A New Compact Nonlinear Model Improvement Methodology for GaN-HEMT

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***Abstract*—The analysis of the nonlinear charge bias dependence according to the input power, with respect to the intermodulation distortion (IMD) product for a GaN-HEMT, is presented. The results obtained from the analysis of the two-tone measurements, are used to determine the GaN-HEMT model deficiencies. An extrinsic non-linear capacitance element is added to improve the accuracy of the core compact model. The simplicity of the measurement procedure and data analysis, makes this a suitable methodology for a good non-linear characterization for GaN-HEMT. A comparison between simulated and experimental data is presented over a $L_m = 0.8\mu m$ GaN-HEMT under different bias and input power conditions to validated the proposed model.**

***Index Terms*—GaN-HEMT characterization, IMD characterization, two-tone measurements, nonlinear effects.**

I. INTRODUCTION

NOWDAYS one of the most promising technologies for the improvement of the RF front-end performance is the GaN high electron mobility transistor (GaN-HEMT) [1]–[5]. This is due to its the high breakdown voltage, high output power figures (P_{out}), high linearity, among others [6]–[8]. The success of the circuit design, from system specifications to package and testing, is determined by the accuracy of the device models [1]. Therefore, procedures and methodologies have to be developed in order to improve the characterization of device and validation of the employed model [1], [9], [10].

Nevertheless, the improvement of the nonlinear device models is based on nonlinear series analysis (mainly Volterra-series) over characteristic I/V and Q/V curves [2], [4], [5], [11]. Thus, if adjacent channel distortion over moderate signal levels is to be minimized, a model capable of accurately reproducing the I/V and Q/V characteristics, at least up to the third order derivative is needed. Considering that I/V and Q/V characteristics curves are strongly dominated by the signal level [2], [12]; the error introduced by the extrapolation to full range of large signal device characteristics is notorious. In addition, the non-linear models are developed according to the signal range employed by the required circuit or system of an specific foundry, which is not always mentioned in the model documentation. Consequently, many works have been done to obtain a nonlinear global model improving the I/V and Q/V curves through extraction or fitting parameters [2], [5], [6], [13]. After doing the improvement in DC or low frequency conditions, the proposed model is validated for high power and frequency operation conditions. Therefore, a comparison between experimental and simulated data using standard harmonic balance (HB) simulator at one or two specific input conditions is done. Because of the adjustment of some of the model parameters values through several measurements and the inclusion of new elements to the core compact model, the previously reported global nonlinear models are to complicated to incorporate in a conventional circuit simulator.

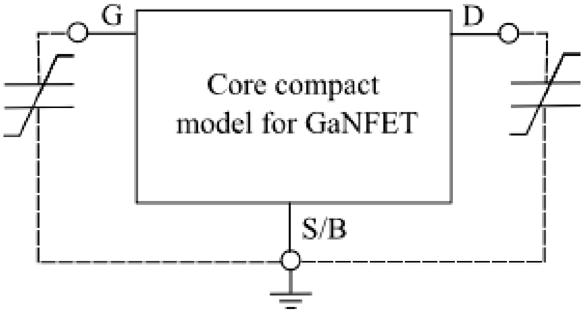

Fig. 1. Proposed non-linear capacitances for the improvement of the IMD calculation

In this paper, the nonlinear model accuracy is improved by adding a extrinsic nonlinear capacitance to the core compact model of a GaN-HEMT (see Fig. 1). The proposed methodology only needs two-tone measurements at several bias conditions while the previously reported global non-linear models needs I/V, Q/V and in some cases S-parameter measurements. Additionally, the proposed methodology use the robustness of the compact model and their parameter extraction given by the foundry, while the previously reported require a partial or complete new extraction procedures. The model improvement shows a good correlation between experimental and simulated data of the IMD for several bias conditions at three different input powers. The model is validated in a $L_m = 0.8\mu m$, $W_f = 200\mu m$, $NF = 2$ GaN-HEMT.

II. MEASUREMENTS

The characterization procedure is based on two tone measurements with $\omega_1 = 1.999GHz$ and $\omega_2 = 2.001GHz$ using a Agilent series spectrum analyzer [14], [15]. The device under test (DUT) was a $L_m = 0.8\mu m$, $W_f = 200\mu m$ and $NF = 2$ common source GaN-HEMT, under several bias (V_{gs} and V_{ds}) and input power conditions (P_{in}). Fig. 2 shows the V_{gs} and V_{ds} bias dependence of the IMD with respect to P_{in}.

For GaN transistors the 2-D space can be substantial because being power devices they can accommodate high

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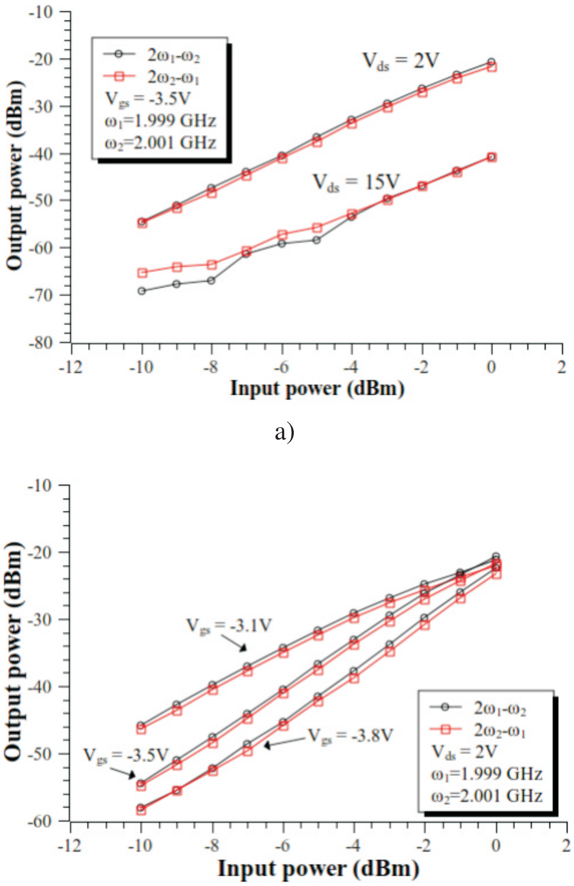

a)

b)

Fig. 2. IMD measurement which shows the bias dependence with a) V_{ds} and b) V_{gs}

voltages for both V$_{gs}$ and V$_{ds}$. For an amplifier employing DS it is preferred that the power of the IMD tones, A$_{2\omega_m-\omega_n}$, generated by the auxiliary transistor(s) exhibit only a moderate variation with respect to bias voltage. This ensures that the distortion-cancelling circuit is robust and sufficiently immune to voltage transients which could degrade the IMD response of the overall system. Thus, the objective of the proposed FET characterization procedure is to quickly and efficiently find a region in the 2-D bias space of the auxiliary transistor where their IMD response is slow-varying. The third-order IMD response of a FET is strongest in its sub-threshold region than in high inversion and the impact of the body effect has to be captured in detail for accurate device modeling.

Taking into account the above observations, the proposed characterization procedure is:

1) Measure the IMD response of the FET at different V$_{ds}$ bias voltages while keeping V$_{gs}$ fixed.
2) Measure the IMD response of the FET at different V$_{gs}$ bias voltages within the sub-threshold and weak inversion region of the device. Meanwhile V$_{ds}$ is kept at a fixed value.
3) Make a 3-D plot of the power of the IMD tones as a function of V$_{ds}$ and V$_{gs}$.

The measurements done in step 2 will reveal the V$_{gs}$ voltages where the FET is most nonlinear and consequently where the strongest IMD tones are produced. The best bias condition for auxiliary FET's in GaN-based circuits employing DS is where the the power of the IMD tones is least sensitive to V$_{gs}$ which leaves V$_{ds}$ as the variable to change. Therefore, the 3-D surface generated in step 3 is inspected to find where the following conditions are met

$$\frac{\partial A_{2\omega_m-\omega_n}}{\partial V_{gs}} \approx 0 \tag{1}$$

$$\left|\frac{\partial A_{2\omega_m-\omega_n}}{\partial V_{ds}}\right| > 0 \tag{2}$$

III. NONLINEAR DEVICE MODEL

The analysis of the measurement procedure begins with the inspection of the behavior of the IMD with the applied voltage at an specific input power. As shown in Fig. 2, a relation between the IMD and bias condition is appreciable. Therefore a mathematical relationship between IMD, V_{gs} and V_{ds} can be estimated. In order to incorporate the experimental trend, an analysis of the I/V and Q/V model equations needs to be done. A common I/V relationship used is: [2]:

$$i_{ds}(v_{gs}, v_{ds}) = \frac{\beta v_{gs3}^2}{1+\frac{v_{gs3}}{V_L}}\left(1+\lambda V_{ds}\right)\tanh\frac{\alpha v_{ds}}{v_{gs3}} \tag{3}$$

where $v_{gs3} = f(v_{gs2})$, $v_{gs2} = f(v_{gs1})$, $v_{gs1} = v_{gs} - V_T$, and α,β and λ are correction factor parameters which are bias dependent. As can be seen from eq. (3), all the adjustment parameters need to be recalculated in order to improve the correlation between experimental and simulation results. This is because, the IMD depends mainly on the coefficients values of the third derivative with respect to the applied voltage. Consequently, the model improvement is more a parameter adjustment procedure that in some cases requires of more adjustment parameters. The same occurs when we try to improve the model through the charge voltage dependence in the device by the adjustment of the Q/V relationship [2]:

$$C_{gs}(v_{gs}) = C_{gs0} + \frac{A_{C_{gs}}}{2}\left(1+\tanh\left[K_{C_{gs}}(v_{gs}-V_{C_{gs}})\right]\right) \tag{4}$$

where C_{gs0} is the capacitance value from gate to source at $V_{gs} = 0V$; $A_{C_{gs}}$, $K_{C_{gs}}$ are adjustment parameters and $V_{C_{gs}}$ is the intrinsic voltage for C_{gs}. Comparing eq. (3) and eq. (4), the procedure of parameter adjustment to improve the accuracy of the model for the IMD is complicated and will not give information about the physical phenomena in the device.

Since the intrinsic compact model can not be improved directly without a complete parameter adjustment, extrinsic elements are used for the insertion of nonlinear effects. In order to determine the influence of V_{gs} over IMD the ∂IMD$/\partial V_{gs}$ at $P_{in} = 0dBm$ is presented in Fig. (3). The large area of ∂IMD$/\partial V_{gs} = 0$ suggest a poor V_{gs} dependence over a wide range of bias conditions. Therefore, nonlinear capacitor is the best option by means of the charge dependence with the applied voltage across this circuit element, while using nonlinear voltage dependent current source will affect the response to the fundamental frequency which is not the goal

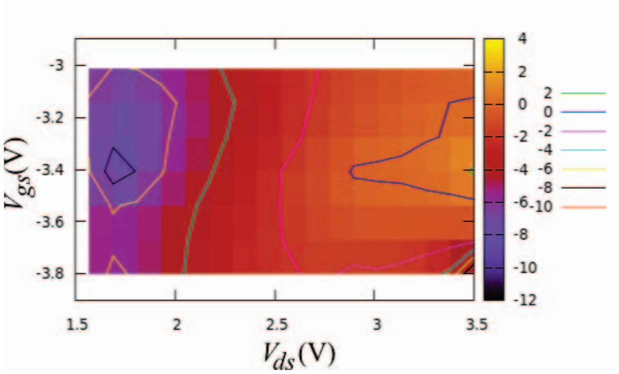

Fig. 3. $\partial\text{IMD}/\partial V_{gs}$ at $P_{in} = 0dBm$ for the determination of the IMD dependence over V_{gs}

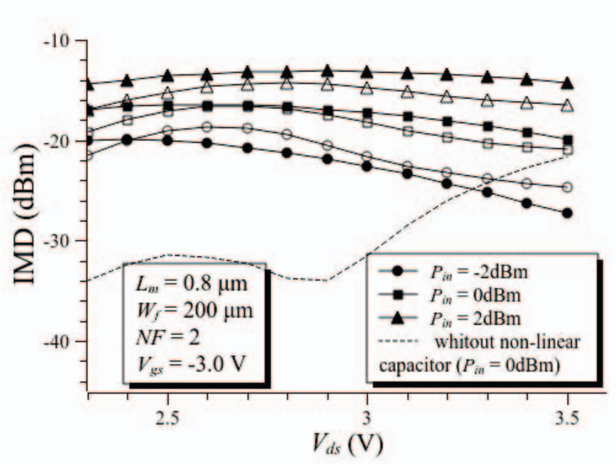

Fig. 4. Comparison of the experimental (filled symbols) and simulated (unfilled symbols) data of the IMD @ $V_{gs} = -3.0V$ for a common source GaN-HEMT under different P_{in} conditions.

of this methodology. As shown in Fig. (1), two capacitors are added at the gate and drain of the compact model to represent the nonlinear charge voltage dependence in each one of the terminals of the device.

IV. RESULTS AND DISCUSSION

As can be see in Fig. (4), good agreement between experimental and simulated data for the IMD, is obtained with the improved model, while without adding the extrinsic elements the model error is notorious. The equation which defines the nonlinear voltage dependence of the extrinsic capacitors is:

$$C_{ks} = C_{ks0} + C_{ks3} v_{ks}^3 \tag{5}$$

where suffix k defines the terminal at which the parameter is evaluated (gate or drain), C_{ks0} and C_{ks3} are the independent and to the third pow voltage dependent coefficients, respectively. The polynomial equation can be expanded to higher powers to improve the nonlinear model for the higher order intermodulated component coefficients. Nevertheless, IMD power is much higher compared with the higher order intermodulated component coefficients, making those more complicated to analyze.

The addition of the nonlinear capacitor is a charge compensation of the intrinsic device compact model. This charge compensation will improve the nonlinear charge dependence with the applied bias conditions. Hence, an analytical procedure can not be applied because is an external adjustment of the compact model nonlinear charge voltage dependence. However, there is important information that can be obtained from the model improvement, as explained here after. The result presented in Fig. (3) is important for the derivative superposition (DS) auxiliary circuit design in high power linear amplifiers, because of the wide range bias independent region. In addition, the improvement of the intrinsic model, only with a nonlinear capacitance, inquires a dominant charge instead of a current dependence of the IMD. Finally, eq. (5), implies a cubic nonlinear voltage dependence rather than hyperbolic (suggested by eq. (4)).

V. CONCLUSIONS

Device characterization of IMD with bias and power dependence was presented. The obtained results and the inclusion of an external nonlinear capacitor to the compact device model, improves the model accuracy. The improvement obtained with the inclusion of the nonlinear capacitor suggest a dominant charge to the third pow voltage dependence of IMD. A good agreement between experimental and simulated data verifies the model accuracy. In order to verify the accuracy of the model in high and low input power, more measurements needs to be done and a improvement in the current model needs to be incorporated. Work is under go in this subject where measurements at different temperature conditions are made in order to identify specific physical effects influencing the nonlinear behavior.

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