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International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-9 Issue-2, December 2019

Fuzzy Logic based Method for the Extraction of Extrinsic and Intrinsic Elements of Microwave Transistors

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Abstract: ***In this paper we propose a new method for the extraction of extrinsic and intrinsic elements for microwave transistors based on a fuzzy logic architecture. The proposed technique uses the experience of the designer in order to extract and optimize in a smart way only the electrical elements required for an accurate multibias scattering parameters prediction. We tested our model with a GaAs MESFET 6 x 120 um and a Al GaAs P-HEMT 6 x 15 um device. It has been demonstrated that the proposed method is more accurate than the conventional one, evaluated with the previous technologies. The global behavior of the transconductance (gm) and gate to source capacitance (Cgs) measured with this technique agrees with the physical properties of the above mentioned technologies. Another advantage of this method is that the conventional "Cold-FET" configurations (Vds=0V) are not required, which warrant the reliability of the microwave transistor. The methodology presented in this work can be used in the RF circuit design industry as a first step for an accurate transistor characterization.***

Keywords ***: Extrinsic elements, equivalent circuit, intrinsic elements, field effect transistor, fuzzy logic, microwaves, telecommunications.***

I. INTRODUCTION

One of the first steps in the design of microwave amplifiers for telecommunication applications is the extraction of extrinsic (parasitic) and intrinsic elements of microwave transistors.

Conventionally, equivalent circuits for microwave transistors represent the extrinsic and intrinsic elements [1]. By using electrical measurements and performing embedding and deembeding equations, it is possible to extract those parameters. However; due to the high number of variables in terms of topology of extrinsics, intrinsics, bias points and frequency ranges, the optimization process used for solving the above mentioned equations is not accurate enough. [2], [3].

"Cold-FET" measurements (zero volts between the drain to source terminals of the transistor) are usually used to extract parasitic elements for the small-signal model of MESFET and HEMTs [4], but sometimes this kind of measurements is not possible to carry out. In these cases, conventional optimization processes are used to calculate realistic values of parasitic, but the results obtained are far away of the good solution. [5], [3].

In this paper an "intelligent" fuzzy expert system is introduced such as an alternative to the cold-FET measurements and conventional optimization. Fuzzy logic is a superset of conventional Boolean logic that has been extended to handle the concept of partial truth-thruth values between "completely true" and completely false". It was introduced by L. Zadeh [6] with the goal to model the uncertainty of natural language. Zadeh shows that rather than regarding fuzzy theory as a single theory, we should regard the process of "fuzzification" as a methodology to generalize any specific theory from a crisp (discrete) to a continuous (fuzzy) form. A fuzzy system is an expert system that uses a collection of fuzzy membership functions and rules, instead of boolean logic, to get conclusions about data. The rules in a fuzzy expert system have usually the form: "if x is low and y is high then z = medium" where x and y are input variables (names for known data values), z is an output variable (a name for a data value to be computed), low is a membership function (fuzzy subset) defined on x, "high" is a membership function defined on "y", and medium is a membership function defined on "z". The antecedent, is called the premise and it is used to describe to what the rule applies, while the conclusion (the rule's consequent) assigns a membership function to each of one or more output variables. Most tools for working with fuzzy expert systems allows more than one conclusion per rule. The set of rules in a fuzzy expert system is known as the rule base or knowledge base, which is extracted from the expertise of the designer.

II. METHODOLOGY

For the extraction of extrinsic and intrinsic elements of microwave transistors we considered the small signal equivalent circuit shown below [7]. This is rather general and it can be applied to the most of microwave devices.

Revised Manuscript Received on December 30, 2019.
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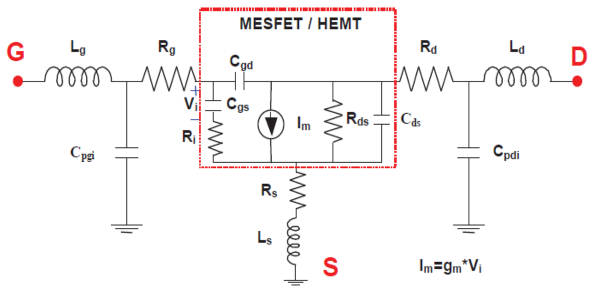

Fig. 1. Small signal model for microwave transistors used in this paper.

The proposed method begins with the extraction of extrinsic elements. By using the technique indicated in [8] we extracted Rg, Rd and Rs. By using the method proposed by [9] we extracted Lg, Ld, Ls. For the extraction of Cpgi, Cpdi and the intrinsic elements we used the method proposed in [7], as a first approximation, which is based on "Hot-FET" S-parameter measurements (Vds>0V). That experimental technique was carried out with a VNA. The data processing of the results takes into account the deembeding of the extrinsics obtained previously in order to extract the intrinsic.

The above mentioned conventional method [7] uses optimization methods to find out the final values of intrinsic elements. However; with this conventional method the final values can be easily trapped in a local minimum and consequently it can produce inaccurate results. To face that issue we propose to use the user experience in order to optimize only the extrinsic elements directly related with the error in a specific S parameter.

For doing that, by using the above mentioned measurements, we performed a preliminary comparison between measured and simulated S parameters. The differences between them were quantified in an error vector for each S parameter. Those vectors were defined as the inputs of our fuzzy system, with different weights according to the RF designer requirements. The extrinsic elements were configured as the outputs of our system, which were used to recalculate the final values of the intrinsic elements. In this way, we optimized in the fuzzy system only the extrinsic elements directly related with the error in a specific S parameter.

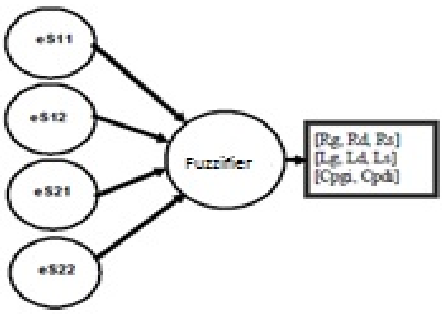

Fig 2. Fuzzy logic architecture for the proposed method for the extraction of extrinsic elements

The membership functions of the input variables of our fuzzy system were Gaussian in order to represent a big, medium or small error. This mathematical function was selected in order to avoid discontinuities in the fuzzy inference process, and to avoid discontinuities in the extraction of the derivatives of gm (transconductance) and gds (output conductance) which are used for intermodulation distortion prediction.

The knowledge of the RF designer, required for our system was implemented in a database called inference engine.

The rules have the following form:

"If error (*Sij*) is positive big, then increase (*Rz*) and decrease (*Lz*) and increase (*Cz*)"

Where:
"*ij*": sub index of S-parameters
"*Rz*": specific extrinsic resistance: Rg, Rd, Rs
"*Lz*": specific extrinsic inductance: Lg, Ld, Ls
"*Cz*": specific extrinsic capacitance: Cpgi, Cpdi.

When all the user knowledge is implemented, the system is able to find the final values of the extrinsic elements. For doing that, the centroid method for defuzzyfication is selected to reduce the time of computing. The use of singleton equation for the defuzzyfication is given by:

$$e = \frac{\left[\int y * U_B(y)\, dy\right]}{\left[\int U_B(y) dy\right]} \qquad (1)$$

Where:
"U_B" is the membership degree of the input variable (error of S parameters),
"*y*" is the maximum value of a fuzzy set,
"*e*" is the final value of the extrinsic element (output of the system).

III. RESULTS AND VALIDATION OF THE METHODOLOGY

The algorithm presented in this paper has been written in MATLAB by taking advantage of the fuzzy toolbox provided on it. The program possibilities the extraction of parasitic elements and intrinsic components of the small signal equivalent circuit for hot FET multibias conditions. This software has two operation modes: manual (using conventional techniques), and automatic (fuzzy) in order to make possible a comparison between both techniques. In our methodology, the input variables are the eight parasitic elements of the small signal model: Rg, Rd, Rs, Lg, Ld, Ls, Cpgi and Cpdi.

Table I shows a comparison between the final values of extrinsic elements obtained with the conventional method and with our proposed method. In that table it is possible to see that values are in the same order of magnitude. Furthermore, for the MESFET device those values are in the order of tenths of pF, for the parasitic capacitances; and tenths of nH for the parasitic inductances, which is typical for this technology. Even lower values for the P-HEMT device were obtained, in terms of capacitances and inductances, which are also typical for this technology.

Table- I: Parasitic elements extracted with the conventional method [7] and with the proposed method (*) for a MESFET and a P-HEMT device.

	Resistances (ohms)			Inductances(nH)			Capacitances (pF)	
	MESFET GEC MARCONI F20 Bath-tub 6x120um							
	Rg	Rd	Rs	Lg	Ld	Ls	Cpgi	Cpdi
*	3,5	2	1,25	0,16	0,1	0,014	0,07	0,16
[7]	4,08	1,99	1,83	0,147	0,122	0,156	0,122	0,28
	P-HEMT Philips 6x15um							
	Rg	Rd	Rs	Lg	Ld	Ls	Cpgi	Cpdi
*	3	9	10	0,035	0,01	0	0,01	0,01
[7]	4,4	9,5	10,3	0,031	0,01	0	0,015	0,009

The intrinsic elements were also extracted and analyzed with both methods. Fig 3 and Fig 4 shows Cgs and gm extracted by using the conventional method.

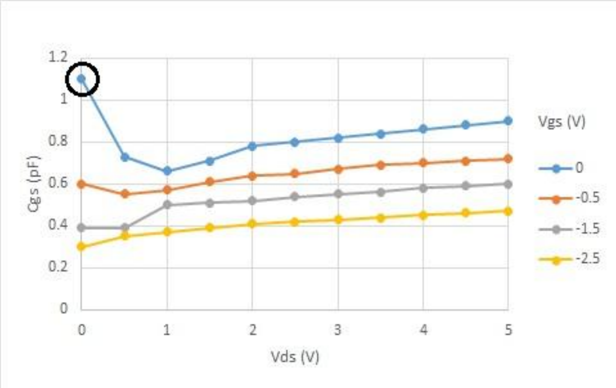

Fig. 3. Values of Cgs extracted by using the conventional method.

In Fig. 3 we can see the normal compression of the gate to source capacitance when Vgs changes towards the pinchoff. The non linear behavior of Cgs for Vds values below 1V corresponds to the transition from the linear to the saturation region in the IV characteristics of the transistor. (knee effect). However; the 1.1pF value (circled) is a big abnormal value than can be attributed to the inaccuracy of the conventional method [7] used for the extraction of Cgs.

The extraction of the transconductance (gm) with the conventional method is shown in Fig 4. We can see in general a normal behavior because it compresses for Vgs values close to pinchoff. However if we consider the mathematical definition of gm (the first derivative of Ids respect to Vgs), we can conclude that the couple of points (circled) are abnormal. In fact, that shape is typical of oscillations or abnormal IV characteristics of the transistor. However, after a proper verification of those parameters, we have seen no oscillations and good behavior of the IV characteristics. So we conclude that those abnormal values of gm are due to the inaccuracy of the conventional method used in this case for the extraction of gm.

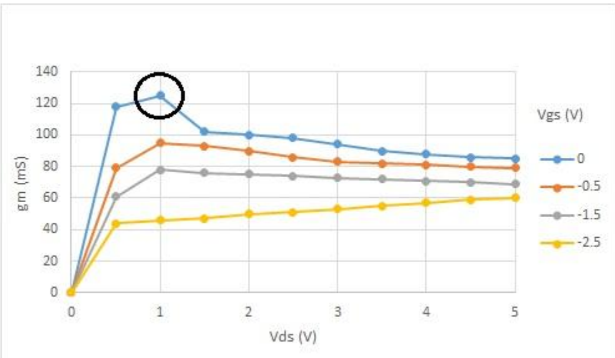

Fig. 4. Values of gm extracted by using the conventional method.

By using the final values of extrinsic elements obtained by our method, shown in Table 1, we proceed to extract the intrinsic elements. Results are shown in Fig 5 and Fig 6.

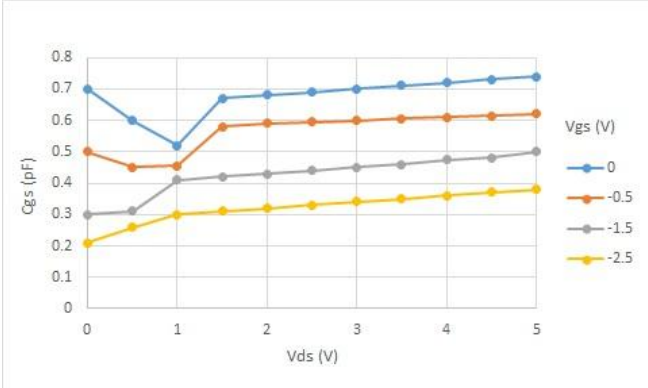

Fig. 5. Values of Cgs extracted by using our proposed method.

The global behavior of Cgs shown in Fig 5 is similar to the one shown in Fig 3. However the abnormal big value of Cgs at Vds=0V is not present. This is due to the use of accurate and realistic values of the extrinsic elements obtained with our method. Fig 6 shows the evolution of the transconductance from the linear to the saturation region for different values of Vgs. In that figure it is possible to see the absence of the abnormal kink shown in Fig. 4.

However; it is important to note that rather than the improvements in the kink of gm, and the peak value of Cgs; the global error is less with the proposed method.

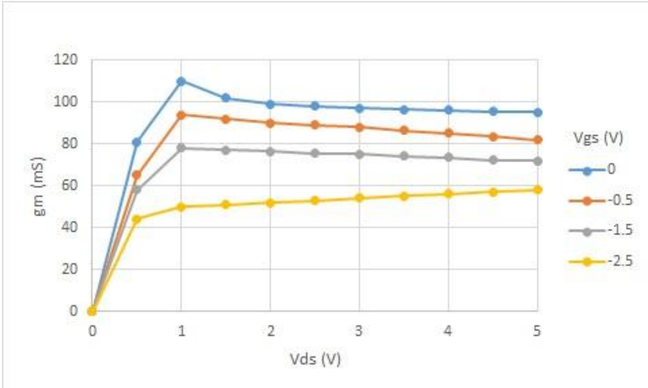

Fig. 6. Values of gm extracted by using our proposed method.

In order to demonstrate that, we extracted a mean square error vector, from S parameters, for both: the conventional and the proposed method in different bias points. Results are shown in Table 2. The differences between measurements and simulations by using our method is lower than the ones obtained with the conventional method. The only exception is in the S12 parameter, which has little impact. In fact due to its very low value it does not affect normally the performances of the final application (i.e. microwave amplifier).

Consequently, the proposed method does not only provide physical coherent values for the extrinsic and intrinsic elements; but it is also more accurate than the conventional methods.

In summary the proposed methodology can be summarized as it follows:

-Use the conventional method [7] to extract the extrinsic elements as initial seeds.

-Use the "Hot-FET" approach to extract the intrinsic elements; but doing the deembeding of the extrinsic elements obtained previously.

-Extract the mean square error in terms of measured and modeled S parameters.

-Implement a fuzzy system, by building a set of rules extracting the knowledge of the RF designer, which will optimize in smart way only the extrinsic elements required to reduce the error vector in S parameters.

Table- II: Comparison between the errors generated by the conventional method and the proposed technique.

	S11 Error (%)	S21 Error (%)	S12 Error (%)	S22 Error (%)
Conventional method	4.1	2.7	2.1	9.6
Proposed method	2.0	1.6	2.9	4.1

IV. CONCLUSION

A new methodology for the extraction of parasitic elements of the small signal models for microwave transistors has been reported. This paper shows that it is possible to use the conventional method [7] to get the initial seeds for the extrinsic elements, and then by using a fuzzy system, it is possible to improve the conventional multiviariable optimization algorithms which produces accurate results in terms of extrinsic and intrinsic elements. The proposed methodology was tested in GaAs MESFET and AlGaAs P-HEMTs devices. The fuzzy logic based algorithm used for the extraction allows the calculation of the values of all parasitic elements with no especial "Cold-FET" measurements. A comparison between the conventional method and our approach shows the superiority of the proposed technique.

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