An Improved MESFET Model for Prediction of Intermodulation Load-Pull Characterization

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Abstract

An accurate characterization of the nonlinear distortion caused by the Ids(Vgs,Vds) current in a MESFET, does not allow the common approach of splitting this nonlinear equivalent circuit element in two voltage dependent nonlinear current sources, Gm(Vgs) and Gds(Vds). By an improved laboratory characterization procedure, it was possible to show that the cross terms of the Ids(Vgs,Vds) Taylor Series expansion can give an important contribution to the prediction of MESFET's intermodulation load-pull behavior.

I. Introduction

The standard analysis technique for the prediction of distortion properties of medium power systems and devices has been Volterra Series Analysis[1,2]. In fact, since the seventies many authors have applied this method in new, in-house or commercial, CAD/CAE software tools for the analysis and design optimization of GaAs MESFET amplifier circuits[3,4,5,6].

In the published papers, dealing with the intermodulation problem, a great effort was made to accurately model Ids(Vgs,Vds). Its parameter set is some times adjusted to match the derivatives of Ids(Vgs,Vds), which is measured at DC, or, more commonly, adjusted by a least-square polynomial fit to AC measured transconductance for several Vgs, and Vds dependent output conductance[4]; or even from intermodulation distortion data[3]. Model parameter extraction based on DC data is almost completely useless for RF simulation due to the FET's low frequency dispersion and errors associated with the successive differential operations. Those errors, that primarily result from the experimental measurement process, are then increased by the derivatives. Although the higher order coefficients obtained from AC data are not influenced by the dispersive effects, they are also affected by the measurement errors, either by the successive derivation or by the poorly accurate fitting process. Recently, S. Maas and A. Crosmun[7] proposed a new method based on low frequency harmonic measurements that allowed the direct characterization of Gm2 and Gm3. However, we are not aware of any published work, in which the cross terms, involving vgs and vds (Gmd, Gm2d and Gmd2), were included in the analysis, or even evaluated.

The aim of this paper is to show that the contribution of the cross terms to the prediction of GaAs MESFET intermodulation load-pull behavior can be important, and to present a method for the complete experimental characterization of the drain-source current nonlinearities.

II. Sources of Intermodulation in the Drain Current

The study presented in this section is intended to provide qualitative information about the dependency of nonlinear intermodulation distortion on the devices' bias point (selected in terms of V_{GS}, or percentage of I_{DSS}, for a given V_{DS}).

Because the low intermodulation distortion amplifiers are supposed to be biased for class-A operation, we will restrict our analysis to the FET's saturation zone. This is the situation where only the gate-source capacitance, Cgs, and the drain-source current, Ids, have to be considered as nonlinear. Ids is, by far, the element of the FET's equivalent circuit model (Fig. 5) that mostly contribute to the nonlinear behavior of the device [2,5]. It is known from MESFET's operation that this current is simultaneously controlled by the intrinsic gate-source, and drain-source voltages, Vgs and Vds. As Ids is dependent on two control voltages it admits a Taylor Series expansion of the form:

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$$\begin{aligned}
Ids(Vgs,Vds) = {} & I_{DS} + \\
& \frac{\delta\, Ids}{\delta\, Vgs} vgs + \frac{\delta\, Ids}{\delta\, Vds} vds + \\
& \frac{1}{2}\frac{\delta^2 Ids}{\delta\, Vgs^2} vgs^2 + \frac{\delta^2 Ids}{\delta Vgs\, \delta Vds} vgs.vds + \frac{1}{2}\frac{\delta^2 Ids}{\delta\, Vds^2} vds^2 + \\
& \frac{1}{6}\frac{\delta^3 Ids}{\delta\, Vgs^3} vgs^3 + \frac{1}{2}\frac{\delta^3 Ids}{\delta Vgs^2\, \delta Vds} vgs^2.vds + \\
& \frac{1}{2}\frac{\delta^3 Ids}{\delta Vgs\, \delta Vds^2} vgs.vds^2 + \frac{1}{6}\frac{\delta^3 Ids}{\delta\, Vds^3} vds^3 \qquad (1)
\end{aligned}$$

where I_{DS} is the bias current, $Ids(V_{GS},V_{DS})$; Vgs, Vds are the deviations of Vgs and Vds from the bias point: $vgs=Vgs-V_{GS}$, $vds=Vds-V_{DS}$; and all derivatives are evaluated at $Vgs=V_{GS}$, $Vds=V_{DS}$. In terms of incremental voltages and currents (1) can be rewritten as:

$$\begin{aligned}
ids(vgs,vds) = {} & Gm.vgs + Gds.vds + \\
& Gm2.vgs^2 + Gmd.vgs.vds + Gd2.vds^2 + \\
& Gm3.vgs^3 + Gm2d.vgs^2.vds + Gmd2.vgs.vds^2 + \\
& Gd3.vds^3 \qquad (2)
\end{aligned}$$

where the various coefficients are the correspondent derivatives of (1). A physical meaning of these values will be given, because it is useful in the evaluation of their relative importance, and in future device parameter extraction.

Gm and Gds are the FET's linear transconductance and output conductance, that can be extracted from conventional small signal parameter measurements. Gm2, Gm3 describe the transconductance variation with Vgs; and Gd2, Gd3 play the same role for the output conductance and Vds. Following that reasoning, Gmd and Gm2d represent the first and second order nonlinear dependence of Gds on Vgs and Gmd, Gmd2 the dependence of Gm on Vds. These three coefficients arise from the physical interaction observed between the input and the output of a MESFET, that is responsible for the nonlinear mixing of vgs and vds signals.

Fig. 1 to Fig. 3 represent the nonlinear coefficients of (2), measured on a general purpose FET with the procedure explained in the next section. The input sources of distortion are evident in the graph of Fig. 1, because they follow directly from the strong dependence of Gm on Vgs.

In the usual sense, the output sources of distortion are attributed to the dependence of Gds on Vds. However, it is widely known that Gds in saturation is almost constant with Vds, while it exhibits a non negligible dependence on Vgs (compare the magnitudes of the nonlinear coefficients Gmd and Gm2d of Fig. 2 with those of Gd2 and Gd3, Fig. 3). This has two main consequences. First, new sources of intermodulation distortion, describing the interacting input

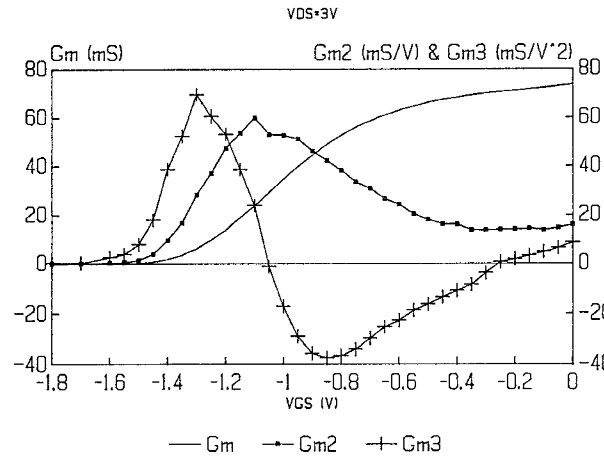

Fig. 1. Measured Gm, Gm2 and Gm3 of a NE70083 for $-1.8V<V_{GS}<0V$, $V_{DS}=3V$

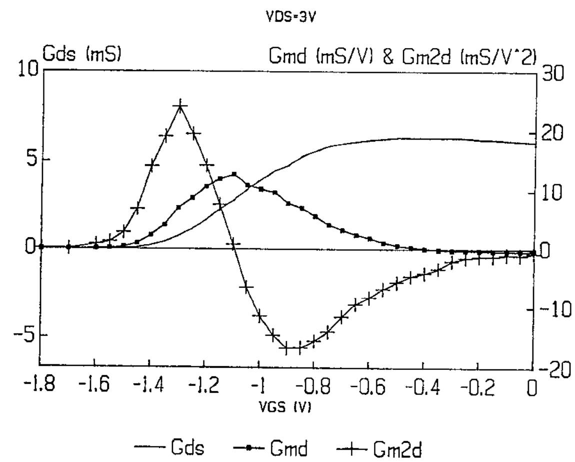

Fig. 2. Measured Gds, Gmd and Gm2d of the NE70083 for $-1.8V<V_{GS}<0V$, $V_{DS}=3V$

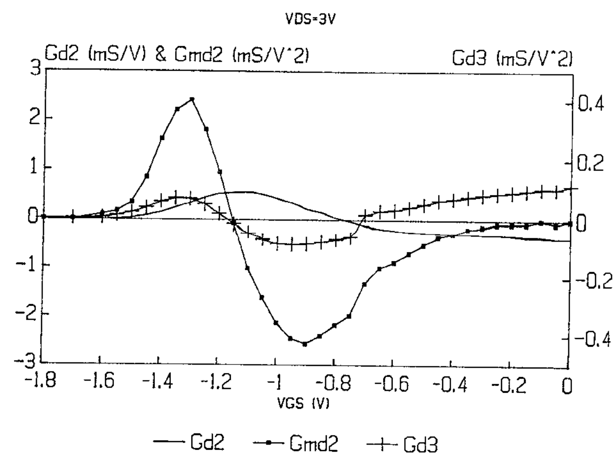

Fig. 3. Measured Gd2, Gmd2 and Gd3 of the NE70083 for $-1.8V<V_{GS}<0V$, $V_{DS}=3V$

and output (that appear as the modulation of the output conductance by the input control voltage), should be included in the MESFET model; and second, it should not be surprising that this new sources can give a greater contribution to the overall device's distortion than the one given by the output itself.

III. Experimental Characterization Procedure

The experimental Ids characterization procedure uses the test system shown in Fig. 4.

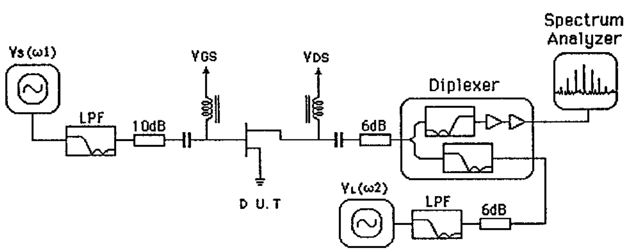

Fig. 4. Experimental setup used for the measurements of harmonic output power ratios

Two signals (of very good spectral purity and low level) of frequencies ω1 and ω2 (145MHz - Pav=-19.5dBm and 155MHz - Pav=-6.6dBm) are injected at the gate and the drain terminals of the MESFET. The diplexer is composed of two elliptic filters, one low-pass and the other high-pass, connected in parallel, and optimized to present good input match at all fundamental and harmonic output frequencies. The high-pass way is then followed by a two stage broad band monolithic amplifier.

The second and third order output power ratios between the carriers Po(w1), Po(w2) and the mixing products at 2ω1, ω1+ω2 and 2ω2; and 3ω1, 2ω1+ω2, ω1+2ω2 and 3ω2, are measured in a spectrum analyzer. Because this instrument is only capable of measuring amplitude, some care must be taken in order to obtain phase information (at low frequencies, the sign of the output signals). A good way to do that, is to develop an educated guess of the MESFET's harmonic behavior (based on the qualitative reasoning proposed in section II), and then look for the measured power nulls that correspond to points of changing sign.

From the first set of measurements, a linear system of 3x3 equations is constructed, in which predictions obtained by Volterra-Series analysis of the equivalent circuit of Fig. 5, are compared to the practical results. This system is solved for the unknown Gm2, Gmd and Gd2.

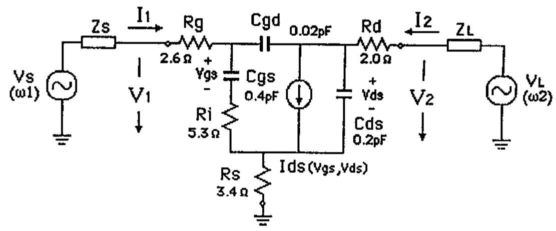

Fig. 5. Equivalent circuit used for nonlinear analysis

These second order terms are then used to predict third order output power ratios that are compared to the ones measured. This creates a set of four linear equations in the unknowns Gm3, Gm2d, Gmd2 and Gd3, that can be easily solved.

The main advantage of this method resides in the fact that it generates very well conditioned systems of equations. Because of the low frequency used (compared to the f_T of a typical MESFET) the transistor is practically unilateral, which indicates that there is almost no voltage Vgs(ω2) induced by V_L. The consequence of this, is nearly only one contribution for (Po(2ω2)) (from Gd2) and (Po(3ω2)) (from Gd3), only two for (Po(ω1+ω2)) (from Gmd and Gd2) and for (Po(ω1+2ω2)) (from Gd3 and Gmd2), etc. In mathematical terms, this means that each system of equations is described by an approximately triangular matrix. However, the full matrices were used in the solution.

IV. Prediction of Intermodulation Load-Pull Behavior

For the evaluation of the relative contributions of the new distortion coefficients to the overall nonlinear performance of a MESFET, a simple circuit was analyzed with the Nonlinear Currents Method of Volterra Series. This was the technique used to derive an efficient Two-Tone Input Describing Function, capable of generating contours of constant output power and carrier-to-third order intermodulation ratio (C/I), in a Smith chart of load impedances[8].

The objective of this TSIDF is to describe the nonlinear behavior of the circuit by closed form functions, in which the dependence on the load impedance, Z_L, is clearly expressed. This was accomplished by solving the linear circuit only once, in terms of its impedance matrix (see reference [2]). This matrix relates the input, output and control voltages, to the nonlinear currents generated by

Ids(Vgs,Vds) and Cgs(Vgs) (the schottky diode model was assumed for that capacitance). In order to maintain Z_L an optimization variable, the [Z] matrix calculation was made in two steps. First an infinite Z_L was considered and a [Z]' matrix was obtained. Then, the Z_{ij} parameters were evaluated with the true Z_L and the Z_{ij}', using some simple n-port-network theory expressions. This approach allowed the derivation of the Z_{ij} as products of two factors: a very complicated one (numerical that does not depend on ZL) and a simple one, where the contribution of Z_L is clearly evident.

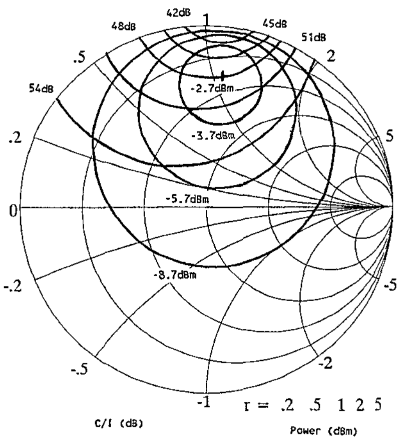

Fig. 6. Simulated load-pull contours of constant output power and intermodulation distortion ratio, using the old model. NE70083 @ V_{GS}=-0.7V, V_{DS}=3V, Input Power=-15dBm, fo=10GHz.

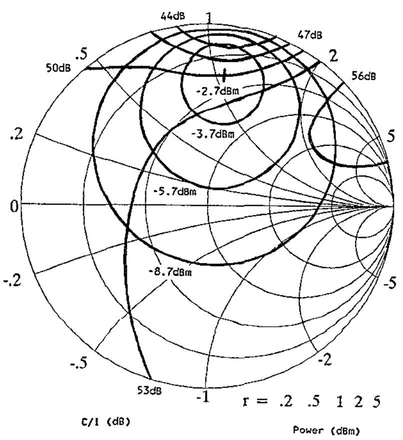

Fig. 7. Simulated load-pull contours of constant output power and intermodulation distortion ratio, using the new complete model. NE70083 @ V_{GS}=-0.7V, V_{DS}=3V, Input Power=-15dBm, fo=10GHz.

Fig. 6 and Fig. 7 are results of load-pull prediction at 10GHz and 100MHz separation of tones, with a model that neglects the cross coefficients[7] and with the new model, respectively. The differences observed, that are mostly evident outside the high gain zone (conjugate matching), can be justified in terms of the lack of capacity of the old model to predict MESFET behavior in conditions of voltage gain, Vds/Vgs, far from those where its parameters were extracted. This leads to the conclusion that the new complete model can be very useful in the simulation of intermodulation performance of many circuits, like broad-band and transimpedance amplifiers, linearized power amplifiers, etc.

Acknowledgment

The authors thank Dr. Pablo D. Naranjo for providing the NE70083 linear model elements.

This work has been supported by a NATO fellowship offered by Comissão Permanente Invotan, and the project TIC89-0023-C02-01, National Board of Scientific and Technological Research (CICYT - Spain).

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