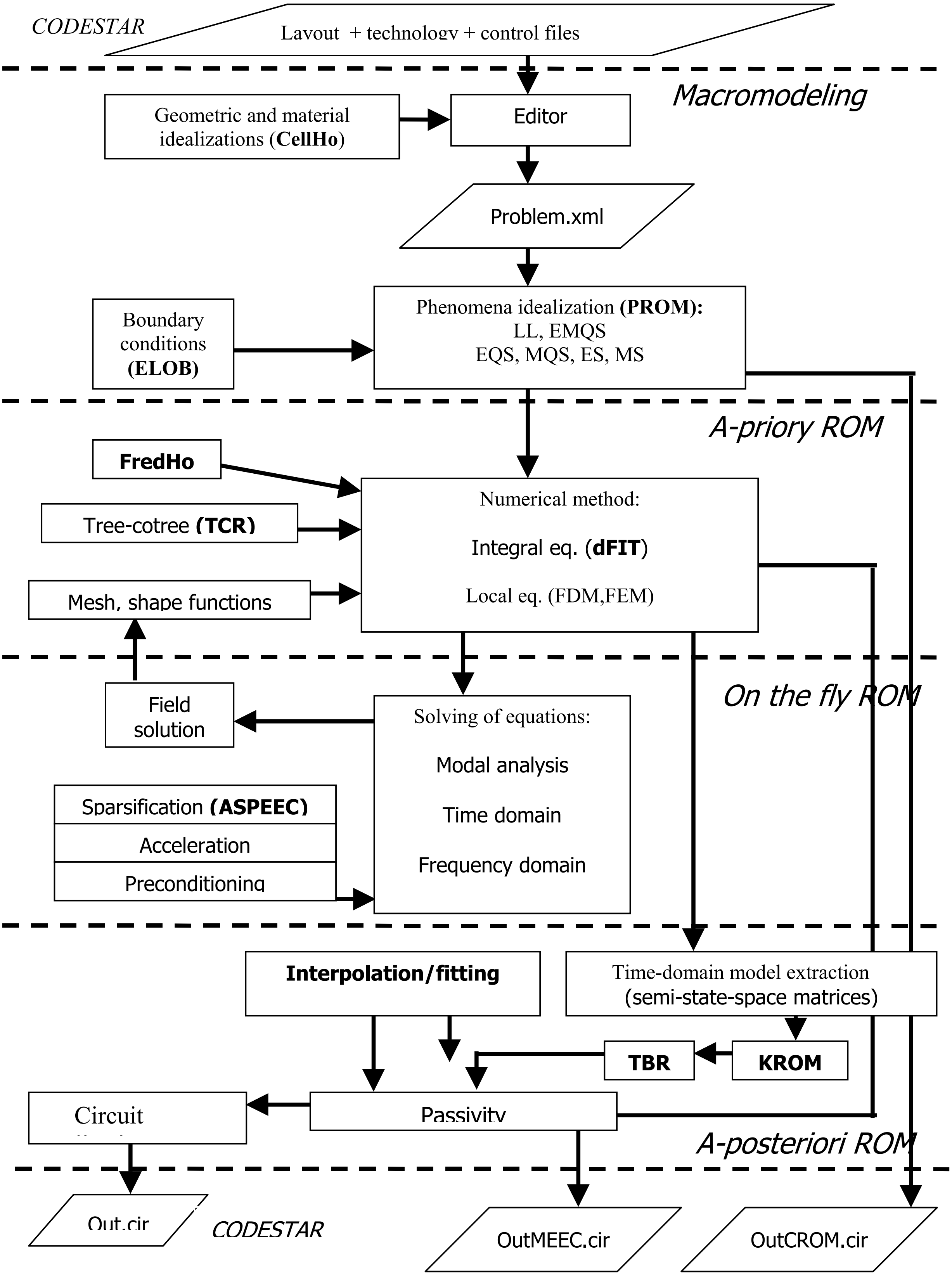

Fig.1 View of electromagnetic modeling process, applied to VLSI systems

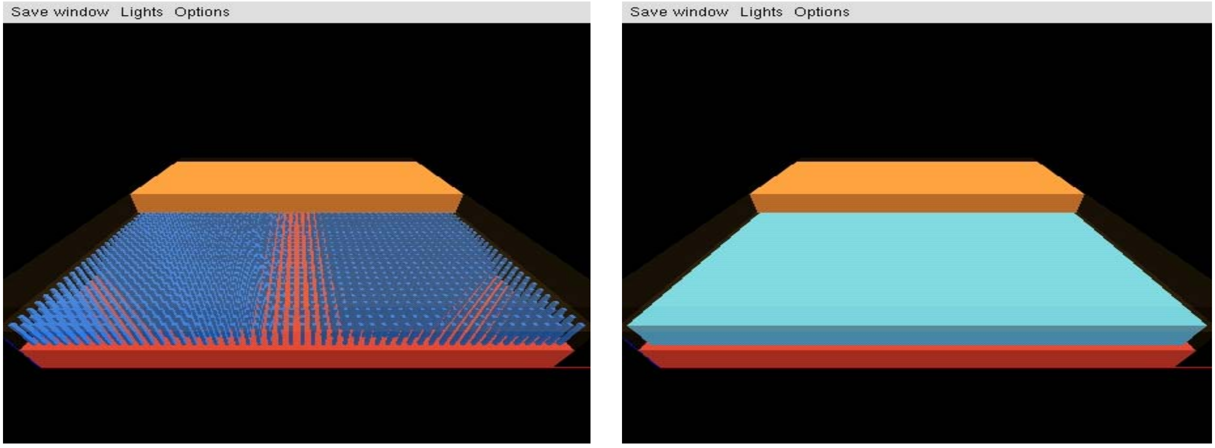

Fig.2 Cell homogenization

The phenomenon idealization (*phenomenological ROM - PROM)* step selects the most appropriate regime of the electromagnetic field e.g. full-wave loss less (LL); electro-quasistatic (EQS); magneto-quasistatic (MQS); electro-magneto-quasistatic (EMQS) which uses different regimes in different parts of computational domain, e.g. MQS in metallic conductors, EQS in insulators; electrostatic (ES); magneto-static (MS), or ESMS. This step requires the correct setting of boundary conditions. In most cases, an open-boundary type condition is required. The ALLROM strategy uses an *Equivalent Layer Open Boundary* (ELOB) condition [3].

B. A-priori ROM

The *a-priori ROM* stage consists mainly in applying a numerical method to discretize the phenomenological model (having an infinite number of dofs) built in the macromodeling stage. Thus, the number of dofs become a finite one. There are several numerical methods available, either based on integral equations (such as the finite integration technique – FIT), or on local ones (such as the finite difference – FDM or the finite element method – FEM). All these methods need a mesh that discretize the domain, and some of them (e.g. FEM) need also shape functions. This discretization step is very important for the model quality as well.

Our new, original solving method named dual FIT (dFIT) [4] is obtained by improving the classical finite integration technique. As in FIT, in the proposed method global variables are used as degrees of freedom, but unlike the FIT, the Hodge operator is obtained by Galerkin projection, using shape functions, as in Withney (Edge) Finite Element Method. Using both staggered grids as graphs for the electric network and for the magnetic network as well, the new method allows an efficient accuracy control. The dual approach allows the effective control of an adaptive procedure for global and local mesh refinement. DFIT accelerates the solution process, tests showing that there are 50 times less degrees of freedom needed to obtain the same solution accuracy as in FIT.

One of the new implemented innovative aspects is related to the boundary conditions. Up to now, most high frequency models are based on scattering S parameters, not suitable for the coupling with extern lumped (SPICE) circuits. The innovative aspect consists of using the "electromagnetic circuit element" concept [5], which ensures a natural field-circuit coupling.

Moreover, two new techniques are implemented with dFIT. One of them addresses the issue of gauging by using a tree-cotree reduction (TCR) procedure to reduce the number of dofs [6]. The other one uses frequency dependent Hodge operators (FredHo) that allows the modeling of the skin-effect with very few mesh cells [7].

C. On the fly ROM

The next stage is the reduction on the fly. This reduction is related to the solving of the system of equations assembled previously. The solving can be carried out either in the time domain, or in the frequency domain. Numerical procedures of acceleration and preconditioning are be used. One of them is ASPEEC – Algebraic Sparsified Partial Equivalent Element Circuit - that allows the reduction of the dofs [8]. In brief, by means of algebraic successive transformations of Schur complement type, an intermediate numerical model is generated, having the state variables associated to the discontinuity surfaces only. If the values that can be neglected are dropped, a useful sparsification occurs and the model tends to an idealization of partial element equivalent circuit (PEEC) type.

The solution obtained after this step can be used to check the quality of the discretization, and to refine it in order to obtain a more accurate solution.

D. A-posteriori ROM

The a-posteriori reduction uses classical ROM methods. There are three main approaches. The first one is to start from the time domain model extracted after the discretization process. It requires the assembly of the semi-state matrices it uses methods based on moment matching techniques (explicit, or implicit like Krylov type methods). In this case, the system solving is not required. Another possibility is to use the truncated balanced reduction method (TBR) [9] which can start from the modal analysis. Last, but not least, the frequency domain response can be used as input for an interpolation/fitting procedure [10] which is able to find an approximation of the transfer matrix. All these methods can be chained in order to obtain a smaller and smaller model

3. CIRCUIT REALIZATION

The final goal of CODESTAR was to obtain a net-list that describes the input/output relation of the interconnect-system or passive back-end structures in the static regime as well as in the high-frequency range. That is why the flow in fig.1 ends with circuit realization and synthesis of a circuit. Since the devices considered are passive, it is very important that the final reduced model keep this feature, otherwise the obtained model is use-less this it may generate instabilities when used in the design cycle.

It is important to note that the ALLROM strategy is able to obtain circuits that describes the input/output relationship, even before the a-posteriori stage. Thus, from the static analysis, a lumped circuit can be extracted, having a very low complexity, which approximates the behavior of passive devices at low frequencies. We call this step *coarse reduced order modeling* (*CROM*). Moreover, during the a-priori ROM stage, a distributed equivalent circuit may be extracted. Its complexity depends on the mesh complexity and therefore it can be used ad input for circuit solvers (such as SPICE) only for medium meshes. Therefore, it is useful either for checking the solver accuracy , or as an alternative data structure storage method. We call it *magneto-electric-equivalent circuit* (*MEEC*).

4. THE ROM WORKBENCH

One important issue was to decide which ROM technique is the most appropriate for the a-posteriori ROM stage. For this reason, a new tool called *CODESTAR ROM Workbench* was conceived. Its aim is to allow the user to reduce models by means of as many ROM techniques as possible, and to compare the results. In this way the behaviour of every reduction method applied to a CODESTAR model (output of the field solvers) is investigated and a specific reduction strategy to be applied for every type of CODESTAR benchmark and solver could be recommended. Basically, the ROM workbench consists of: a series of benchmark problems; a set of model order reduction methods; criteria for results evaluation and comparison. Fig. 3. shows the main blocks of the ROM workbench. Thick lines illustrate its main goal.

The benchmark problems are either linear time invariant systems described by means of state space matrices, frequency characteristics described by the variation of impedance, admittance or S-parameter matrices with respect to the frequency, or net lists described in the SPICE language.

The reduction can be carried out by means of various methods. These methods include: explicit moment matching, Krylov subspace techniques [11], Laguerre techniques [12], a two step Lanczos strategy, also a new two step reduction strategy, based on a PRIMA technique followed by a truncated balanced reduction, and truncated balanced realization procedures [9]. A very robust technique included in the ROM Workbench is the vector fitting method proposed in [10].

The workbench is able to compare responses obtained for different systems. The comparison can be carried out either on the time responses (step, impulse, etc.) or on the frequency responses (Bode, Nyquist, Smith, etc). Lumped parameters, quality factors or line parameters can also be compared. Since the available measurements are for S parameters, the main criteria used for comparison is the computation of an error estimator based on the Frobenius norm $\|.\|_F$: rms $\|S_{ref}-S_{an}\|_F$ / $\max_f \|S_{ref}\|_F$, where S_{ref} are S parameters for the reference system (output of field solver or measurements), and S_{an} are S parameters for the analysed system (reduced one).

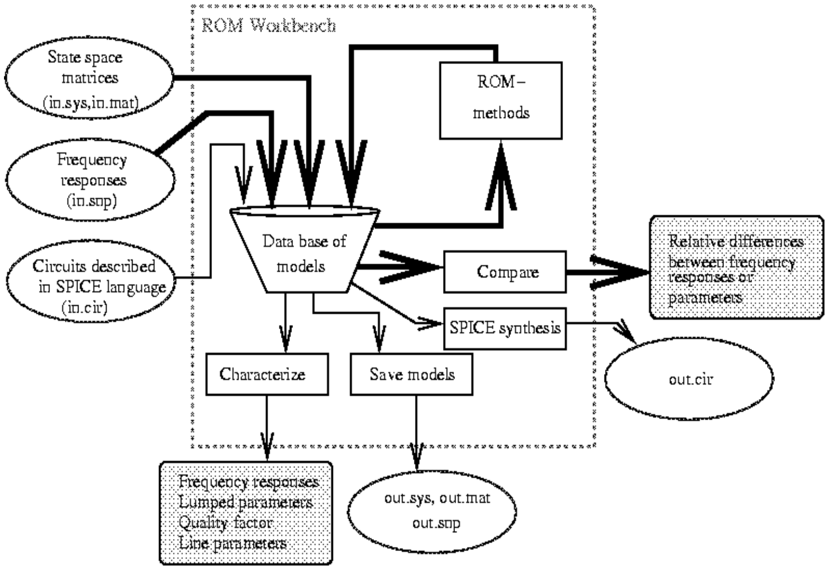

Figure 3 Main blocks of the ROM Workbench.

Considering the final aim of the Codestar project, i.e. the generation of reduced model synthesized by a SPICE circuit, the ROM workbench includes techniques for circuit synthesis as well. There are two methods implemented. One of them is the Direct Stamping method, more appropriate for reduced models that generated reduced state space matrices (such as Krylov type methods). The other method is the Differential Equation Macromodel, more suitable for reduced order methods that generated transfer functions (such as vector fitting) [13]. In this way, the ROM workbench allowed not only the testing of ROM techniques but also of SPICE synthesis algorithms.

5. NUMERICAL RESULTS

Table I holds the results obtained with the ALLROM strategy for the U-shaped benchmark resistor. The reduction is impressive: from 10 millions degrees of freedom to 1. All the other benchmarked tested within CODESTAR behaved similarly, the maximum order being 10.

No.	ROM technique	Modeling aspect	n = dofs before	q = dofs after	Efficiency = n/q
1	CellHo	Non-Manhattan interfaces	1e7	8.3e6	1.2
2	ELOB	Boundary conditions	8.3e6	8.5e5	9.8
3	dFIT	Optimal mesh step	8.5e5	1.9e5	4.2
4	PROM	Displacement current and induced voltage	1.9e5	1e5	1.9
5	TCR	Gauge condition	1e5	71930	1.5
6	FredHo	Skin effect	71930	11380	6.3
7	ASPEEC	SiO2/Low k insulator	11380	883	12.9
8	SSA	Si substrate modeling	-	-	
9	KROM	Essential moments	883	10	88.3
10	TBR	Essential singular values	10	6	1.6
11	VECTORFIT	Frequency behaviour	6	1	6
Global			1e7	1	1e7

Table I: Numerical results obtained with the ALLROM strategy for one of the CODESTAR benchmarks (U-shape resistor)

6. CONCLUSIONS

The secret of a successful modeling of VLSI systems is to find a quasi-optimal path from the field problem description to the “equivalent” circuit of the device under analysis. Each process step can influence not only the number of state variables, but also the model quality.

The ALLROM strategy we propose is based on 11 ROM techniques that include: phenomenon idealization as a main modeling technique, dual FIT as solver for the a-priori ROM stage, use of approximate Schur complement technique to eliminate the “internal” variables, as a main on the fly ROM, followed by classical a-posteriori ROM methods, out of which we strongly recommend the vector fitting procedure..

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