Two-Tone Intermodulation Distortion Simulations in the Time Domain Using a Quasi-2D Physical pHEMT Model

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***Abstract* — The need for both linear and efficient pHEMTs for modern wireless handsets necessitates a thorough understanding of the origins of intermodulation distortion at the device level. For the first time, two-tone time domain simulations of a microwave pHEMT using a quasi-two-dimensional physical device model in a CAD environment are presented. The model fully accounts for device-circuit interaction and is validated experimentally for a two-tone experiment around 5 GHz.**

I. Introduction

The requirement of linear performance is particularly critical in digital radio where spectral regrowth and in-band distortion are limiting factors in performance. There is an inherent trade-off between maximising efficiency and minimising spectral regrowth and inband distortion. Large peak-to-average ratios mean that amplifiers must have good intermodulation performance. For wireless handsets issues of cost, size and complexity limit the extent to which predistortion and feed-forward linearization can be used. An alternative to this is to optimize device structures for low intermodulation distortion (IMD). The work presented here enables accurate insight into the impact of device structure on linearity. For the first time we present intermodulation distortion results calculated using the Leeds Physical Model (LPM). The very large peak-to-average ratio encountered with a multi-tone input requires extensions to the model to ensure greater accuracy and provide the numerical refinement to extract intermodulation data, especially at low powers.

Equivalent circuit-based models are commonly used to investigate large-signal device performance. However, these models require extensive characterization of the device after fabrication, as well as some knowledge of process variation statistics. For the well-proven physical model used here there is no need for an extensive series of measurements since all the data is provided from the process and physical structure of the device. Equivalent circuit models also suffer from problems associated with curve-fitting errors and discontinuous or inaccurate high order derivatives in current and voltage expressions. This leads to inaccurate predictions of intermodulation distortion. Physical models explicitly solve the semiconductor equations for the device and avoid the problem of an ill-defined relationship between equivalent circuit elements and physical behavior.

In the past, equivalent circuit-based models (such as the Root model [1]) have been extracted by us from multi-bias S-parameter simulations using the physical model in order to examine large-signal behavior [2]-[5]. The present paper extends this previous work by embedding the device model directly in a circuit to account fully for device-circuit interactions. The simulations run on circuit CAD time scales allowing two-tone performance to be assessed for a particular device structure prior to fabrication. Internal device behavior (in terms of electric field, charge etc.) can be examined and related to global device-circuit performance. By this means it is possible to optimize device structures for low distortion. This is critical for devices used in modern wireless mobile communications. To the authors' knowledge this is the first reported two-tone device-circuit simulation carried out on a microwave pHEMT using a fully physical device model. We believe that this is the first step in optimizing device epitaxy and geometry for best combined distortion performance and efficiency. Our ultimate goal is to relate low-level device characteristics to system-level performance parameters such as spectral regrowth, inband distortion and bit error rate [8].

II. The Physical Model

The pHEMT model employed utilises a quasi-two-dimensional (Q2D) carrier transport description, which has previously been reported [2]-[7]. The model requires a description of the geometry and epitaxy of the device and has been used to successfully predict DC, S-parameter and large-signal performance. Thermal effects are also included.

The Q2D model is based on a simplified solution of the following hot electron hydrodynamic transport model,

$$\frac{\partial n}{\partial t} + \nabla.(n\mathbf{v}) = 0 \quad (1)$$

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}.\nabla\mathbf{v} = \frac{q}{m^*}\mathbf{E} - \frac{2}{3m^*n}\nabla(nw) + \frac{1}{3n}\nabla(nv^2) - \frac{\mathbf{v}}{\tau_p} \quad (2)$$

$$\frac{\partial w}{\partial t} + \mathbf{v}.\nabla w = q\mathbf{v}.\mathbf{E} - \frac{2}{3n}\nabla.\left[n\mathbf{v}\left(w - \frac{m^*}{2}v^2\right)\right] - \frac{1}{n}\nabla.\mathbf{Q} - \frac{w - w_0}{\tau_w} \quad (3)$$

Where q represents the charge on an electron and $\nabla.\mathbf{Q}$ represents the energy flux, n is the electron density, $\mathbf{v}$ the electron velocity, $\mathbf{E}$ electric field, m^* effective mass, τ_p and τ_w momentum and energy relaxation times respectively, and w average electron energy. The parameters $m^*(w)$, $\mu(w)$, τ_p and τ_w are all extracted as functions of average energy from characteristics obtained from Monte Carlo simulations for the various material systems.

The model assumes that carrier transport takes place primarily in a plane parallel to the device surface [7]. This assumption is based on results from full 2D simulations, which show that equipotential lines in the undepleted part of the HEMT active channel are almost parallel. This approach has been validated with respect to both measurements and Monte Carlo simulations [7]. A schematic of the model is shown in Fig. 1

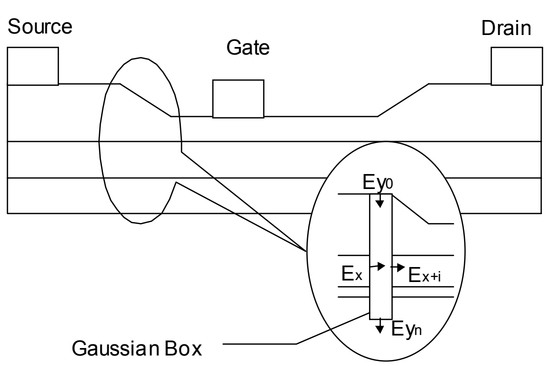

Fig. 1 The quasi-two-dimensional approach to pHEMT modeling

The transport model includes current continuity, energy and momentum equations, allowing us to account for hot electron effects. The charge-control model includes quantum effects and accounts for trapping and injection of electrons into the buffer.

The charge-control model is implemented via a series of Gaussian boxes along the channel as illustrated in Fig. 1. For each Gaussian box the Poisson and one-dimensional Schrodinger equations are solved self-consistently to determine the charge within the box. This is done under a range of conditions and the data stored in a charge-control look-up table. This calculation is time-consuming but only needs to be performed once for a given epitaxial layer structure. The terminal voltages and currents are obtained by stepping along the channel from source to drain and solving the transport equations self-consistently with the charge-control data in the look-up table. In spite of the Q2D nature of the model two-dimensional charge control is retained and the simulation runs over 1000 times faster than full 2D models.

III. SIMULATIONS

To simulate device-circuit performance the Q2D model was embedded in an external circuit model as shown in Fig. 2. The linear networks contain sources, loads, parasitic element networks and bias circuitry. The linear networks were modeled by forming second order linear differential nodal current and voltage equations. These were then discretized in the time domain and the resulting set of simultaneous linear equations solved using Gaussian elimination. The derivatives of the currents and voltages in the linear networks were calculated using a simple backward difference scheme. The trapezoidal method was employed to evaluate integrals.

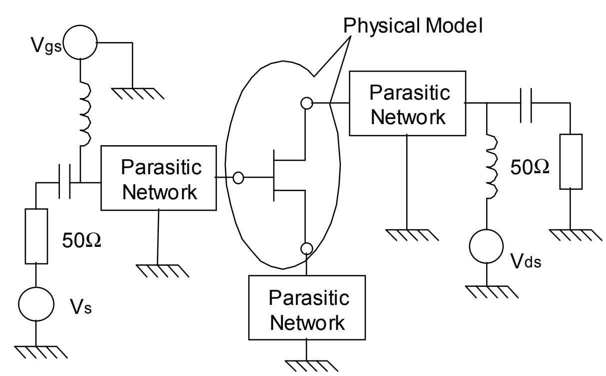

Fig. 2 Schematic of the device-circuit simulation

In order to account for device-circuit interaction the Q2D model equations were solved consistently with those of the linear networks using a Newton-Raphson scheme. Careful attention was paid to the size of time step used to ensure an efficient and stable solution. Large time steps were used for the first few time points. The time step size is subsequently reduced as the simulation progresses.

Care must be taken in choosing the resolution of the charge-control look-up table. A coarse mesh results in 'spikes' in the currents and voltages at the device terminals for large signals. This is due to the fact that a large signal will traverse a greater range of the look-up table than a small signal. On the other hand a very fine mesh is expensive in terms of simulation time and data storage.

Convergence is rapid, with simulations taking, on average, 0.6 CPU seconds per time point on a 450 MHz Pentium III workstation with 64 Mb of RAM. Steady state is reached typically within 100 time points.

IV. Model Validation and Results

In order to validate the model a 6×60μm double recessed pHEMT with 0.23μm gate length was measured and simulated. The device was terminated with 50Ω source and load impedances and biased with V_{ds}=3V and V_{gs}=-0.2V in class A configuration. Two-tone measurements and simulations were performed with tones at 4.75 GHz and 5.25 GHz. Fig. 3 shows fundamental output power against available input power for the tone at 4.75 GHz. Excellent agreement between measurements and the model is achieved across the range of input powers. Agreement is within 0.5 dB through a broad range of input powers into 4.5 dB of gain compression.

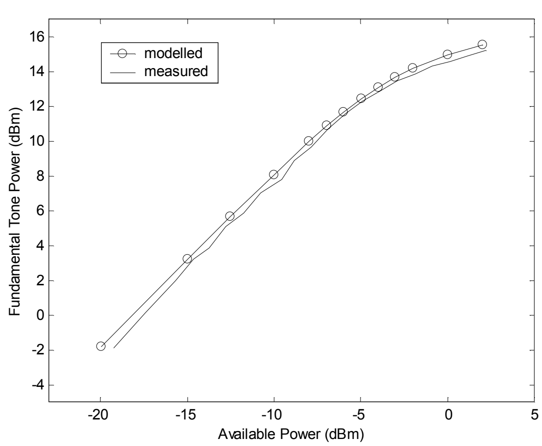

Fig. 3 Fundamental output power at 4.75 GHz against available input power for two-tone test with tones at 4.75 GHz and 5.25 GHz

If we let f_1=4.75 GHz and f_2=5.25 GHz, it can be shown that the biggest problem distortion products for circuit designers are caused by third order intermodulation products at $2f_2$-f_1 (5.75 GHz) and $2f_1$-f_2 (4.25 GHz), along with fifth order products at $3f_2$-$2f_1$ (6.25 GHz) and $3f_1$-$2f_2$ (3.75 GHz).

Fig. 4 shows third order intermodulation distortion results (data taken at 5.75 GHz). Modeled and measured results show excellent agreement. The results are within approximately 1 dB throughout the range of input powers but agreement is very good well into compression. Fig. 5 shows fifth order distortion results (data taken at 6.25 GHz). Again, there is excellent agreement across the full range of input powers with the maximum discrepancy around 1 dB. The results correspond especially well in the region of gain compression. The agreement between modeled and measured results across a range of powers and at significant frequencies was found to be excellent. Not only are the results very close but the general shape of the responses are remarkably similar. To the authors' knowledge these represent some of the best multi-tone results obtained with either physically-derived, empirical or measurement-based models. The results suggest that phenomena that significantly affect large-signal performance (such as hot electron effects, gate conduction, trapping etc.) are well modeled and that the physical model used here is suitable for large peak-to-average-ratio multi-tone simulations.

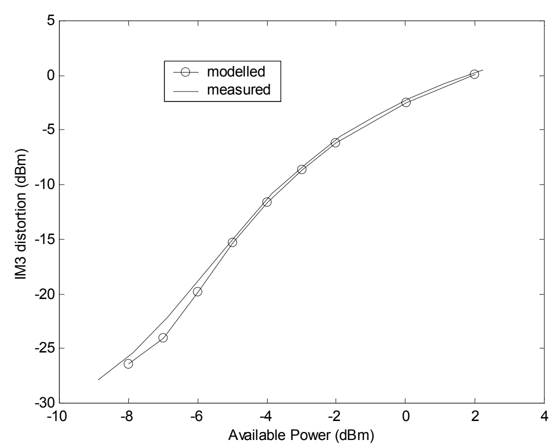

Fig. 4 Measured and modeled third order intermodulation distortion against available input power at $2f_2$-f_1=5.75 GHz

Fig. 6 shows the simulated voltage across the load at the output of the transistor for a two-tone signal. The origin of IMD can be seen in the compression of the envelope peaks. We can see the classic beat pattern of two-tone signals. The waveform is smooth even at the peaks where excursions into the highly nonlinear knee and pinch-off regions occur. Note also the asymmetry in the waveform, indicating different modes of distortion in the knee and pinch-off regions.

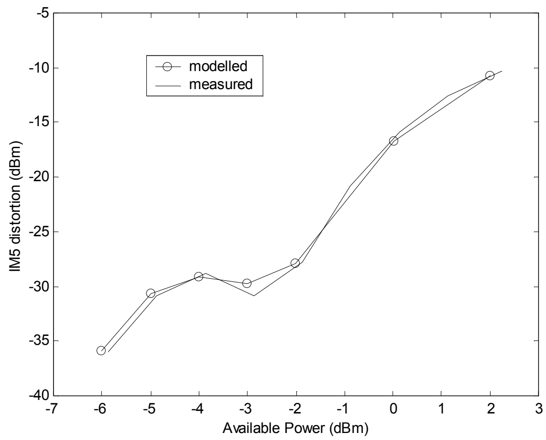

Fig. 5 Measured and modeled fifth order intermodulation distortion against available input power at $3f_2$-$2f_1$ =6.25 GHz

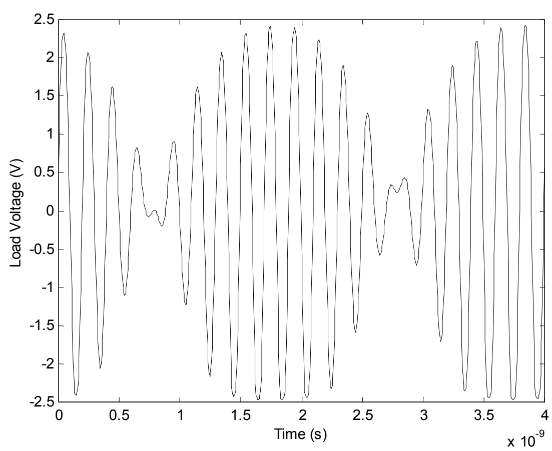

Fig. 6 Simulated distorted two-tone load voltage

V. Conclusion

An accurate, fully physical, simulator for CAD has been presented which is capable of simulating pHEMT intermodulation performance based on a description of device epitaxy and geometry. Simulated two-tone results have been presented which agree very well with measured data into gain compression of up to 4.5 dB. The authors believe that these are among the best results presented for multi-tone simulations using either physically-derived, measurement-based or empirical models for microwave pHEMTs. Using the model it is possible to examine internal device behavior such as charge or electric field variations along the channel as a function of time. This allows us to relate device level behavior to global device-circuit performance.

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