COUPLED LOCALIZED AND DISTRIBUTED ELEMENTS ANALYSIS APPLYING AN ELECTROMAGNETIC SOFTWARE IN THE FREQUENCY DOMAIN

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ABSTRACT

A coupled localized and distributed elements analysis applying the F.E.M. in the frequency domain is described. First, two studies concerning a two port network and a gunn diode amplifier, are performed to prove with success the efficiency of our method.

Then the main objective of this paper is to present an electromagnetic analysis of the passive area of a transistor (FET) taking into account all its physical and geometrical characteristics.

Theoretical and experimental results are compared and they show encouraging agreement.

I - INTRODUCTION

New microwave applications, involving high working frequencies, complex hybrid and monolithic high integrated circuits are subjected to indirect electromagnetic interactions, which must be taken into account during the theoretical analysis. So, the segmentation approach generally applied to analyze such devices becomes inadequate. Indeed, this approach consists of dividing the circuit into several segments which may be modelled independently from each other by using different analysis techniques. These active and/or passive models are then put together to obtain the response of the total circuit, but the indirect couplings between those models are not taken into account.

To overcome these difficulties, different numerical analysis have been proposed recently to design rigorously complex devices containing passive and/or active elements [1,2,3,4]. In this paper, the Finite Element Method (F.E.M.) [5] defined in the frequency domain is applied to a global electromagnetic modellisation of devices containing both passive distributed areas and active and/or passive localized elements or networks.

In the first part of this paper, this method will be described. Then, its efficiency will be illustrated by the study of a two port network (figure 1), and a linear reflection amplifier at 10 GHz (figure 4).

At last, the main objective of this paper concerns an electromagnetic analysis of a transistor applying the localized

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F.E.M. approach. The global study of this device will be divided into two parts : the active area analysis presented in a future paper and the passive area one described in this article. We'll present here a new theoretical approach applying the F.E.M., and then encouraging comparisons between theoretical and experimental results.

The final objective of this study is to connect to the localized access introduced in the passive area analysis, an active equivalent circuit deduced from the physical semi-conductor laws. Thus a new transistor model will be established taking into account the physical and electromagnetic characteristics.

II - NUMERICAL ANALYSIS

The theoretical analysis is performed applying the free or forced oscillations 3D F.E.M. in the frequency domain between the access ports of the device. The F.E.M. is well known to be useful for solving Maxwell's equations. This method has been already explained in several papers [6,7].

We have now to introduce two types of access we can describe, to analyze complex devices containing distributed and localized elements.

The classical **distributed access planes** are perpendicular to the propagation axis of coplanar or microstrip line, metallic guide, coaxial probe… They define a boundary of the mesh.

For scattering matrix computations, electromagnetic currents are imposed on these access planes, to analyze the couplings between the considered excitation systems and the device. If we define PA physic access noticed p, $p \in \{1,PA\}$, we can express the electromagnetic fields by a linear relation between the eigen modes, in these access. So, in the p access, we define EAp electric access, and each mode m, $m \in \{1,EAp\}$ can be expressed introducing the voltage current waves (a(p,m) , b(p,m)).

The electric $\vec{Je}_p$ and magnetic $\vec{Jm}_p$ surface distribution currents in the access, are defined by :

$$* \ \vec{Jm}_p = \sum_{m=1}^{EAp} \left(a(p,m) + b(p,m)\right) \vec{Jm}_r(p,m) \qquad (1)$$

with $\vec{Jm}_r(p,m) = -\vec{n}_p \wedge \vec{E}_t(p,m)$ (2)

$$* \ \vec{Je}_p = \sum_{m=1}^{EAP} \left(a(p,m) - b(p,m)\right) \vec{Je}_r(p,m) \qquad (3)$$

with $\vec{Je}_r(p,m) = \vec{n}_p \wedge \vec{H}_t(p,m)$ (4)

* $\vec{n}_p$ is a perpendicular vector to the p access and directed to the inside structure.

* $\vec{E}_t(p,m)$ and $\vec{H}_t(p,m)$ are the normalized electromagnetic fields in the p access.

The new **localized access** are linear and can be defined in the studied volume or on a boundary. They replace localized elements and permit to describe them with current voltage relations.

If we consider the localized access noted l, $l \in \{1, LA\}$, the current I_l on this line is defined by :

$$I_l = (a_l - b_l) Io_l \qquad (5)$$

with * a_l, b_l : the voltage current waves at the l access

* Io_l : the normalized current on the l access

The potential difference V_l at the terminals of the l element, is defined by :

$$V_\lambda = -\int_\lambda \vec{E} \cdot \vec{d\lambda} = (a_\lambda + b_\lambda) Vo_\lambda \qquad (6)$$

with Vo_l the normalized voltage on the l access. Moreover, Vo_l and Io_l are lied by :

$$Vo_\lambda = Ro \ Io_\lambda \quad (7) \quad \text{and} \quad \frac{1}{2} Vo_\lambda \ Io_\lambda = 1 \quad (8)$$

with R_o = 50 Ω, the normalized impedance.

Moreover, to apply electrostatic laws, the l access length must be short compared to the wavelength.

The next step of the computation, is to solve the following equations deduced from the Maxwell's ones :

$$\vec{rot}\left(\frac{1}{\mu_r}\left\{\vec{rot}\right\}\vec{E} - k_0^2 \varepsilon_r \vec{E}\right)$$

$$= \sum_{p=1}^{PA} \sum_{m=1}^{EAP} \left[\left(a(p,m) - b(p,m)\right)\left(-j\omega\mu_0 \vec{Je}_r(p,m)\right)\right]\delta S$$

$$+ \sum_{\lambda=1}^{LA} \left[(a_\lambda - b_\lambda)(-j\omega\mu_0 Io_\lambda)\right]\delta\Gamma e \qquad (9)$$

with $k_0^2 = {}^2 {}_0 \mu_0$ (10)

The equation (9) defines the electric field in the studied structure taking into account the conditions imposed :

* on the *distributed access*

$$\left(-\vec{n}_p \wedge \vec{E}\right)\ Sp\ =\ \sum_{m=1}^{EAp}\left[\left(a((p,m)+b(p,m)\right)\vec{Jm}_r(p,m)\right]\ Sp \qquad (11)$$

with $p \in (1, PA)$

* on the *localized access*

$$\int_{\Gamma e}\vec{E}\bullet\vec{t}_e\ =\ (a_l + b_l)Vo_l \qquad with \qquad l \in (1, LA) \qquad (12)$$

* by the *electric conditions on the boundary of the mesh*

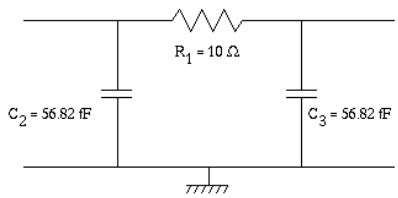
$$\left(\vec{n}_e \wedge \vec{E}\right)\ Se\ =\ \vec{0} \qquad (13)$$

To solve the Maxwell's equations on each node of the mesh, we apply a vectorial E formulation using mixed finite elements of Nedelec with second ordre polynomials.

III - APPLICATIONS OF THE F.E.M. LOCALIZED APPROACH

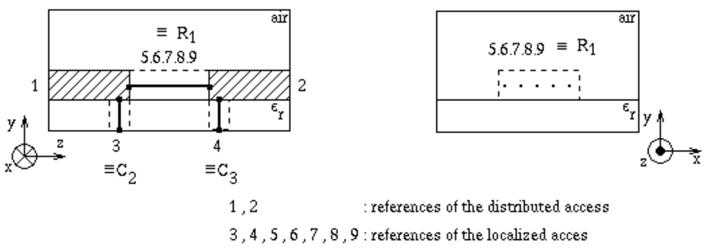
III-1 - Localized passive network electromagnetic analysis

We now analyze applying the F.E.M. the two port network shown in the figure 1. The circuit is supplied by two microstrip transmission lines.



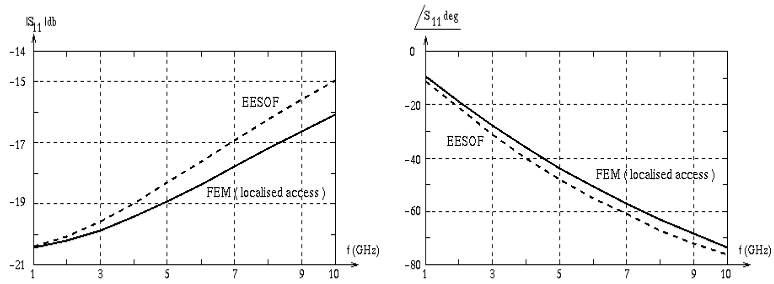
- Figure 1 -
Two port network

At it is presented previously, the components R_1, C_2 and C_3 have been replaced by the localized access. To define these components we use only one localized access for each capacitances, but five parallel ones for the resistance. In this case, the distribution of the current through R_1 is equal on the five localized access. We describe in the figure 2, the localized access position in the studied structure. To define the [S] matrix of the network between its two physical access, an equivalent circuit is connected on each localized access.



- Figure 2 -
Description of the π network with the localized access

The figure 3 presents the comparison between the S_{11} modulus and arguments parameters as a function of the frequency obtained by the F.E.M. localized approach and the software “HP EESOF“. We can note a good agreement between these results. However, around 20 Ghz, the results differ because the length of the localized access is not negligeable compared to the wavelength, so the electrostatic laws can not then be applied.

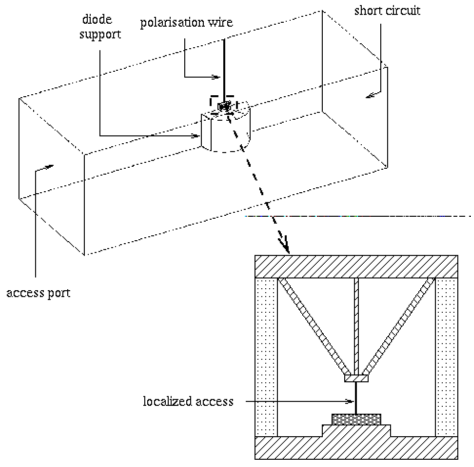


- Figure 3 -
Comparison between experimental and theoritical S_{11} modulus and arguments parameters as a function of the frequency

So we can deduce that our modelling is suitable for lumped passive elements and we will apply this technique to the total characterization of devices containing both passive and active parts.

III-2 - A gunn diode amplifier analysis

The next studied device (figure 4) is designed to act as a linear reflexion amplifier at 10 GHz. The structure is composed of an X band rectangular waveguide, a GaAs gunn diode (AH 445 from Thomson Microwave Components) and the connections to polarize the diode (Vp = 10 V). The short circuit is about a quater wavelength away from the diode.

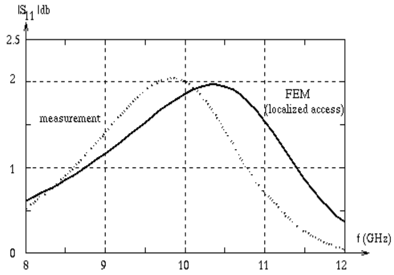


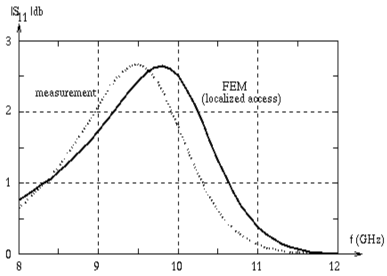
- Figure 4 -
Description of the gunn diode amplifier

In this case, we want to perform a global electromagnetic analysis of this device applying the F.E.M. localized approach.

First, the active part of the diode is described by only one localized access placed in the diode axis. The scattering matrix is established between this access, and the distributed access which is perpendicular to the waveguide propagation axis. During this computation, all the physical phenomena which describe the device are taken into account. Secondly, an equivalent circuit of the diode is connected to the localized access, to define the S_{11} modulus of the gunn diode amplifier as a function of the frequency.

The figures 5 and 6 present the theoretical and experimental results obtained for different positions of the short circuit. The theoretical and experimental gain values and the curve shape, are in good agreement. There is however a slight shift in frequency between these curves.





- Figure 5 - - Figure 6 -

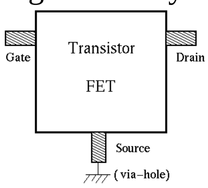
Comparison between the experimental and theoretical S_{11} modulus for a short circuit localized at 12 mm (Figure 5) and at 15 mm (Figure 6) from the diode axis

III-3 - Extrinsic domain electromagnetic characteristics of a FET

The main objective of this study is to develop a new model of a transistor. First, the passive and active domains of the FET are analyzed independently from each other.

We present in this paper the passive part analysis applying the F.E.M. localized approach . We describe here the passive behaviour of the transistor taking into account the electromagnetic effects applying our theoretical analysis method. A scattering [S] matrix between the physical ports defined by the gate and the drain access will be established and some localized access could be defined to introduced the active model of the FET under its electrodes. At last, the real active domain will be described by an equivalent circuit connected to the localized access to characterize the global behaviour of the studied transistor between the gate and the drain ports.

In this article, the transistor is considered as a multipole described in the figure 7. The studied FET is a classical one, with four gate fingers, the drain and source ports, two via-holes, two air-bridges, and two microstrip access lines connected to the drain and gate ports. The real geometrical dimensions of the metallic ports (σ = 3 10^7 S/m) and the substrat characteristics (AsGa ; ε_r = 12,9) are taken into account in our electromagnetic analysis applying the F.E.M.



- Figure 7 -

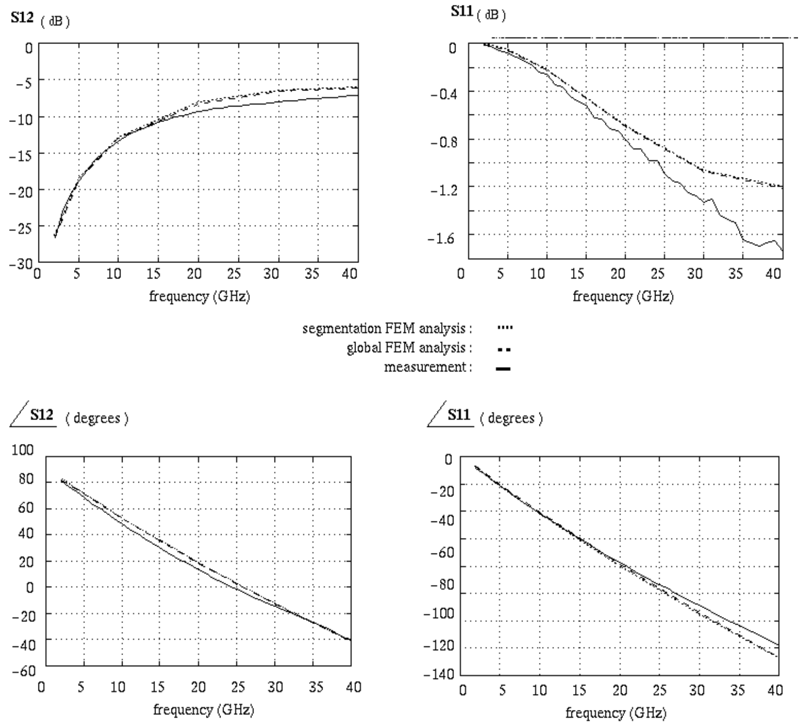
Description of the transistor as a multipole

The electromagnetic behaviour of the device, is established by a global analysis. The device is first segmented into three segments : the drain segment, the gate segment and the third segment to describe the couplings between the gate, the drain and the source fingers.

The main interest of a segmentation analysis is to establish each segment behaviour independently from each other and to introduced in the third segment the localized access used to connect the active equivalent circuit. Then for each segment, a generalized [S] matrix is established and at last, these matrix are chained together to obtain the [S] matrix of the transistor between the gate and drain ports.

The segmentation approach is faster compared to the global analysis, and allows us to establish in a short computing time the [S] matrix of the FET for any modifications of the physical and/or geometrical characteristics and of the active equivalent circuit.

Comparisons between theoretical and experimental results are presented in the figure 8. The theoretical [S] matrix are performed in the [2 - 40 GHz] frequency band on a HP Workstation 735, and for this presentation the localized access are not introduced.



- Figure 8 -
Comparisons between the experimental and theoretical S_{11} and S_{21} modulus and arguments parameters as a function of the frequency [2 -40 Ghz]

First, the results obtained with the segmentation approach verify those obtained with the global analysis. The comparisons between experimental and theoretical results show encouraging agreement. Indeed, the shape of the curves are identical for the modulus and the arguments. Moreover, in this first analysis, metallic and dielectric losses are not considered, which can explain the higher level of the theoretical S_{21} curve compared to the experimental one.

IV - CONCLUSION

With the increasing power of the workstations, the 3D F.E.M. becomes an efficient tool to analyze complex microwave structures.

In this paper, a new electromagnetic analysis has been developed. This method based on the F.E.M. permits to define a global electromagnetic modelisation of devices containing both passive areas and localized active components.

To prove the efficiency of our method, a two port network and a gunn diode amplifier have been studied with success.

The main objective of this paper is to apply our method to develop a new transistor modelization. We present here an electromagnetic analysis of the passive area of the FET taking into account all the physical and geometrical characteristics. Then theoretical and experimental results are compared and show encouraging agreement.

During the next step of this study, we'll define a new active equivalent circuit based on the physical semi-conductor laws. This circuit will be connected to the passive area threw the localized access. Thus a new transistor modelization will be established taking into account the physical and electromagnetic characteristics.

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