A NEW GLOBAL FINITE ELEMENT ANALYSIS OF MICROWAVE CIRCUITS INCLUDING LUMPED ELEMENTS.

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ABSTRACT

A new fullwave global analysis of complex inhomogeneous structures including passive or active, linear or non linear lumped elements is presented. Only one electromagnetic simulation of the distributed part, by a 3D finite element method using edge elements, is needed corresponding to the insertion of several lumped elements placed at the same position. Results for a resistor, a diode inserted in a microstrip circuit as well as a Gunn diode amplifier are presented and comparisons with measurements are given for an active structure.

INTRODUCTION

Since few years, thanks to the continuous improvement of computer calculation capacity, much attention has been focused on the investigation of complex microwave circuits based on a numerical solution of Maxwell's equations for the whole circuit. By complex circuits we mean, those composed of distributed elements like various transmission lines and discontinuities and of lumped elements like resistors, capacitors, diodes or other active devices. A complete analysis of such circuits is generally performed by dividing the structure into several parts, that are studied independently from each other and recombined from a circuit point of view to give global results. This technique may be a simple one providing accurate results when reference planes separating different domains are easily defined and when electromagnetic coupling between different circuit parts can be neglected. But these conditions are not achieved in complex and highly integrated present systems. A global electromagnetic (EM) simulation is necessary in these cases for a precise determination of the whole circuit performances.
Few proposals [1], [2] and [3] for such global EM simulations are found in the literature for which the major drawbacks are their dependence on the type of the studied localized element or their applicability only on planar microwave circuits.
Our paper presents a new electromagnetic analysis for characterizing such complex circuits based on the use of the Finite Element Method. The proposed technique has of course the advantages that presents a 3D finite element analysis using edge elements [4] (namely : characterization of arbitrary shaped structures and elimination of parasitic solutions). Furthermore, it has the advantage of being a fast practical technique for the simulation of a circuit containing variable lumped elements, as only one electromagnetic simulation is needed for the distributed circuit part.

OUTLINE OF THE TECHNIQUE

Edge elements are now well known as being adequate basis functions for the Finite Element Method applied on Maxwell equations [4]. They allow a space discretization of the field : the degrees of freedom (dof's) are directly the circulations of the field along the edges. This formulation can be put in matrix form as :

$$[Y].[e]=[i]$$

where [e] is the vector of dof's (in Volts), [i] is the excitation current vector (in Amperes) and [Y] is an admittance matrix which relates the interaction between edges. In fact, an edge element can be thought of, as a probing function of the electric field along edges.

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According to circuit definitions, one edge can be directly compared to a port whose own voltage and current characteristics are respectively e_e and i_e (fig.1). We can write :

$$i_e = \sum_{k=1}^{M} Y_{ek}\, e_k$$

where M is the number of dof's.

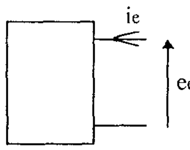


Fig.1 : Edge compared to an external usual port.

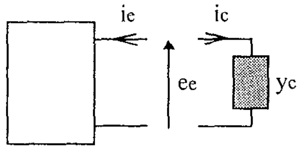


Fig.2 : Lumped element connected to an edge.

If a lumped component is connected to this port (fig.2), the Kirchhoff's laws can be written as :

$$i_e + i_c = 0$$

where i_c is the current in the lumped component. This law may be rewritten in two different ways :

$$\textit{Eq.1 :}\quad \sum_{k=1}^{M} Y_{ek} \cdot e_k + y_c \cdot e_e = 0$$

or

$$\textit{Eq.2 :}\quad \sum_{k=1}^{M} Y_{ek} \cdot e_k = -y_c \cdot e_e = -i_c$$

The first equation is used to introduce an additional term that corresponds to the admittance y_c of the lumped element in the admittance matrix [Y], as is done in the moment method matrix [3]. This method is restricted to simple lumped components like resistors, capacitors, inductors, whose parameter y_c is well known. Moreover a complete electromagnetic simulation has to be performed each time the value of the lumped component changes.

We prefer to use the second formulation given in (eq.2). The inclusion of the lumped element is taken into account in the excitation current vector. In a first step, the edge corresponding to the location of the component becomes a kind of port that has to be considered like other usual external ports. It is either connected to a current source (fig.3) or open-circuited, in the same procedure as is explained in [3]. This operation provides an impedance matrix that is converted to a scattering matrix which represents the distributed part of the circuit. In a second step, the obtained matrix is connected to the lumped element using a circuit simulation software. The final result is the usual scattering matrix of the complete device.

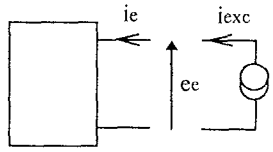


Fig. 3 : Edge connected to a current source.

This technique presents several advantages. Indeed, its formulation is quite simple, direct and general : the insertion of any linear or non linear, passive or active components can be considered (we note that the method used for the analysis of non linear circuits is the Harmonic Balance Method (HBM)). Moreover, the lumped components can be as close as desired to circuit discontinuities, since electromagnetic coupling is taken into account. Finally, these lumped elements can be changed without needing further electromagnetic simulation for the circuit distributed part.

RESULTS

Three simulations are compared in the following studies : the first one is entirely based on the use of the commercial circuit analysis software Hewlett Packard (MDS), the second one is purely an electromagnetic analysis using directly the admittance matrix [Y] of the Finite Element Method, as explained above in (eq.1) (named EF), the third one is our technique that uses the Finite Element Method to simulate the distributed part and a circuit analysis tool to add the lumped component characteristics (named EF+MDS).

Firstly, we simulate a 100 Ω resistor connected to a microstrip line through a gap (fig.4). The results give the variations of the magnitude and the phase of the S-parameters as a function of frequency (fig.5).

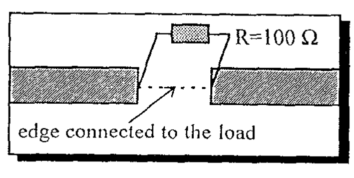


Fig.4 : Resistor connected to a microstrip line. (w=2.3mm, h=0.794mm, ε_r=2.32)

The comparison between our simulation (EF+MDS) and the second one (EF) shows the equivalence of both approaches and their difference from the equivalent circuit model approach (MDS). It proves the importance of global electromagnetic simulation even for relatively non complicated circuits.

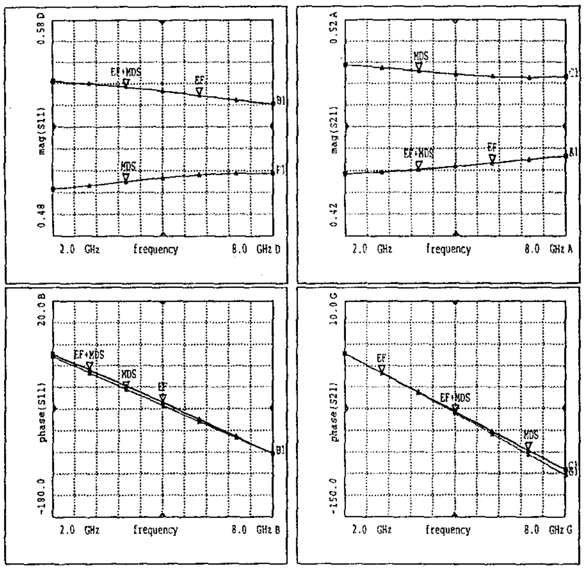


Fig.5 : S-parameters for the structure of (fig.4).

The variations of the S-parameters are studied when the resistor value changes from 1 Ω to 100 kΩ at a frequency of 4 GHz (fig.6). Note that, contrary to the MDS and EF+MDS simulations, the second method requires a new electromagnetic simulation for each new resistance value. As expected, both other simulations are equivalent when the resistor value is very large : the S-parameters converge towards those characterizing the gap (fig.7). But if the resistor value is very small, results of the two simulations differ : the circuit analysis results (MDS) are closest to those characterizing the simple microstrip line without gap (fig.8), while the electromagnetic simulation (EF+MDS) shows more reflection because the discontinuity due to the lumped element is taken into account. The same remark was reported in reference [3] when using the moment method for a test case of a coplanar waveguide loaded by a resistor.

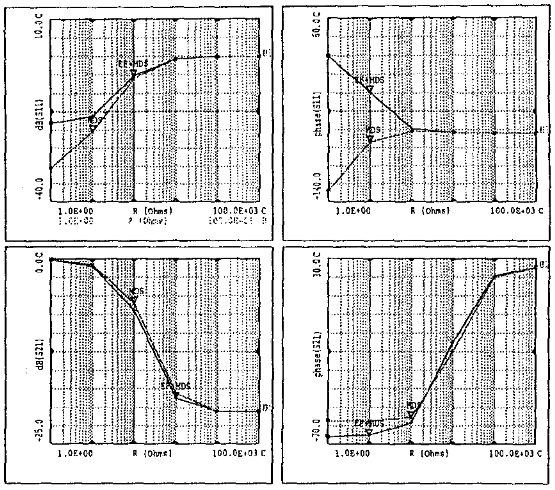
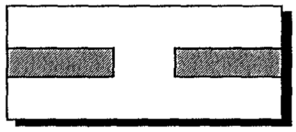
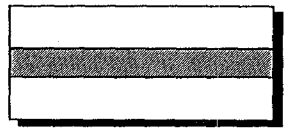


Fig.6 : Variations of the S-parameters with the resistor value for the example of (fig.4).



$$\begin{cases} |S_{11}| = -0.039\text{dB}, \langle S_{11} = -64.1^\circ \\ |S_{21}| = -20.49\text{dB}, \langle S_{21} = -25.6^\circ \end{cases}$$

Fig.7 : Comparison with the gap.



$$\begin{cases} |S_{11}| = 0 \\ |S_{21}| = 0\text{dB}, \langle S_{21} = -55.77^\circ \end{cases}$$

Fig.8 : Comparison with the microstrip line.

Another interesting test case is that shown in (fig.9) : it consists of a diode connected to a microstrip line through the use of an air-bridge. Results presented for the diode voltage and current responses in (fig. 10) show that there is a good agreement between the results when calculated by our combined simulator and those calculated using the circuit analysis non linear tool (MDS). These results prove the adaptability of our technique to characterize circuits containing linear or non linear lumped elements.

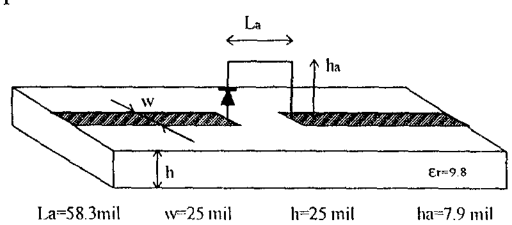


Fig.9 : An air-bridge connecting a diode to a microstrip line.

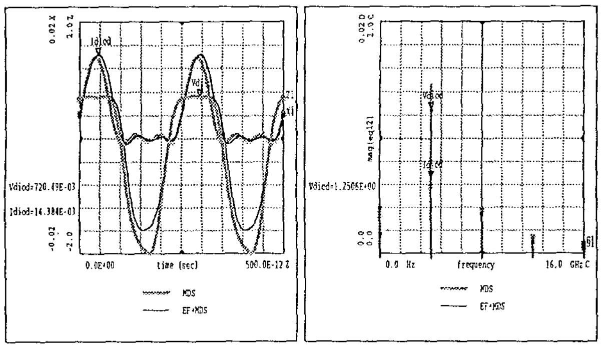


Fig.10 : Temporal and spectral responses of diode voltage and current for the structure of (fig. 9).

Finally, our technique is used to simulate an active microwave structure : a linear Gunn diode amplifier (fig.11). Our results (fig.12) are in a very good agreement with the measurements published in [1]. A deviation of less than 1.2 per cent is reported between the two results.

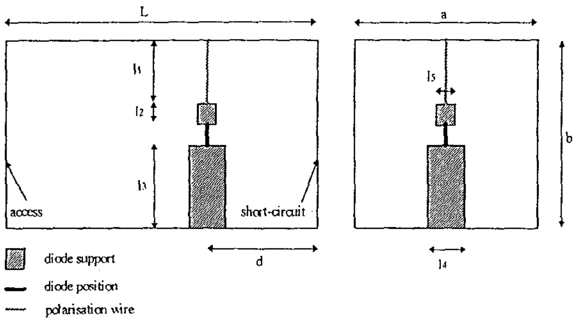


Fig.11 : Gunn diode amplifier. (a=22.86mm, b=10.16mm, L=35mm, l_1=6.16mm, l_2=0.25mm, l_3=3.2mm, l_4=4mm, l_5=1.3mm)

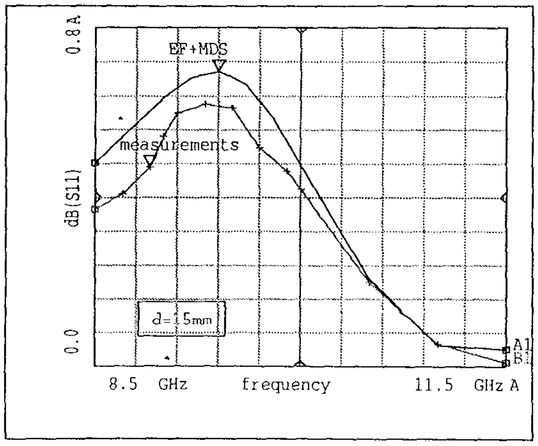


Fig.12 : Comparison between our results and the measurements for the structure of (fig.11).

CONCLUSION

We have presented a new efficient method to simulate the insertion of any lumped passive or active, linear or non linear components into a distributed microwave structure. Through the presentation of some test cases, we have shown its adaptation to complex, linear or non linear, designs without needing any particular treatment. Based on the use of a 3D finite element method using edge elements, our technique can be used to characterize any structure geometry without having parasitic solutions.

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