Efficient analysis of high frequency electronic circuits by combining LE-FDTD method with static solutions

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Abstract

Due to the increasing complexity of electronic systems and subsystems, versatile simulation approaches, able to combine electromagnetic full-wave analysis with models of non linear electronic devices, are becoming very attractive. Among them, the so called Lumped Element (LE)-FDTD method, for its characteristic to easily account for non linearities is one of the most promising ones. Unfortunately, its application to practical circuits is still limited by the long simulation time needed to achieve the biasing condition all over the structure. This work proposes a way to avoid the simulation of the transient, thus allowing efficient FDTD analysis of the dynamic behaviour of interest. The approach has been validated by simulating a simple but comprehensive BJT CE amplifier enclosed in a metallic package. Results show an improvement of the efficiency without any reduction of the accuracy.
1 Introduction

The Finite-Difference Time-Domain algorithm (FDTD), [1], [2]) provides a powerful and flexible approach to the numerical solution of Maxwell's equations. In 1992, Sui et al. [3] proposed a method to incorporate lumped element models into the original scheme. Since then, several papers appeared, refining the approach [4], and validating the technique to a variety of applications ranging from the active antennas [5], to the high speed digital signal degradation [6], to strong circuit package interaction [7] and to millimeter-wave integrated circuits [8]. In most of the HF electronic circuits, however, a severe limitation to a practical use still exists: the long simulation time required for steady state to be achieved. In such circuits the transient depends on some reasons, namely: the reactances of the electronic devices (junction capacitances as well as parasitics); the static reactances of the passive circuit and, probably the most significant item, the often unavoidable mismatching between interconnections and electronic devices. The latter causes bias signals to bunch back and forward along the interconnecting lines before they reach stable voltage values. This behaviour is evident, for instance, in high speed digital circuits, where a well known “staircase” waveform is usually observed during the biasing transient [6]. Unless the analysis aims just at the investigation of the transient, the computing time needed to overcome this part is actually wasted, and it can be several times the time required for the analysis of the dynamic behaviour.

This paper proposes a way to avoid the simulation of the transient, thus rendering accurate LE-FDTD dynamic analysis affordable. The method is based on the idea of obtaining the steady condition by solving the electro- and magneto-static problems instead of by letting the transient stabilize. To this purpose, a Finite Difference (FD) solver of Laplace equations has been implemented [9]. I-V characteristic relations of lumped devices are incorporated as additional constraints for the static problem. The static solution for E and H fields can be used as the initial condition for the LE-FDTD analysis. The time domain evaluation of the entire transient is thus replaced by the calculation of the static solution that is orders of magnitude more efficient.

2 The Method

In order to reduce the simulation time due to the biasing of the non-linear electronic devices, a non-zero field distribution is adopted for the initialization of the simulation. This distribution is obtained by evaluating the electro- and magneto-static field solution due to the biasing sources with the boundary conditions stated by the structure.

The electric field $\mathbf{E}$ can be derived from a scalar potential $\phi$ as:

$$\mathbf{E} = -\nabla \phi.$$ 

(1)
The electro-static potential satisfies the Laplace equation:

$$\nabla^2 \phi = 0$$

(2)

with the following boundary conditions: equation (3) in the presence of a metallic surface at potential $V$ and equation (4) through an interface between two materials with different dielectric constants:

$$\phi(\mathbf{r}) = V \quad \text{for } \mathbf{r} \in S$$

(3)

$$\oint_S \epsilon \frac{\partial \phi}{\partial n} dS = 0$$

(4)

The magnetic field $\mathbf{H}$ has been computed by following the approach suggested in [9].

This approach is based on the introduction of a Potential Partitioning Surface (PPS) connecting each inner conductor of the structure with the outer boundary of the computational domain. If the PPS is chosen in such a way that every possible path around the currents cross the PPS, the region obtained by eliminating the PPS from the computational domain is a simply connected region. In this region the magnetostatic field can be derived, as the electrostatic field, from a scalar potential $\psi$:

$$\mathbf{H} = -\nabla \psi$$

(5)

which, in turn, satisfies the Laplace equation. The PPS behaves as a source of the magnetostatic field; the relevant boundary condition being:

$$\psi(\mathbf{r}^+) - \psi(\mathbf{r}^-) = I.$$

(6)

Unlike the potential $\phi$ at the PPS, that is not continuous, the derivatives of the potential along a direction orthogonal to the interface ($r$) must have the same value at both sides close to the interface itself.

$$\left. \frac{\partial \psi}{\partial n} \right|_{r^+} = \left. \frac{\partial \psi}{\partial n} \right|_{r^-}$$

(7)

In the equation above the left and right derivatives are indicated with the subscripts $r^-$ and $r^+$ respectively. The boundary conditions at a metallic surface are given by:

$$\left. \frac{\partial \psi(\mathbf{r})}{\partial n} \right|_{\mathbf{r}} = 0 \quad \text{for } \mathbf{r} \in S$$

(8)

which follows from the condition $\mathbf{B}_n = 0$ inside the metallic material.

The electro- and magneto-static problems have been solved numerically by using a conventional Finite Difference (FD) algorithm. In both the cases the structure has been discretized using exactly the same grid adopted for the LE-FDTD simulator. The resulting system of equations have been inverted by means of the biconjugate gradient algorithm, with no preconditioning of the coefficient matrix.
3 An Application Example

In order to validate the approach, a simple but comprehensive example has been conceived. It consists of a microstrip BJT CE amplifier enclosed in a metallic package; this circuit includes microstrip distributed matching networks as well as metal strips to bias the lumped device. Bias parameters for the BJT adopted (PHILIPS BFG 540 X) are: $V_{cc} = 12 \text{ V}$, $I_{o} = 37 \text{ mA}$, $V_{be0} = 0.8 \text{ V}$, $V_{ce0} = 2 \text{ V}$. Table 1 summarizes the parameters of the BJT model according to the topology described in [6]. The whole structure has been discretized using a $16 \times 4 \times 51$ uniform mesh with $\Delta x = \Delta y = \Delta z = 1 \text{ mm}$ and $\Delta t = 1.96 \text{ ps}$. Lumped devices have been connected to the distributed circuit by means of lumped resistors, the resistance of which has been chosen close to $0 \text{ \Omega}$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>E-Junction</th>
<th>C-Junction</th>
<th>Unit</th>
</tr>
</thead>
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<tr>
<td>$I_{0}$</td>
<td>1.045</td>
<td>1.045</td>
<td>fA</td>
</tr>
<tr>
<td>$T$</td>
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<td>K</td>
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<tr>
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<tr>
<td>$\alpha$</td>
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<td>0.97777</td>
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</table>

4 Results

Fig. 1 shows the collector voltage during the biasing transient of the circuit. This response has been obtained with an LE-FDTD simulation initialized by the zero-field solution. The biasing values of the DC generators have been reached by means of step waveforms with a rise time of about $1.3 \text{ ns}$. After the entire bias transient, the collector current and voltage are about $37 \text{ mA}$ and $2 \text{ V}$ respectively, as expected. At least $500 \text{ ns}$ are required to reach the steady state. With conventional approach, this interval is to be simulated, afterward dynamic analysis can start. Using the static solution, the dynamic behaviour can be investigated after a very short transient. Fig. 2 shows the output voltage once a $1 \text{ GHz}$ sin-wave with an amplitude of $2.2 \text{ mV}$ has been applied at the input port of the amplifier. The value of the output signal amplitude is not distinguishable from that obtained by initializing the simulation with the zero-field condition.
Figure 1: Transient voltage at the collector during bias. The data have been obtained without static initialization.

Figure 2: Output voltage obtained by using the static initialization. Note the 20 mV spike at the begin of the dynamical FDTD simulation.

5 Conclusions

In this paper the FDTD analysis of circuits including lumped element models has been speeded up by adopting a non-zero field initial condition. The method replaces the entire time domain analysis of the transient with the static field solution the constraints of which are determined by the physical and geometrical parameters of the structures and by the presence of lumped devices (i.e. lumped currents). A great saving of computing time without reducing the inherent accuracy of the method has been demonstrated.
References


