Temperature Dependence of Intermodulation and Linearity in GaN Based Devices

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***Abstract* - Gain, intermodulation distortion of an AlGaN/GaN device operating at RF, have been analyzed using a general Volterra series representation. The circuit model to represent the GaN FET is obtained from a physics based analysis. Theoretical current-voltage characteristics are in excellent agreement with the experimental data. For a 1μm x 500μm $Al_{0.15}Ga_{0.85}N$/GaN FET, the calculated output power, power added efficiency and gain are 25 dBm, 13% and 10.1dB, respectively at 15dBm input power and are in excellent agreement with the experimental data. The output referred third order intercept point *IP3* is 39.9dBm at 350 K and 33 dBm at 650 K. These are in agreement with the simulated results from Cadence which are 39.34 dBm and 35.7 dBm, respectively. At 10GHz, third order intermodulation distortion *IM3* for 10 dBm output power is –88 dB at 350K and –82 dB at 650K. At 350K *IM3* is –97dB at 5 GHz and –88 dB at 10GHz. For the same frequencies *IM3* increased to -90dB and -82dB, respectively, at 650K.**

I. INTRODUCTION

Recently GaN based HEMTs are being vigorously pursued for possible applications in microwave circuitry operating at high power and high temperature. The use of these devices for high power applications requires that a nonlinear analysis is carried out. The standard process is to extract the circuit parameters from experimental results for a given circuit topography. This prescription may yield the optimized circuit parameters of any device, for a given topography, but can not be used to design a device for optimized performance. This paper presents a more general analysis procedure based on the Volterra series, which includes interactions between the nonlinear parameters and spectral components at intermodulation frequencies. The analysis is also implemented on CADENCE circuit simulator so that it may readily be extended to more complex networks involving multistage amplifiers

II. NONLINEAR GaN HEMT MODEL

The equivalent circuit of the GaN HEMT is shown in Fig. 1. The output resistance r_{ds}, transconductance g_m and the gate-source capacitance C_{gs} are associated with the non-linearity of the GaN amplifier. The non-linear circuit parameters p (g_m, r_{ds} or C_{gs}) are represented by a power series expansion up to the third term as:

$$p = p_1 + p_2 v_{gs} + p_3 v_{gs}^2 \qquad (1)$$

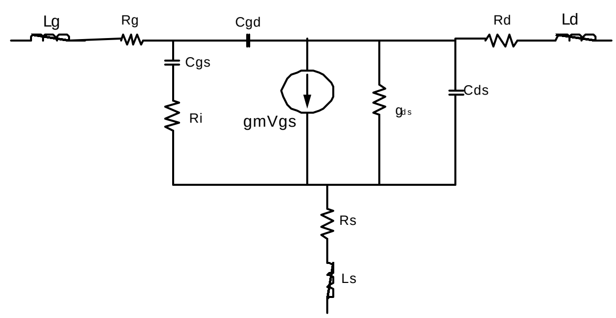

Fig.1. HEMT equivalent circuit model.

The values of the different terms in the power series are shown in Table I. The determination of the intrinsic circuit parameters proceed by first formulating the charge control based upon a self-consistent solution of Schroedinger and Poisson's equations [1]. The incorporation of the mobility and saturation velocity as obtained from an ensemble Monte Carlo simulation, provides the theoretical current voltage characteristics as shown in Fig. 2. The simulation is carried out for a 1μm x 150μm $Al_{0.25}Ga_{0.75}N$/GaN HEMT as reported by Binari et al. [2]. As observed the theoretical results are in excellent agreement with experimental data.

The temperature and bias dependence of the channel electron concentration and the transport parameters make the circuit parameters both temperature and bias dependent. Therefore, circuit non-linearity is not only bias dependent but also is a strong function of temperature. The temperature dependent mobility as obtained from

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ensemble Monte Carlo simulation for a 1μm long sample is: $m_n(T) = -8.7\text{x}10^{-5}\ T^2 - 0.4T + 411$ cm^2/V-s. The above relationship takes into account the effect of non-stationary transport. The saturation velocity decreases from 1.8x10^7 cm/sec at 350K to 1.66x10^7 cm/sec at 650K. With increasing temperature g_m decreases whereas r_{ds} and C_{gs} increases.

III. TEMPERATURE DEPENDENT NONLINEARITY ANALYSIS

The simplified nonlinear circuit of the GaN based HEMT amplifier consists of an input signal source $v_s(t)$ with source impedance $Z_s(f)$ and terminated by the load impedance $Z_L(f)$. Assuming that the nonlinear circuit under consideration can be represented by Volterra series expansion, the output voltage of the amplifier $v_o(t)$ may be expressed as a function of the input signal as:

$$v_o(t) = \int_{-x}^{x} h_1(t_1) v_s(t-t_1) dt_1 + \int\int_{-x}^{x} h_2(t_1,t_2) v_s(t-t_1) v_s(t-t_2) dt_1 dt_2 \quad (2)$$

$$+\int\int\int_{-x}^{x} h_3(t_1,t_2,t_3) v_s(t-t_1) v_s(t-t_2) v_s(t-t_3) dt_1 dt_2 dt_3 + \ldots\ldots\ldots$$

where $h_n(t_1, t_2, t_3, \ldots\ldots, t_n)$ is the nth order Volterra kernel, whose Fourier transfer function $H_n(w_1, w_2, w_3, \ldots\ldots, w_n)$ are the corresponding nth order nonlinear transfer functions in the frequency domain. Assuming low distortion and mild nonlinearities the first three terms of the Volterra series are used to characterize the HEMT.

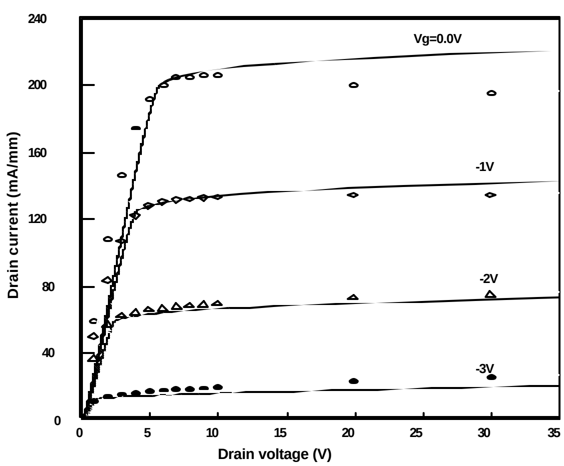

Fig.2. Calculated (solid line) and experimental (dotted) current-voltage characteristics [2].

The first order transfer function $H_1(w_1)$ expresses the linear response of the amplifier in the frequency domain. The second and third order transfer functions $H_2(w_1, w_2)$ and $H_3(w_1, w_2, w_3)$ are expressed in terms of the circuit parameters to investigate nonlinearity.

Intermodulation is defined for the case of two equal amplitude sinusoid signals at the incommensurate frequencies w_1 and w_2 applied to the HEMT input:

$$v_s(t) = V_s \cos w_1 t + V_s \cos w_2 t \quad (3)$$

The in band third order intermodulation products are generated at frequencies $2w_1 - w_2$ and $2w_2 - w_1$.

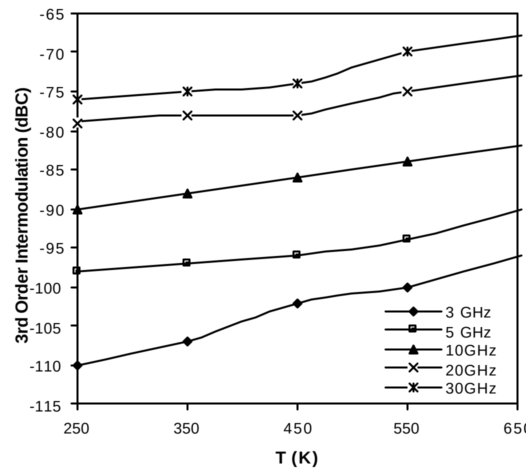

Fig.3.Third order intermodulation as a function of temperature

Second and third order intermodulation distortion (IM_2 and IM_3) are defined as the ratio of the second and third order distorted output power to the fundamental output or desired signal power at w_1 in load. The IM_2 and IM_3 may be expressed in terms of amplifier nonlinear transfer function [5]

$$IM_2 = 20\log_{10}\left[V_s \frac{|H_2(w_1,w_2)|}{|H_1(w_1)|}\right] \quad (4)$$

$$IM_3 = 20\log_{10}\left[\frac{3}{4}V_s^2 \frac{|H_3(w_1,w_1,-w_2)|}{|H_1(w_1)|}\right] \quad (5)$$

TABLE I
PARAMETER VALUES FOR VOLTERRA - SERIES ANALYSIS

Parameter	T=250 K	T=350K	T=450K	T=550K	T=650K
C_{gs1} (pF)	.2275	.2213	.2166	.2457	.262
C_{gs2} (pF)	.0422	.0182	.0045	-.0051	-.0128
C_{gs3} (pF)	.0276	.0086	-.00007	.0003	.0022
g_{m1}(mS/mm)	201.34	180.4	143.18	87.409	61.229
g_{m2}(mS/mm)	14.548	21.083	21.048	19.543	15.343
g_{m3}(mS/mm)	-13.89	-8.875	-3.342	-1.703	-0.753
r_{ds1} (Kohm)	48.457	34.294	23.037	44.409	49.146
r_{ds2} (Kohm)	34.502	14.105	1.885K	28.693	35.462
r_{ds3} (Kohm)	-29.232	-14.114	-4.757	-28.229	-33.661
C_{gd} (pF)	.07	.07	.07	.07	.07
C_{ds}(pF)	.05	.05	.05	.05	.05
R_d (Ohm)	2.5	2.5	2.5	2.5	2.5
R_i (Ohm)	1	1	1	1	1
R_s (Ohm)	1.7	1.7	1.7	1.7	1.7

The third order intercept point defined as the output power at which the intermodulation distortion component equals the fundamental frequency output, when both are extrapolated linearly from low signal levels is expressed as [7]:

$$IP3 = 20\log_{10}\left[\frac{2}{3}\frac{\mathrm{Re}[Z_L]}{\left|Z_L^2\right|}\frac{\left|H_1(w_1)\right|^3}{\left|H_3(w_1,w_1,-w_2)\right|}\right] \qquad (6)$$

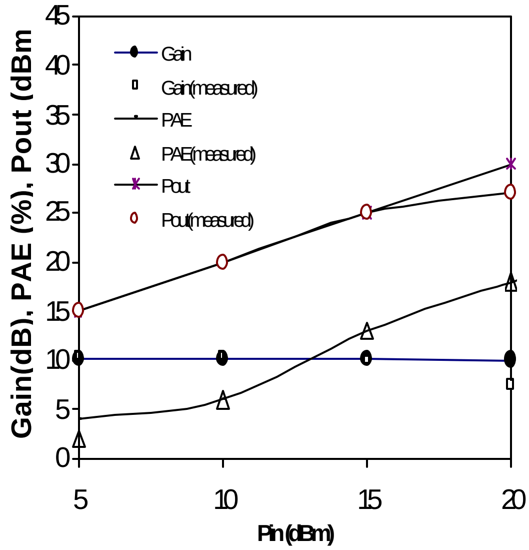

Fig.4. Gain and power added efficiency and output power as a function of input power [10].

IV. PERFORMANCE AND EXPERIMENTAL VERIFICATION

In Fig.3 third order intermodulation distortion have been plotted as a function of temperature. The calculation is for an output power of 10dBm for varying frequencies. The device simulated is 1µm x 1mm $Al_{0.25}Ga_{0.75}N$/GaN HEMT. The third order intermodulation increases with temperature being –107 dB at 350K and –96dB at 650K. The temperature dependence of *IM3* is due to the dependence of *Cgs*, r_{ds} and *gm* on temperature. At higher output power levels the 5th and higher order intermodulation terms contribute resulting in a rapid increase in *IM3*. At a given temperature *IM3* also increases with frequency being –97dB at 5GHz and –75dB at 30GHz.

Fig. 4 shows the calculated gain, power added efficiency and output power for an AlGaN/GaN HEMT. The device considered is a 1µm x 500µm $Al_{0.15}Ga_{0.85}N$/GaN FET [10]. The calculated power added efficiency of 13%, gain of 10.1dB and Pout of 25dBm at 15dBm input are found to be in excellent agreement with experimental data [10]. The temperature dependence of the above quantities is depicted in Fig. 6, for an input power of 15dBm. Power added efficiency decreases from 30% to 4%, gain decreases from 15 dB to 0dB and output power decreases from 30dBm to 15.5dBm for temperature changing from 100K to 600K.

Fig.6.shows the output referred third order intercept point as a function of temperature. The amplifier is fed from a 50 Ω signal source and is terminated with a 50 Ω load. The double tone excitations frequencies are f_1 = 2 and 4

GHz with $f_2 = f_1 + Df$ and Df = 1 MHz. The theoretical third order intercept point (*IP3*) at 2GHz is 39.9dBm at 350 K, which decreases to 33 dBm at 650 K. These numbers are in excellent agreement with the results obtained from CADENCE as seen from Fig. 6. With increasing temperature nonlinearity increases resulting

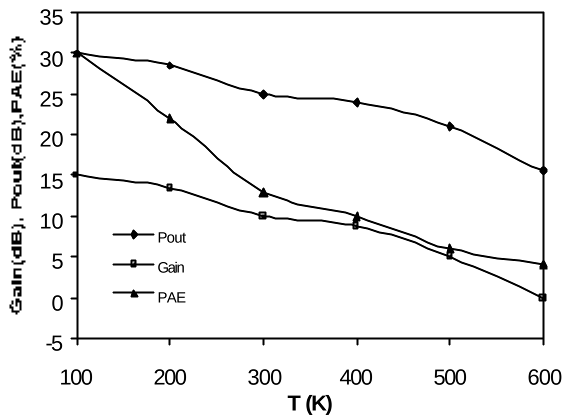

Fig.5. Gain, power added efficiency and output power as a function of temperature

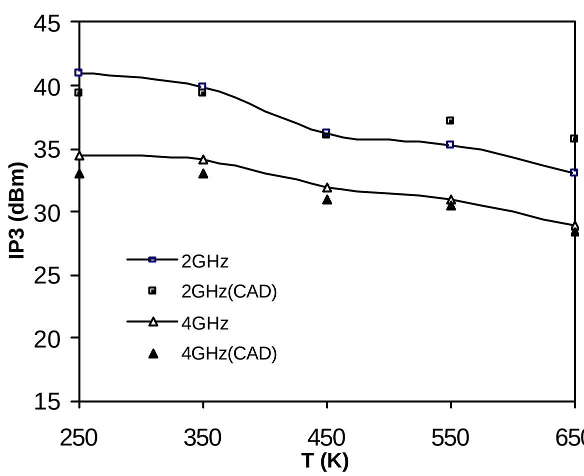

Fig.6. Output referred third order intercept point as a function of temperature

in a lowering of *IP3*. *IP3* at 450K decreases from 36.2 dBm at 2 GHz to 32 dBm at 4GHz and are in excellent agreement with results obtained from Cadence.

V. Conclusion

Intermodulation distortion and nonlinearities in GaN amplifier operating at RF have been analyzed using general Volterra series. Theoretical calculations for gain, PAE and P_{out} at room temperature are in agreement with experimental data. With increasing temperature gain, PAE and P_{out} decreases monotonically. Theoretical IP3 is in excellent agreement with the simulated results obtained from Cadence.

Acknowledgement

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