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USING MULTIPROCESSOR SYSTEMS FOR ELECTROMAGNETIC MODELLING OF SPIRAL INDUCTORS

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Due to high frequencies of signals in nowadays Integrated Circuits (ICs), the electromagnetic field effects cannot be neglected anymore and that leads to very large models, which have to be further reduced by using model order reduction techniques. In order to get a resonable modelling time, high performance computing (HPC) on multiprocessor systems is used. This paper is presenting a new parallel implementation of adaptive sampling algorithm based on MATLAB parallel features and it highlights the way on how multiprocessors systems can be used in the electromagnetic modelling of integrated inductors.

Keywords: high performance computing, parallel computing, electromagnetic simulation

1. Introduction

The most important aspect in design of ICs refers to the effective modeling of electromagnetic field effects at high frequency. This means that Maxwell Equations (ME), which take into account all electromagnetic field effects, have to be solved. To obtain a finite model, an appropriate numerical method has to be used in order to discretize the ME. In [1] such a numerical method and its algorithmic implementation, based on Finite Integration Technique (FIT), for discretization of ME with Electro-Magnetic Circuit Element (EMCE) boundary conditions [2] is presented. The discretized ME are written as a system of Differential Algebraic Equations (DAE) called Maxwell Grid (MGE), which are assambled as a semi-state space matrix linear time invariant (LTI) Multiple Inputs Multiple Outputs (MIMO) system. This first step of the modelling process leads to a model with a finite number of degrees of freedom (DoFs).

Due the fact that the number of degrees of freedom is still large (having order proportional with the number of cells in FIT mesh), the second step of electromagnetic modelling process is the reduction of order for this discretized model. In [3] a model order reduction (MOR) technique, based on an Adaptive Frequency Sample by Vector Fitting (AFS-VF) algorithm, aiming to solve this problem is presented .

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A MOR technique transforms a large model into a smaller model, with fewer state variables but having a similar relationship between input-output signals. The use of HPC techniques on multiprocessor systems for MOR was proposed in [4] [5].

All electromagnetic modelling software packages (ANSYS HFSS, SONNET, Momentum, ASITIC) have implemented different techniques which use parallel computing or distributed computing, in order to benefit of multiprocessors systems. An integrated circuits electromagnetic modelling software called Chamy, based on procedure described above, was developed in Numerical Modelling Methods Labratory from Electrical Engineering Department within a series of European projects. This paper aims to present the developing process and improvement of Chamy, by exploiting the HPC capabilities described in [6].

2. Problem formulation

The model for integrated inductors is characterized by an internal field problem and by an external circuit problem. In order to include both high and low frequencies electromagnetic effects, the full wave (FW) regime described by ME are used. Using EMCE as boundary conditions the uniqueness of the field solution is ensured, but at the same time the compatibility and interconnection with external circuits is provided.

The continuous model of the field problem is discretized by FIT. The discretized model is assembled as a semi-state space model

$$\begin{cases} \mathbf{C}\frac{\mathrm{d}\mathbf{x}(t)}{\mathrm{d}t} + \mathbf{G}\mathbf{x}(t) = \mathbf{B}\mathbf{u}(t) \\ \mathbf{y}(t) = \mathbf{L}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t) \end{cases}, \tag{1}$$

where $\mathbf{x} \in \mathbb{R}^n$ is the state space vector, $\mathbf{u} \in \mathbb{R}^m$ is the vector of input signals and $\mathbf{y} \in \mathbb{R}^m$ is the vector of output signals, $\mathbf{C}, \mathbf{G} \in \mathbb{R}^{n \times n}$ are real matrices with very sparse structures and $\mathbf{B} \in \mathbb{Z}^{n \times m}$ and $\mathbf{L} \in \mathbb{Z}^{m \times n}$ are topological matrices with sparse structure as well.

The state of field, continuous model is represented by components of electromagnetic field $\mathbf{E}$,$\mathbf{D}$, $\mathbf{B}$, $\mathbf{H}$, $\mathbf{J}$, ρ and the state of discrete model is described by the integrals of these quantities on the geometric elements (faces or edges) of FIT mesh. From the designer's point of view, the only thing that matters is the relationship between the input and output signals. Therefore, by solving the system (1) in frequency domain the transfer matrix is obtained

$$\mathbf{Y}(\omega) = \mathbf{H}_{\mathrm{FIT}}(\omega) = \mathbf{L}(\mathbf{G} + j\omega\mathbf{C})^{-1}\mathbf{B}, \tag{2}$$

as the relationship between the input and output signals. The frequency characteristic of circuit function $\mathbf{Y}(\omega)$ is used to extract a reduced order model, which is next synthesised as an equivalent SPICE circuit with lumped parameters [7].

3. Parallel extraction of the reduced order model

For the computation of $\mathbf{Y}(\omega)$, a system of linear, complex equations have to be solved. In order to decrease the computational effort, we propose a self-adaptive frequency sample AFS. It starts with an initial sample set of frequencies S and an additional test frequencies S', which are interleaved between these sample frequencies. In the second step, the frequency response $\mathbf{Y}(\omega)$ is computed for every sample of both sets. In the next step an approximation of frequency response $\mathbf{Y}(\omega)_{approx}$ is computed by using a linear or polytropic interpolation procedure [3] on the sample frequencies S. The final step checks an imposed threshold for every sample in the set of test frequencies S'. If the threshold imposed is not verified then the test frequency becomes a sample frequency and a new interleaved test frequency is added and the sequece is repeated from step two until the convergence is reached.

AFS-VF algorithm is a conjunction between AFS scheme and a rational approximation procedure VF [8]. In the third step of AFS sequence of steps, instead interpolation we use the VF procedure in order to approximate the frequency response with a rational one:

$$\mathbf{Y}_{\text{approx}}(\omega) = \sum_{i=1}^{q} \frac{\mathbf{K}_i}{j\omega - p_i} + \mathbf{K}_\infty + j\omega\mathbf{K}_0 \ . \qquad (3)$$

defined by: p_i - poles, $\mathbf{K}_i \in \mathbb{C}^{m\ \times m}$ - the residual matrix and $\mathbf{K}_\infty$ and $\mathbf{K}_0 \in \mathbb{R}^{m\times m}$ - two constant terms.

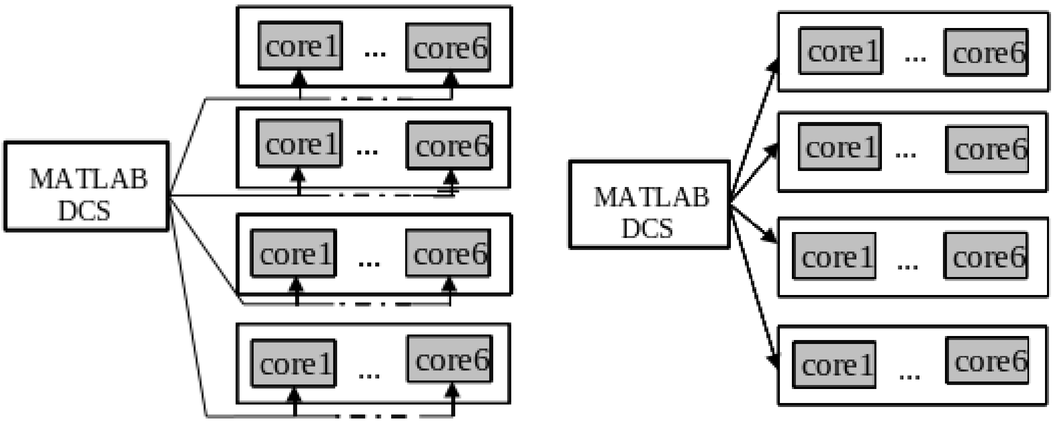
Using parallel computing the computational time can drastically be reduced by simultaneously computing $\mathbf{Y}(\omega)$ for several frequency samples on multiple machines. This task can be executed in parallel by the following sequence of steps:

(1) split the frequency set in equal subsets (as evenly as possible);
(2) send the data to the worker machines (subsets frequencies and state space matrices);
(3) compute simultaneously $\mathbf{Y}(\omega)$ on each worker machine, for every subset of frequencies received;
(4) collect the frequency response from each worker machine and send it to master machine.

The parallel approach presented above known as ”frequency sweep” can be used for each method of model extraction presented in this section. Frequency sweep is one of the most common parallel features used by electromagnetic modelling programs mentioned in previous section.

Two parallel approaches of AFS-VF algorithm were proposed in [5]. First approach is mapped on computer cores (Figure 1a) by using MATLAB parallel features and the second one is mapped on computer nodes (Figure 1a) by using Phyton parallel features, also known as one level of granularity approach and with two levels of granularity, respectively.

In [6] a new parallel implementation of two levels of granularity approach is proposed and implemented in MATLAB. The main difference between the two approaches is that for the first one it was used MATLAB JobManager [9] as scheduler and for the new one it was used an open-source scheduler called Torque [10].

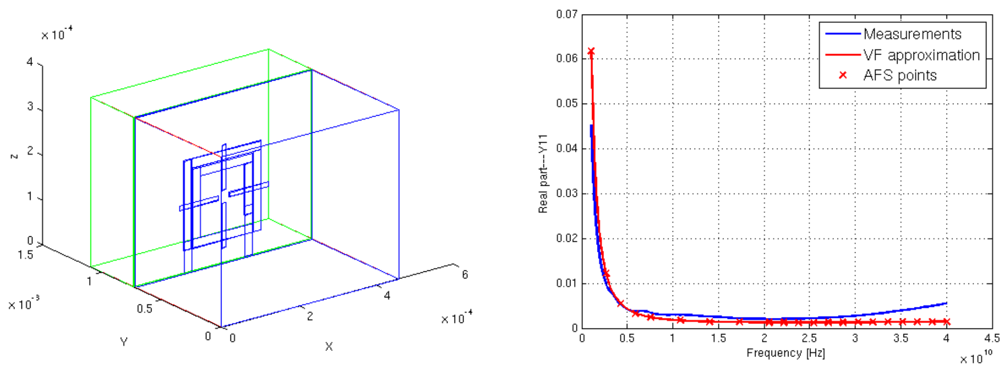


(A) One level of granularity (B) Two levels of granularity

FIGURE 1. AFS-VF parallel approaches

4. Performance and results

The performances of the new implementation were evaluated using a benchmark problem. The problem is modelled with Chamy and consits of a square spiral inductor (Figure 2a) made of Al built on a Si substrate.



(A) Geometry of square spiral inductor (B) Frequency characteristic

FIGURE 2. Benchmark problem

The new implementation was tested on the Atlas multiprocessor system installed in LMN (http://www.lmn.pub.ro/resources.html), which has a standard configuration for todays HPC systems. Four worker machines were used, having two quad-core Intel Xeon CPUs running at 2.66 GHz with 8 MB of cache memory (a total of 32 cores) and 24 GB of RAM memory for each machine.

The discretized model has 136340DoFs corresponding, to a discretization grid with $28 \times 32 \times 28$ points. The AFS algorithm required 3 iterations to obtain the final reduced model of order 7. The procedure used 4 starting points and $\varepsilon_{AFS} = 10^{-3}$ and $\varepsilon_{VF} = 10^{-5}$ as threshold for AFS algorithm and VF procedure respectively (Table 1). A comparison between simulation results and experimental frequency characteristic is shown in Figure 2b.

Table 1

The convergence of the AFS-VF algoritm

Convergence			
iteration	1	2	3
order	3	6	7
S'	3	6	8
$S+S'$	7	13	21

Solving one linear system with 136340 DoFs required an amount of 6.8GB of memory and 81.97s to obtain solution for a frequency and over 8200s to extract the reduced model with VF on 100 sample frequencies. Using the parallel implementation of AFS-VF the time was reduced from 1722s to 495s meaning a 3.5 speed improvement. Ideally, the maximum speedup using 4 worker machine is 4, so, the 3.5 speedup obtained is showing that the algorithm has a high efficiency exploiting the hardware resources. For the one level granularity, each core worker receive a part of total memory divided to the numbers of cores. That's why one level granularity was not able to solve this benchmark problem. The memory received by each worker core was less then 6.8GB needed (in our case 24/8=3GB).

5. Conclusions

We proposed a new implementation of AFS-VF parallel algorithm, based on MATLAB parallel features. It was shown that the use of multiprocessor systems reduced de execution time by approximately 3.5 times, when 4 computers were used in parallel. If the extraction time required by parallel AFS-VF procedure is compared with the initial one required by sequential VF algorithm, the ratio is over 16, when 4 interconnected computers were used.

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