Advanced Meander Gate p-HEMT Model for Accurate Harmonic Modeling of Switch MMIC Designs

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Abstract — **This paper presents a non-linear model of a meander gate p-HEMT for switch design. The model combines a modified Parker-Skellern IV form with a custom charge model to accurately predict large signal performance of meander-gate based switches. Comparison between modeled and measured results of a 0.5 mm gate length SPDT switch shows a accurate prediction of the 2nd and 3rd Harmonic generation at the output.**

Index Terms — **Design Automation, Microwave switches, MMICs, Mobile Communication, Modeling.**

I. INTRODUCTION

Large signal models have become increasingly important for the design and development of high performance switches for telecommunications systems. Insertion Loss, Isolation and Harmonic Distortion are greatly affected by non-linear effects within the p-HEMT at high drive levels [1]. An effective large signal switch model should accurately predict the transition from the device operating in a linear regime to the non-linear accurately showing the degradation of Insertion Loss and the increase in Harmonic Generation.

Both the TOM3 [2] and Parker-Skellern [3] models produce good current-voltage (I-V) and charge fits in the saturated regime (for amplifier operation) but do not produce good results around Vd = 0V (the switch operating condition). Also the TOM3 model offers less control of the low field resistance required for accurate switch modeling. In order to develop a more accurate switch model a hybrid approach is discussed. Combining the good IV performance of the Parker-Skellern model with a symmetric charge model and custom diode model in order to optimize performance around the switch operating point.

Within this paper we will discuss the development of a model designed to accurately predict non-linear interactions with p-HEMT based switches.

II. CURRENT MODEL EXTRACTION

The first stage in developing the model for the Filtronic meander gate switch process was to decide on a suitable models form for the fitting of the DC-IVs. The modeling of switch isolations (which commonly can be below 40dB) requires the DC model to accurately map the transition from the ON state through threshold into the sub-threshold (OFF state). Earlier models [4] had a discontinuity at the threshold point that causes problems with models that are dependent on the OFF impedance of the device. More recent models use an exponential form in the sub-threshold region allowing a good correlation between the modeled switch performance and the measured device. This is shown in the equation that

$$V_{GT} = V_{ST}\left(1 + M_{VST}V_{DS}\right)\cdot \ln\left(1 + e^{\left(\frac{V_{GST}}{V_{ST}\left(1+M_{VST}V_{DS}\right)}\right)}\right)$$

controls the cut off mode:
where M_{VST} is the sub threshold modulation, V_{ST} is the sub-threshold potential, and V_{DS} is the drain to source voltage.

The Parker-Skellern (PS) model also has the distinct advantage over other more recent models, for switch modeling, is that it includes two parameters to model the low field resistance. This allows independent tailoring of the IV curves around V_D = 0V to give the correct impedance and saturation knee.

Modifying the Parker Skellern Model

The first stage in developing a model that better fits the switch performance was to modify the form of the IV characteristics of the PS model. A switch model does not require thermal effects (because the FET is operated in a cold state) the thermal term of the function was removed. This modifies the i_{DS} within the PS model from:

$$i_{DS} = \frac{i_D}{1+\delta P}$$

to:

$$i_{DS} = i_D$$

where i_{DS} is the total drain to source current, i_D is the calculated current before thermal effects, P is the total power (given by $V_{DS}.i_{DS}$), and δ is thermal reduction coefficient.

Dispersion, if present, is low around Vd = 0V [5] the decision was made to remove the dispersion relations from the PS Current equations. This has the effect of simplifying the current equations to the form:
where Q is the saturated region power exponent and V_{DT} is given by:
here Z is the Knee transition factor, and V_{DP} and V_{SAT} are

$$i_D = \beta\left(V_{GT}{}^{Q} - \left(V_{GT} - V_{DT}\right)^{Q}\right)$$

given by:

$$V_{DT} = \frac{V_{SAT}}{2}\left(\sqrt{\left[\frac{V_{DP}\sqrt{1+Z}}{V_{SAT}{}^{2}}+1\right]^{2}+Z} - \sqrt{\left[\frac{V_{DP}\sqrt{1+Z}}{V_{SAT}{}^{2}}+1\right]^{2}+Z}\right)$$

$$V_{SAT} = \frac{\xi\left(\phi_B - V_{TO}\right)V_{GT}}{\xi\left(\phi_B - V_{TO}\right)+V_{GT}}$$

$$V_{DP} = V_{DS}\,\frac{P}{Q}\left[\frac{V_{GT}}{\phi_B - V_{TO}}\right]^{P-Q}$$

where ξ is the saturation knee potential factor, ϕ_B is the gate junction potential, and VTO is the threshold voltage and P (linear region power law exponent) and Q (saturated region power law exponent) give the advantage within the PS model of being able to independently adjust the low-field resistance and the saturated regime. This allows an accurate representation of the of the IV curves within the switch operating regime.

III. DIODE MODELING

The standard PS model employs standard single diode exponential forms. The effects of leakage current can dominate in the switches OFF regime this requires a more detailed diode model. A better model for a p-HEMT is a double exponential form. In order to approach this effect the gate-junction diodes were modeled as a network of diodes and resistors to better improve the model fitting. (see figure 1)

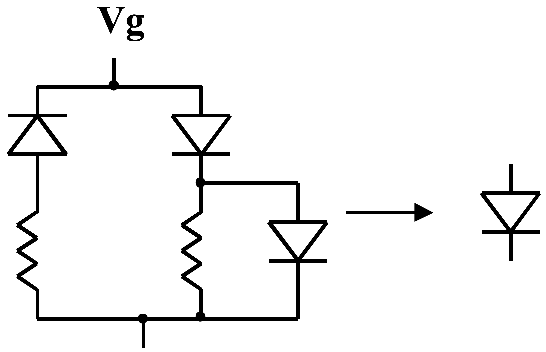

Fig. 1. Modified diode model showing the network of diodes and resistors needed to accurately represent the HEMT diode performance in both the forward and reverse biases

This model employs two different diodes with different saturation currents and ideality factor coupled with a single resistor in order to better represent the diode IV curve in the forward bias. The reverse bias is dealt with using a single diode and resistor combination in order to allow better control of the reverse bias breakdown. The effective fit to measured diode behavior is shown and contrasted with the original diode form in Figure 2.

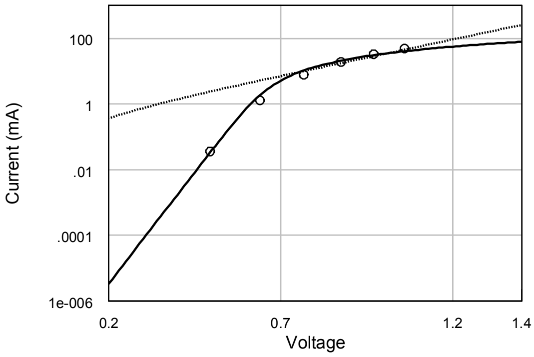

Fig. 2. Comparison of the standard diode model (dotted line) with the proposed modified diode model (solid line) and measured results (circles).

This modified model gives a good fit to the actual HEMT diode performance.

Combining these two models using the equivalent circuit shown in figure 3 gave good fits to measured IVs (figure 4)

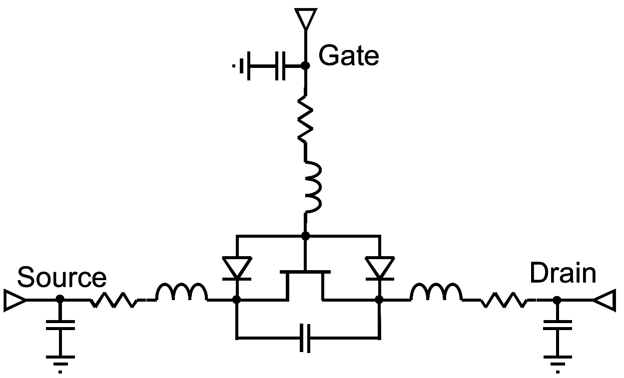

Fig. 3. Equivalent circuit used to model the meander gate p-HEMTs. The FET is modeled using a reduced form of the Parker-Skellern model and the diodes are a combination of several components including a non-linear charge model (see above)

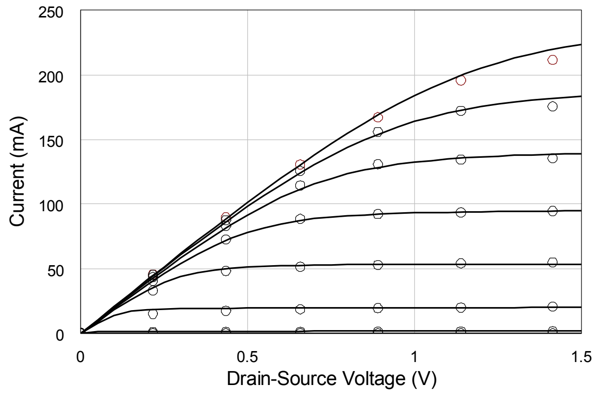

Fig. 4. Modeled (solid black line) vs. Measured (circles) data showing a good fit between the modified Parker-Skellern form and the measured data

IV. DIODE CHARGE MODELS

The final part of the non-linear model is to provide a good charge model for the gate-source/drain junction. The charge model provided in the PS model cannot accurately model the charge around $V_{DS} = 0V$. Therefore a custom model was employed to fit the charge form.

The charge build-up in switch operation is essentially symmetric allowing the capacitive contribution of the gate-source junction and the gate-drain junction was assumed to be equal. The equivalent capacitances at different gate voltages were then extracted from the Y-parameters. Figure 5 shows the measured capacitance data. The diode junction capacitance does not exhibit the standard power form within GaAs based p-HEMTs. This is because the charge layer stops the expansion of the depletion layer.

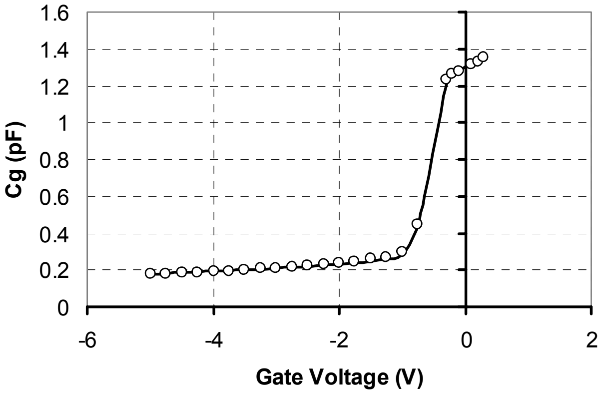

Fig. 5. Modeled (solid black line) vs. Measured (circles) junction capacitance showing the tanh form allows a good fit to the charge over the entire operating regime.

This has the effect of causing a plateau in the capacitance around Vg=-0.5V. This has a significant effect on the modeling of harmonics and hence it is important to accurately model this form. The capacitance form chosen in this case is given by:

$$C_{total} = C_{diode} + C2\left(1 + \tanh\left(\alpha\left(V - V_p\right)\right)\right)$$

where C2 scales the height of the plateau, α controls the slope of the change of the tanh, and V_p sets the point at which the tanh function changes from –1 to 1. C_{diode} is given by the standard SPICE diode capacitance equation [6] and has the form:

$$C_{diode} = C_{j0}\left(1 - \left(\frac{V}{V_j}\right)\right)^{-m}$$

where C_{j0} is the junction capacitance at V = 0V, V_j is the junction potential, and m is the grading parameter. This combined form gives a good fit to the observed device performance (Figure 5)

V. LARGE SIGNAL PERFORMANCE

The main test of a large signal model is its performance modeling non-linear effects at large drive currents. In order to test this model it was compiled into a Microwave Office component then simulations were then run on a SPDT switch and compared to measured results. The switch comprised of two 0.5 mm meander gate p-HEMTs connected to the input power arm. Insertion loss and

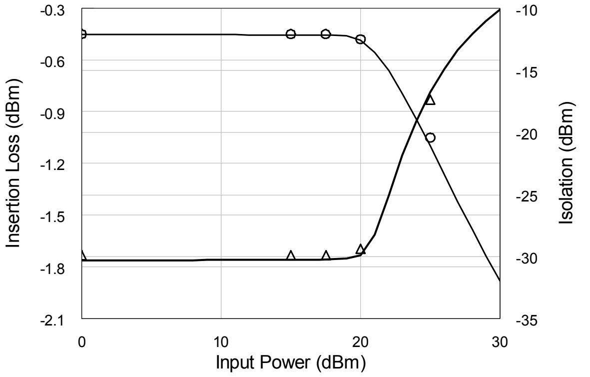

Fig. 6. Shows the effect of increasing input power on Insertion loss (modeled - solid line; measured - black dots), Isolation (modeled – dotted line; measured black triangles)

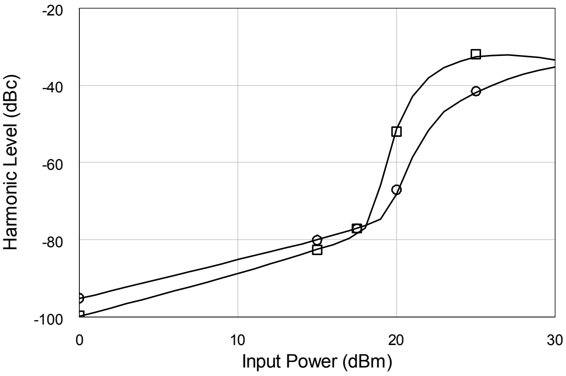

Fig. 7. Shows the effect of increasing input power on 2nd Harmonics (modeled - solid line; measured - circles) and 3rd Harmonic (modeled – dotted line; measured - squares). Values are in dBc referenced to the fundamental output.

isolation are then measured at the ports of the off and on arms.

As input power increases the non-linear effects begin to degrade the switch performance. Compression and increasing non-linear capacitances act to reduce the isolation and increase the thru insertion loss. Figure 6 shows the change in insertion loss and isolation of the switch with increasing input power. The model accurately predicts the changes in isolation and input power showing a good correlation between modeled and measured results.

VI. HARMONIC GENERATION

The final part of the modeling involves comparing the measured harmonic generation of the switch with the modeled harmonics. Harmonic generation is notoriously difficult to model accurately because many different factors of the model effect the final result Figure 7 shows the modeled vs. measured results from the switch model. A good correlation in achieved between measured and modeled with only a 4% error at 25dBm input power on the 2nd Harmonic and a 2% error on the 3rd Harmonic. The slight errors are caused by slight imperfections in the model fitting to the non-linear capacitance and the IVs.

VII. CONCLUSION

A model of meander-gate p-HEMTs for use as microwave switches has been proposed. By modifying the current Parker-Skellern model and adding a improved charge form within the regime of interest good correlation with measured results has been achieved.

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