Electronic devices and FDTD: a decade of research

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Electronic devices and FDTD: a decade of research

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***Abstract* — Since 1966, when FDTD was first introduced by Yee to solve 2D Maxwell's equations numerically, thousands of contributions have been published by the time domain modeling scientific community. In this paper we would like to put at the evidence improvements proposed to extend the FDTD applicability towards applications characterized by heterogeneous mathematical descriptions such as, for instance: MMICs, quasi optical circuits as well as distributed electronic devices.**

***Keywords:-* FDTD, GLOBAL MODELING, NON LINEAR CIRCUITS, LUMPED ELEMENTS.**

I. Introduction

The FDTD method appeared in 1966 [1] as a numerical solver of the 2D electromagnetic problem. For almost a quarter of century new applications and improvements of the method chased one another fostering a great and exciting development of the technique involving researchers from a lot of scientific institutions in the world. Till the early 90's FDTD has been applied and developed only to linear problems thus not exploiting the attractive feature that is the inherent easiness of accounting for non linearities. In 1992 Sui et al. [2] proposed a simple and effective method to account for Lumped Elements within the FDTD leapfrog scheme. Soon after its appearance this technique has been developed and applied to realistc problems [3-6] thus showing both potenzialities and limits. Among the developments of LE-FDTD it is worth mentioning at least the Non Linear Lumped Network NL^{2}N approach [7] that is a generalization of the original LE approach to, in principle, every kind of non linear network and the development of the interface with other simulators such as SPICE like ones [8]. These extensions both give the possibility to interface FDTD scheme with many equivalent circuits of electronic devices regardless of their intricacy.

The other significant development that is worth talking about is the so called "global approach" [9, 10]. Many words have been spent in the past about the rigorous meaning of this definition. The question is somehow still open, nonetheless in this paper we assume that "global modeling" is the time domain numerical solution of a more comprehensive set of equations able to simulate a physical behavior that cannot be described by only Maxwell's equations, but requires a larger set of equations. Typical example of this situation is the analysis of distributed solid state devices where carrier transport equations must be accounted for together with Maxwell's equations in a self-consistent fashion.

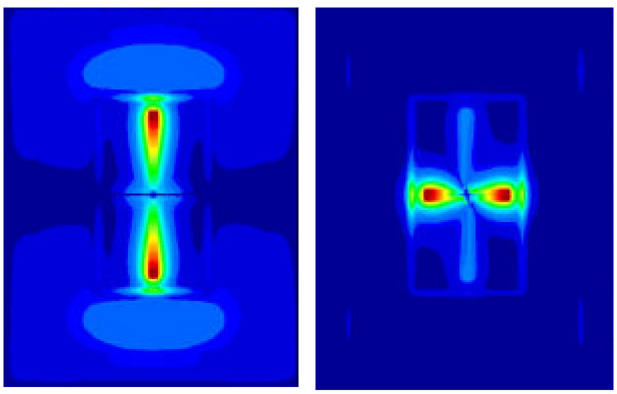
In between from the straight LE-FDTD technique to the "global modeling" we can locate the incorporation of solid state devices modeled by using numerical solvers of charge transport equations. This technique, appeared in 1996 [11], allows very accurate device models, accounting for process parameters, to be incorporated, again under the LE assumption, into the FDTD Yee's marching scheme.

II. Main steps of the evolution

A. Lumped Element FDTD (LE-FDTD)

This technique is based on the formulation of a characteristic expression of an electronic device, usually available as a voltage-current relation, in terms of current density versus electric field. This device description, although non linear, is formally compliant with Maxwell's equations. Under the lumped element assumption, the device is actually seen as an additional current density term of the discretized Maxwell equation. Since this current density can be non linearly dependent on the electric field, iterative solutions must be locally applied to update mesh variables. This method has been developed and widely adopted in several fields ranging from signal integrity [5] to quasi optical circuit analysis [12]. Moreover, a very interesting opportunity opened by this technique is the capability to provide a very effective and realistic way to inject energy into a structure by means of what is called "lumped generator". This source, along with the use of Short Open Calibration technique has been experienced as a easily usable source [13]. As an example we report here the prototype of a quasi-optical Yagi frequency multiplier (Fig. 1) and the field behavior at the frequency of interest obtained after DFT transform (Fig. 2)

Fig. 1. Quasi optical Yagi frequency multiplier based on two crossed dipoles and a couple of dual diodes (operating frequencies 3.5 – 7 GHz).



(a) (b).

Fig. 2. (a) electric field at f_0, (b) electric field at $2f_0$.

Fig. 3 shows an other interesting application represented by the analysis of a spiral inductor realized in CMOS technology (MIETEC 0.35 micron). In this case lumped generator and loads have been adopted along with SOC technique to provide termination ports. Accuracy is testified by the results shown in Fig. 4.

B. Interfacing FDTD with equivalent circuits of realistic components (NL²N-FDTD and interfacing with SPICE)

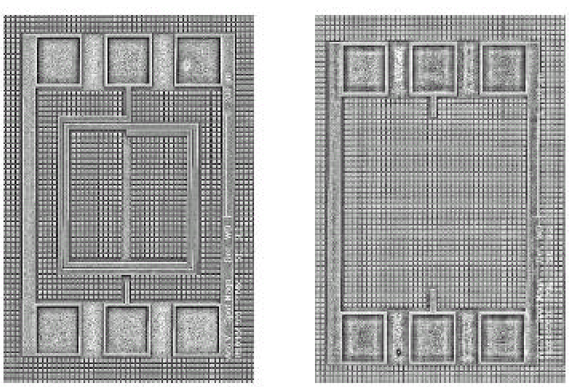


Fig. 3. Fabricated CMOS spiral inductor and probe station calibration structure.

Once the LE-FDTD reached an acceptable level of development, it appeared clearly that incorporation of accurate equivalent circuit could be often cumbersome. This is mainly because of two reasons: first the incorporation of an accurate equivalent circuit, requiring tens of lumped components, needs a corresponding number of cell

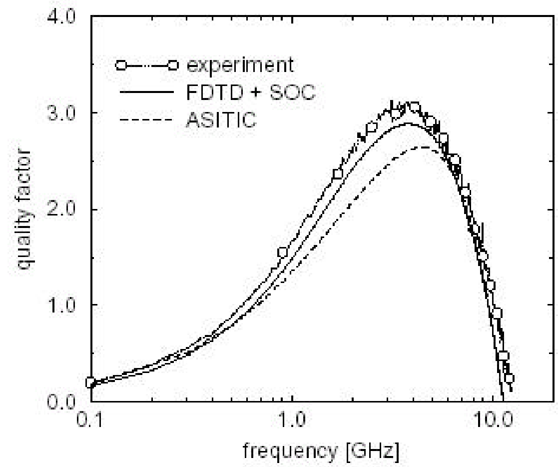


Fig. 4. Quality factor.

branches thus spreading the equivalent circuit over an unrealistic portion of the discretized volume often larger than the actual size of the device; second because again the spreading of the whole device model over many cells inherently lowers the validity of the lumped assumption thus mining the base of the entire derivation. As a result in these cases the method can provide unacceptable accuracy. To overcome these problems at least two different strategies have been proposed: the so called NL^2N-FDTD [7] and the direct interface of FDTD with SPICE [8]. Both techniques allows even complicated device models to be inserted by using only a little number of cells, thus recovering the original accuracy of the LE-FDTD technique also in case of realistic and accurate models of devices.

C. Global modeling approach

A revolutionary approach to the solution of the electromagnetic problem in presence of non linearities has been proposed mainly by two research groups [9, 10]. This technique, in principle very simple, starts from the consideration that in many cases, think for example to distributed MeSFETs or PiN diode modulators, the reality cannot be described by a simple set of equations but by a combination of them. In the significative case of distributed devices, for instance, at least the combination of charge transport equations (Hydrodynamic model [9] or drift diffusion one [10]) with Maxwell's ones is needed. In spite of its theoretical simplicity, this technique requires the solution of a huge amount of unknown by means of non linear iterative procedures, thus resulting very demanding in terms of computing. Moreover in its original formulation it suffers of a severe inefficiency that is mainly due to the fact that the time step required to discretize Maxwell’s equation (stated by the Courant criterion) is much larger than that required by the correct description of transients of device variables (carrier concentrations usually depending exponentially on voltages). For these reasons this technique is so far applied to validation examples. Nevertheless, on one hand the continuous development of fast computers, on the other hand the appearance of interesting improvements of the method [14] render the approach very promising.

D. LE FDTD integrated with physical device modeling

As mentioned in the introduction this can be considered as an intermediate approach. In this case a solid state device is modeled by using a typical device simulator based on the discretization of charge transport equations (drift diffusion approximation) and Poisson equation. The resulting voltage-current equation has been self consistently interfaced with the FDTD algorithm again under the lumped element assumption. This technique, although not applicable to distributed devices allow for a very accurate modellization of solid state devices and, in turn, allows accurate modellization of high frequency electronic circuits directly on the basis of device process parameters. This feature makes possible the evaluation of the response of the circuit not only as a function of the circuit layout but also, directly as a function of process parameters without the continuous and tedious de-embedding of equivalent circuit parameters. Fig. 5 shows the example of a 76 GHz SPDT and Fig. 6 shows the variation of the circuit response as a function of doping concentration of the diodes.

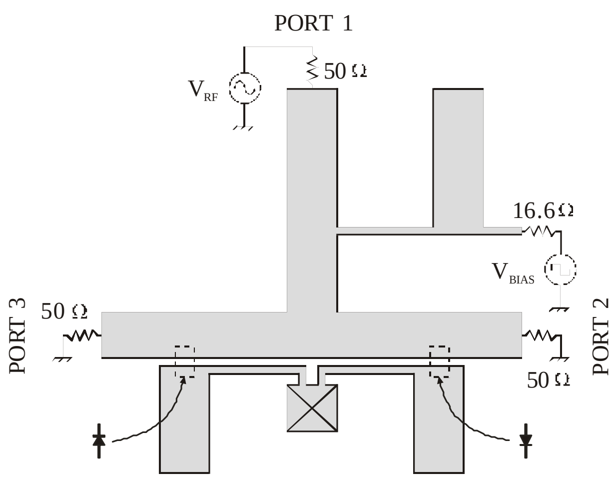


Fig. 5. 76 GHz PiN diode SPDT (simplified layout).

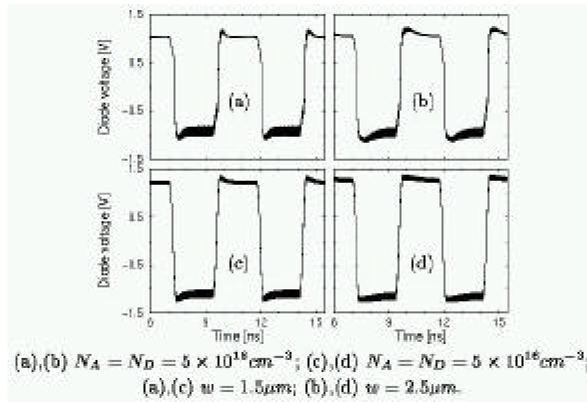


Fig. 6. Output voltage waveforms versus PiN diode doping and lenght.

III. Conclusions

Concurrent simulation of non linear devices in distributed environments (larger than a wavelenght), as well as “global modeling” of electronic devices are challenging fields of development for time domain methods and in particular for FDTD. In the last decade several approaches appeared. Research is still open, nevertheless some trends can be ultimately carried out.

The LE-FDTD method is easy to implement and allows for agile incorporation of lumped elements in a simulation of a high frequency electronic circuit. It suffers the intrinsic limitation of being developed under the lumped element assumption, moreover is not very suitable for incorporation of complicated device models. The typical field of application of this technique is the simulation of MIC characterized by the hybridization of printed planar circuits with lumped devices operating at wavelength much longer then their dimensions. This technique is quite stable and research development in this area is nowadays oriented to overcome the aforementioned limitations.

Global modeling is for sure the most attractive among the cited techniques. In principle it allows to extend the field of application to a variety of components and circuits never experienced before. In spite of this promise, however it is limited by the huge request of computer resources. Global modeling research is mainly addressed to increase the computational efficiency but for an extensive application of the method we have likely to wait for a new generation of computers.

Mixed techniques can be seen as acceptable compromise to solve some classes of problems. Among them we mentioned the concurrent simulation of planar, even monolithic, circuits by using straight FDTD, and electronic devices the constitutive relation of which is obtained by directly discretizing and solving the charge transport equations. This technique , although a bit more demanding than the original LE approach allows, in principle a more accurate and flexible simulation of electronic devices and is quite useful for the analysis of customarily conceived MMIC where the circuit response can be directly related to the device process parameters.

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