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Accurate characterization procedure of FET's reactive nonlinearities for intermodulation analysis.

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Abstract: This paper deals with FET's reactive nonlinearities characterization for intermodulation distortion prediction. An experimental procedure for extracting the second and third order coefficients of the Qg(Vgs,Vgd) bidimensional power-series expansion is suggested. It is based on Volterra-Series analysis and requires a previous extraction of Ids(Vgs,Vds) derivatives. The Qg(Vgs) characterization results for a HEMT in its saturated region are also shown and discussed, along with some considerations to improve the method.

I. Introduction.

Intermodulation distortion has been a major concern in microwave systems during the last decades because it usually imposes the upper limit for their dynamic range, thus, many works on the subject of modeling FET devices have dealt with its analysis and prediction. Models are usually derived trying to reproduce I/V and Q/V characteristics, but without taking its second and third order derivatives into consideration. This generally leads to a poor description of the derivatives behavior, and consequently, to an inadequate small-signal nonlinear distortion prediction.

The nonlinear current method approach for Volterra-series analysis [1-3] has been the most widely employed technique for small-signal intermodulation calculations. The traditional methods for Taylor-series coefficients extraction, least-squares fitting and successive numeric differentiations, proved to be inadequate for second and third order derivatives. Maas and Crosmun [4] suggested an experimental direct characterization for the Ids Taylor-series expansion in Vgs, based on harmonic level measurements. Maas and Neilson [5], modified the original technique to improve its sensitivity and accuracy. The transconductance derivatives, despite of being those of most relevance, were unable to predict the device intermodulation behavior in load-pull condition. Pedro and Pérez [6] solved this inconvenient, for frequencies not too high, with a significant procedure to extract cross and output derivatives as well. In [7], an alternative method using different load resistances was also considered for this purpose. The Ids(Vgs,Vds) derivatives were presented for MESFETs in certain typical quiescent points, and were recently used by Peng et. al. [8-9] to describe the intermodulation distortion behavior of gate and resistive mixers.

However, the intermodulation distortion description becomes inadequate when frequency increases in the microwave range due to the influence of the reactive nonlinearity that seems not to be conveniently modeled for small-signal nonlinear distortion purposes. As far as we know, no published paper has dealt with the direct extraction of Qg(Vgs,Vds) second and third order bidimensional Taylor-series coefficients, and thus, its still unclear role in small-signal intermodulation distortion becomes of great interest.

In this work, we propose a method, also based on nonlinear currents technique, to characterize this reactive nonlinearity. The test setup and the basic matrix expressions to get this purpose are suggested. As Ids is the predominant nonlinearity in these devices, it usually hides the Qg contribution and consequently, characterizing the latter becomes quite difficult. Some considerations to overcome these difficulties are also discussed. We present the results for a unidimensional expansion Qg(Vgs) of a saturated HEMT, and we consider some points to improve the measurement and the corresponding extraction.

II. Reactive nonlinearity characterization.

The nonlinear equivalent circuit for MESFET/HEMT devices is shown in Fig. 1. There are two fundamental nonlinearity sources, the resistive type nonlinear current source Ids(Vgs,Vds) and the reactive Qg(Vgs,Vgd) split in two nonlinear capacitors C_{GS}(Vgs,Vgd) and C_{GD}(Vgs,Vgd). As it is stated in [3] , we could write both power-series expansions as follows,

$$\begin{aligned} \mathrm{Ids(Vgs,Vds)} &= \mathrm{Idso} + \mathrm{Gm1.vgs} + \mathrm{Gds.vds} + \mathrm{Gm2.vgs}^2 + \mathrm{Gmd.vgs.vds} + \\ &+ \mathrm{Gd2.vds}^2 + \mathrm{Gm3.vgs}^3 + \mathrm{Gm2d.vgs}^2\mathrm{.vds} + \mathrm{Gmd2.vgs.vds}^2 + \mathrm{Gd3.vds}^3 + \ldots \end{aligned} \tag{1}$$

where Gm2, Gmd and Gd2 are the second order coefficients, and Gm3, Gm2d, Gmd2 and Gd3 the ones of third order.

$$\begin{aligned} \mathrm{Qg(Vgs,Vgd)} &= \mathrm{Qgo} + \mathrm{Cgs.vgs} + \mathrm{Cgd.vgd} + \mathrm{Cgs2.vgs}^2 + \mathrm{Cgsgd.vgs.vgd} + \\ &+ \mathrm{Cgd2.vgd}^2 + \mathrm{Cgs3.vgs}^3 + \mathrm{Cgs2gd.vgs}^2\mathrm{.vgd} + \mathrm{Cgsgd2.vgs.vgd}^2 + \mathrm{Cgd3.vgd}^3 + \ldots \end{aligned} \tag{2}$$

where Cgs2, Cgsgd, and Cgd2 represent the second order coefficients, and Cgs3, Cgs2gd, Cgsgd2 and Cgd3 those of third order.

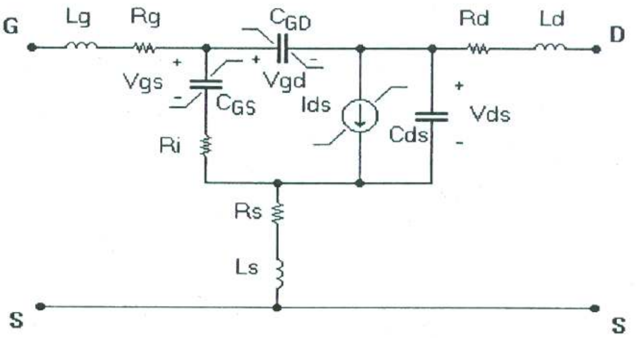


Fig.1 MESFET nonlinear equivalent circuit.

Once we have made a preview extraction of the Ids derivatives using Pedro and Pérez technique [6], we propose to extract Qg derivatives with a test system as the one shown in Fig. 2. We measure the power levels at the amplifier output for the second and third band frequencies: 2ω1, ω1+ω2, 2ω2, 3ω1, 2ω1+ω2, ω1+2ω2 and 3ω2; then, we refer these values to the fundamental harmonic levels, measured with the directional coupler, at ω1 and ω2 in the way of intermodulation ratios in order to reduce the influence of the spectrum analyzer absolute power level measurement errors. As the contribution of the main nonlinearity, Ids, is lower in gate port, and as Qg influence on distortion increases with frequency, we considered convenient to use two microwave generators and to measure in gate port. With both decisions we pretended to avoid Qg contribution from being hidden by Ids, to improve the matrix condition and to reduce measurement errors propagation.

With the corresponding intermodulation ratios and the elements of the small signal linear equivalent circuit, extracted from S parameters, we can directly calculate the 'measured' absolute values for the second and third order nonlinear transfer functions, $|H_2(\omega i, \omega j)|_{meas}$ and $|H_3(\omega i, \omega j, \omega k)|_{meas}$, where $H_2(\omega i, \omega j)$ and $H_3(\omega i, \omega j, \omega k)$ relate the phasors that represent the second and third order frequency components in gate current to the corresponding excitations. It is also convenient to define the auxiliary second order nonlinear transfer functions, $H_{gs2}(\omega i, \omega j)$, $H_{gd2}(\omega i, \omega j)$ and $H_{ds2}(\omega i, \omega j)$, relating the phasors for the second order frequency components in the three nonlinear current sources of the second order equivalent circuit with the previously mentioned excitations.

By the nonlinear currents analysis, we are able to determine the matrixes $[K_{G2(\omega i, \omega j)}]$ and $[K_{B2(\omega i, \omega j)}]$ with the respective contributions of the second order resistive coefficients, Gm2, Gmd and Gd2, and the reactive ones, Cgs2, Cgsgd and Cgd2, to $H_2(\omega i, \omega j)$. The reactive coefficients can then be extracted from (3),

$$\begin{bmatrix} Cgs2 \\ Cgsgd \\ Cgd2 \end{bmatrix} = \left[K_{B_2(\omega i,\omega j)}\right]^{-1}_{3x3} \cdot \left\{ \begin{bmatrix} |H_2(\omega 1,\omega 1)|_{meas} \cdot \angle\alpha_2(\omega 1,\omega 1) \\ |H_2(\omega 1,\omega 2)|_{meas} \cdot \angle\alpha_2(\omega 1,\omega 2) \\ |H_2(\omega 2,\omega 2)|_{meas} \cdot \angle\alpha_2(\omega 2,\omega 2) \end{bmatrix} - \left[K_{G_2(\omega i,\omega j)}\right]_{3x3} \cdot \begin{bmatrix} Gm2 \\ Gmd \\ Gd2 \end{bmatrix} \right\} \qquad (3)$$

with i,j = 1,2.

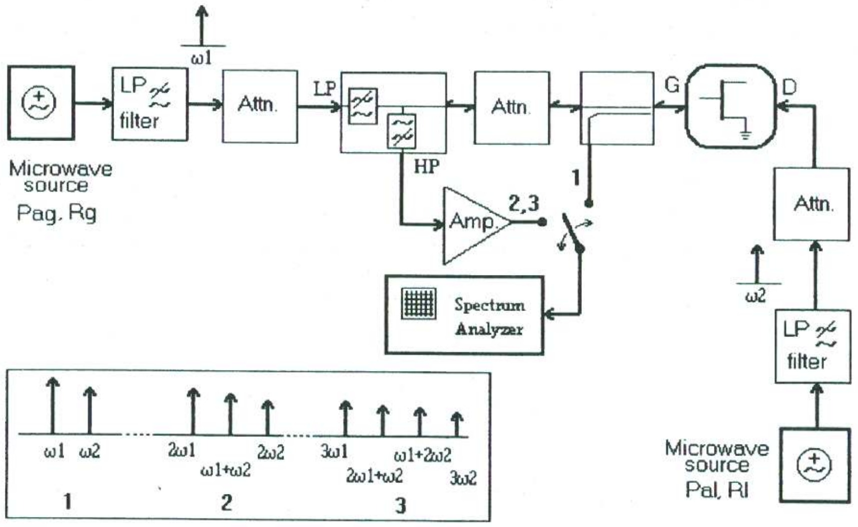


Fig.2. Test setup for reactive nonlinearity characterization.

For the third order coefficients an analogous expression has been deduced. If we denote $[K_{Hgs1(\omega i)}]$, $[K_{Hgd1(\omega i)}]$, and $[K_{Hds1(\omega i)}]$ as the matrixes with the corresponding contributions from $H_{gs2}(\omega i, \omega j)$, $H_{gd2}(\omega i, \omega j)$ and $H_{ds2}(\omega i, \omega j)$ to $H_3(\omega i, \omega j, \omega k)$; while $[K_{G3(\omega i, \omega j, \omega k)}]$ and $[K_{B3(\omega i, \omega j, \omega k)}]$ represent both the contributions of the third order resistive coefficients, Gm3, Gm2d, Gmd2 and Gd3, and those of reactive nature, Cgs3, Cgs2gd, Cgsgd2 and Cgd3, to the proper third order nonlinear transfer function, we can use the following equation to complete the characterization,

$$\begin{bmatrix} Cgs3 \\ Cgs2gd \\ Cgsgd2 \\ Cgd3 \end{bmatrix} = \left[K_{B3(\omega i,\omega j,\omega k)}\right]^{-1}_{4x4} \cdot \left\{ \begin{array}{l} \left[\left|H_3(\omega i,\omega j,\omega k)\right| \angle \alpha_3(\omega i,\omega j,\omega k)\right]_{4x1} - \left[K_{G3(\omega i,\omega j,k)}\right]_{4x4} \cdot \begin{bmatrix} Gm3 \\ Gm2d \\ Gmd2 \\ Gd3 \end{bmatrix} + \\ -\left[K_{Hgs1(\omega i)}\right]_{4x3} \cdot \left[H_{gs2}(\omega i,\omega j)\right]_{3x1} - \left[K_{Hgd1(\omega i)}\right]_{4x3} \cdot \left[H_{gd2}(\omega i,\omega j)\right]_{3x1} + \\ -\left[K_{Hds1(\omega i)}\right]_{4x3} \cdot \left[H_{ds2}(\omega i,\omega j)\right]_{3x1} \end{array} \right\} \tag{4}$$

with i,j,k = 1,2.

A proper method for determining the appropriate argument for the second and third order nonlinear transfer functions, $\alpha_2(\omega i, \omega j)$ in (3) and $\alpha_3(\omega i, \omega j, \omega k)$ in (4), is also critical in an adequate extraction. The real nature of the reactive coefficients, the defined relations among them, as well as using pinch-off region for starting the extraction are some of the clues to overcome the uncertainties also present in the Ids derivatives extraction.

III. Experimental results.

As a first experimental step, we considered C_{GS} (Vgs) as the only reactive nonlinearity, a common practice for FETs biased in their saturated region, in order to simplify the procedure to a situation similar to Maas transconductance extraction.

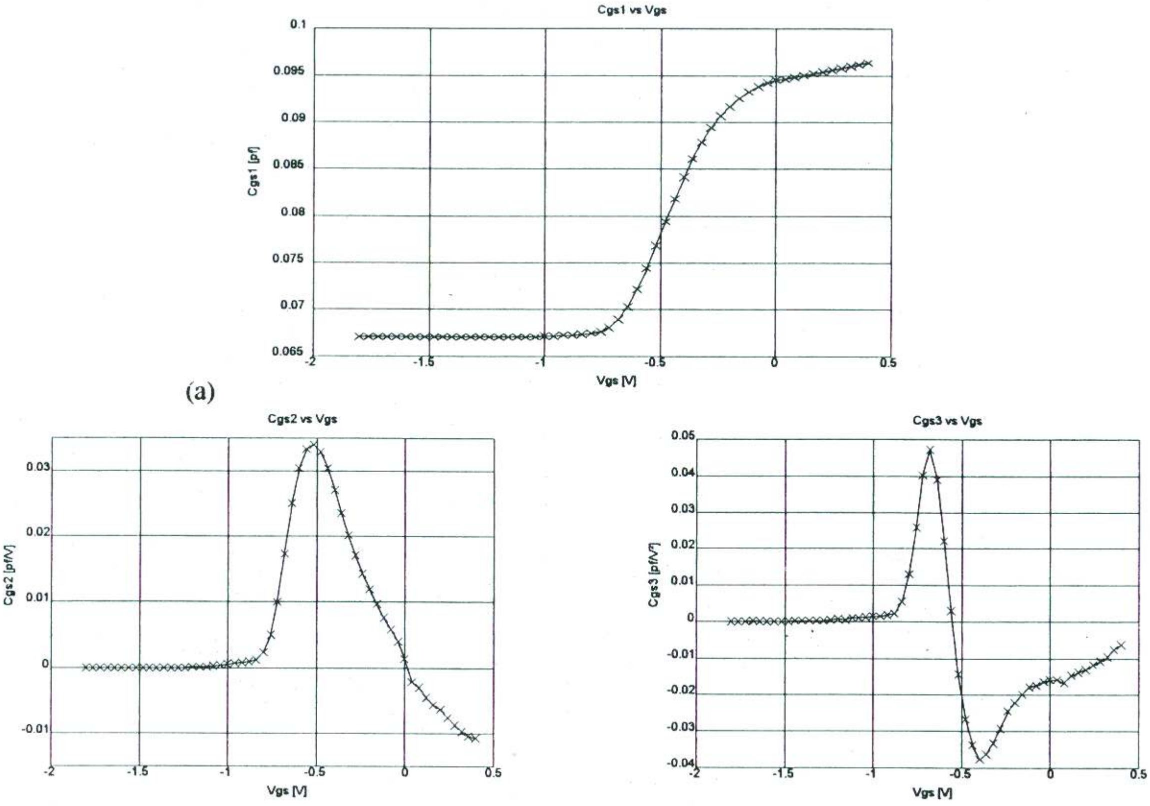
After characterizing the Ids(Vgs,Vds) derivatives, we proceeded to extract Cgs2 and Cgs3 for a D02AH HEMT from Philips with Vds = 3V and $-1.8V < Vgs < 0.4V$. These results are shown in Fig. 3.

As it has been supposed, the Cgs2 and Cgs3 behavior seems to be similar to Gm2 and Gm3, supporting a soft pinch-off, something according to the common control mechanisms for the depletion region in these devices. The C_{GS} (Vgs) dependence results more complex than what a uniform doping profile would suppose, and confirms the necessity of using a function of exponential nature to properly model the device as it was considered in [7] . For Vgs > 0 V, where Cgs2 and Cgs3 were supposed to be smaller according to the Cgs1 variation with Vgs, Gm2 and Gm3 seems to hide their effects and determine some differences in the extraction. There would have to improve the experimental setup, increasing ω1 and ω2 for instance, in order to avoid Ids derivatives predominance in that region.

There is a lot of work left to do in the reactive nonlinearities characterization if we want to determine their true role in the intermodulation distortion. Along with C_{GS}(Vgs) characterization, it would be relevant to determine the contribution from C_{GD}(Vgd) derivatives as well as the cross terms in the nonlinear distortion performance of these devices, something limited in our case by the diplexer requirements. This results could give us a complete description for the small signal intermodulation distortion in MESFETs and HEMTs, and new approaches to apply linearization techniques.

IV. Conclusions.

An experimental procedure, based on harmonic measurements, is proposed to conveniently extract second and third order reactive derivatives in MESFETs and HEMTs. The characterization results for C_{GS} (Vgs) nonlinearity in a HEMT are presented for the first time, and some important remarks about their behavior are made. The differences detected in the extraction are considered to improve the test setup and the validity of the results for the most critical region.



(a)

(b) (c)

Fig. 3. C_{GS} derivatives extraction for a D02AH with Vds=3V. (a) Cgs1, (b) Cgs2 and (c) Cgs3.

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