A Large-Signal GaAs MESFET Model for Nonlinear Circuit Simulation

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***Abstract*— A GaAs MESFET large-signal model suitable for use in time-domain circuit simulation CAD tools such as PSPICE has been developed. The improved model includes accurate analytic representation of the transconductance and conductance dependence upon the operating voltages. The new model gives better fit to GaAs MESFET I-V characteristics over a wider bias voltage range compared with the Curtice quadratic model. It also provides a simpler and more efficient parameter acquisition procedure in comparison to the TriQuint model. The procedure for extracting the model parameters using the bias dependence of the small-signal elements is also described.**

I. Introduction

A NUMBER of current-voltage relationships have been proposed for large signal modeling the GaAs MESFET [1]–[5]. Among the widely used models are those proposed by Curtice [2], Statz (Raytheon) [3] and McCamant (TriQuint model) [4]. The Curtice quadratic model fails in predicting the nonlinear dependence of the transconductance upon the gate voltage, V_g [3]. The Statz model provides more accurate representation of the nonlinear dependence of the transconductance on the gate voltage compared to Curtice model. Unfortunately, it fails to predict the drain conductance variation with the drain to source voltage V_{ds} [4]. The TriQuint model overcomes this problem by reformulating the Statz model and provides an improved fit to the small-signal elements over a wider bias range at the expense of additional fitting parameters. However, both models suffer from the complexity in their parameters extraction procedure. The model proposed by Maas [5], addresses the poor fit between the measured and predicted higher order derivatives in earlier models [1]–[2].

In this investigation, a new current-voltage model is described. The new model provides a good fit for both the linear and saturation regions compared with the quadratic Curtice model. Beside its simple and compact form, the model parameter acquisition procedure is particularly efficient and more expeditious compared with the TriQuint model. Additionally, we describe a simple procedure for the extraction of the model parameters from the bias dependence of the elements of the small-signal model. Furthermore, the improved model has been implemented in PSPICE and used in the simulation of a single ended mixer.

Manuscript received October 29, 1991. This work was supported by the Center for Design of Analog-Digital Integrated Circuits at Washington State University.

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IEEE Log Number 9107678.

II. The New Model

The new large-signal model has been developed with the objective of providing an accurate representation of the measured I-V data, and assuring convergence to steady-state conditions during time-domain transient analysis. The model is developed from the experimentally determined bias dependence of the small-signal device elements *(quasistatic model)* and involved s-parameter measurements over a frequency range 0.1 to 3.0 GHz and optimization of the small signal parameters at several bias points [6], [7]. The empirical equation chosen for this model is a modification to the ones proposed by Curtice and TriQuint and is given by

$$I_{ds} = \beta(V_g - V_t)^Q(1 + \lambda V_{ds})\frac{1 - e^{-\alpha V_{ds}}}{1 + ke^{-\alpha V_{ds}}}, \qquad (1)$$

where β, Q, λ, α, and k are fitting parameters, and V_t is the threshold voltage. This equation reduces to the Curtice model [2] with k and Q set equal to 1 and 2, respectively. In this equation, the parameter Q is necessary to model the nonlinear dependence of the transconductance on gate voltage, and the nonsquare law dependence of the drain current. This parameter was also reported in the TriQuint model. The the noninteger values of the parameter Q results in higher order derivatives that are different from those of the earlier models [2]–[3]. For example, the values of Q for 1×300 μm depletion and enhancement MESFET's, were 1.72 and 2.15, respectively. The new model parameter k is chosen to address the poor fit at the curve knee and at the saturation region (see Fig. 1). The values of the parameter k were very small (typically $7.8 \times 10^{-6} \approx 0$) for the enhancement ($1 \times 300$ and 1.5×450 μm) and depletion (1×300 and 1×450 μm) TriQuint QED process MESFET's that were investigated. These MESFET's have a recessed gate structure and a buried p-layer which significantly reduce the effects of surface states and the traps in the substrate which are responsible for the low frequency dispersion problems [8]. Fig. 1 illustrates the good agreement between the predicted I-V characteristics by the new model and measured I-V data for the 1×300 μm depletion and enhancement MESFET's. A comparison between the measured and modeled transconductance as a function of the gate to source voltage at $V_{ds} = 2.5$ V is shown in Fig. 2. This demonstrates that the model keeps track of the measured transconductance values over a wide range of gate to source voltages.

The implementation of this model in PSPICE or other circuit simulation tools requires the specification of the model parameters β, λ, α, Q, and k. These are determined in this

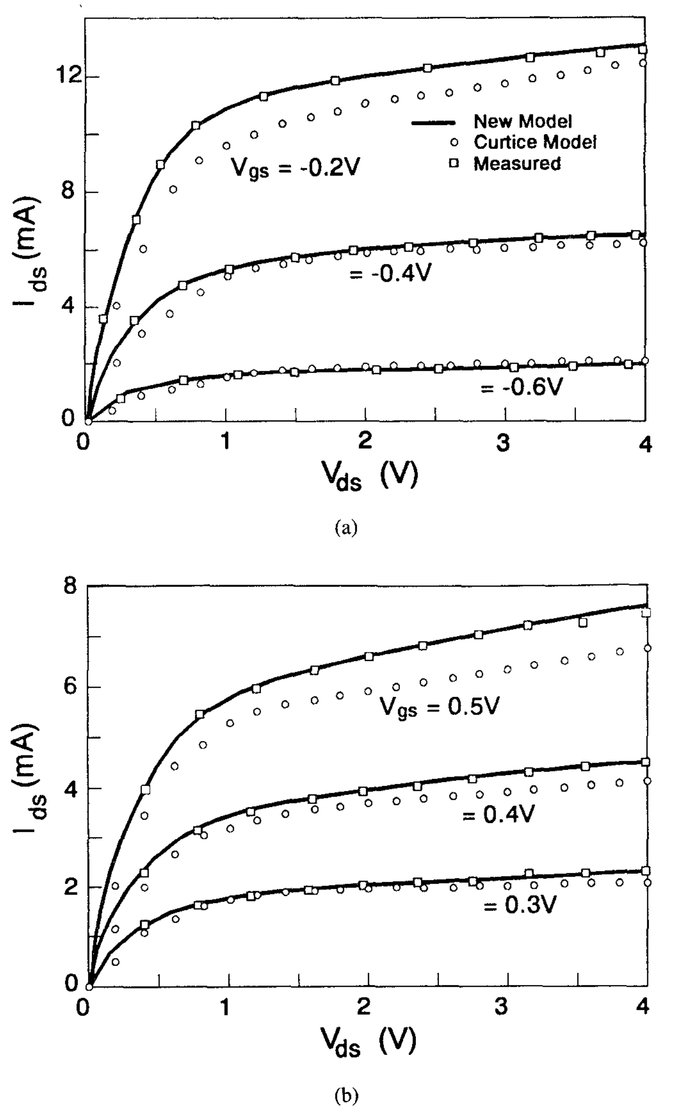

Fig. 1. Comparison between measured (open circles) and new model prediction (solid lines) I-V data for: (a) depletion, (b) enhancement GaAs MESFET's.

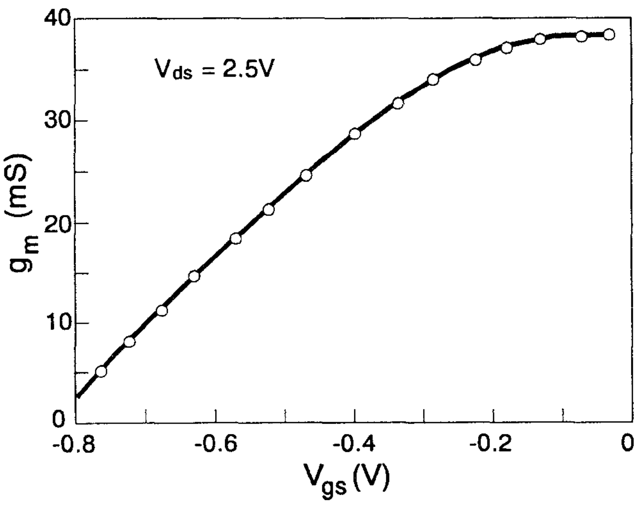

Fig. 2. Plot of measured (open circles) and modeled (solid line) transconductance as a function of gate voltage.

work from the bias dependence of the small-signal transconductance and conductance following the procedure proposed by O'Callaghan and Beyer [9]. In this approach, the previous expression for the drain current is expressed as a product of two single-variable functions:

$$I_{ds} = P_g(V_g)P_d(V_{ds}), \tag{2}$$

where

$$P_g(V_g) = \beta(V_g - V_t)^Q \tag{3}$$

and

$$P_d(V_{ds}) = (1 + \lambda V_{ds})\frac{1 - e^{-\alpha V_{ds}}}{1 + ke^{-\alpha V_{ds}}}. \tag{4}$$

Additionally, at a given operating drain to source voltage, V_{dso}, the function $P_d(V_{dso})$ is set equal to one. This amounts to equating the function P_g to the values of the transfer characteristics. The parameters β and Q are then determined by fitting the values of the transconductance measured at V_{dso} for several values of V_g to the expression $\frac{\partial P_g}{\partial V_g}$. On the other hand, the parameters λ, α, and k are determined by fitting the measured values of the conductance at the operating gate voltage, V_{go}, for several values of bias voltage V_{ds} to the expression $P_g(V_{go})\frac{\partial P_d}{\partial V_{ds}}$ subject to the condition $P_d(V_{dso}) = 1$. Any simple nonlinear least square program could be used for the determination of these parameters. This extraction procedure provides a decoupling between the I-V model and its derivatives resulting in a good agreement with the real device behavior [6], [7]. Additionally, it can be used for MESFET's with dispersive transconductance and conductance, where the only required device measurements are the RF characteristics [7]. Also, the extraction method is suitable for circuit designers since the model parameters are determined from the above measurements only. Furthermore, the model could be implemented by the user in circuit simulation tools such as PSPICE and SABER, which allow users to define their model equations.

III. Simulation Results

The previous model was implemented in PSPICE and used in simulating two prototype circuit examples. The values of the model parameters used in these simulation were: $\beta = 0.0264\ \mathrm{A/V}^Q$, $Q = 1.7219$, $\alpha = 2.98$/V, $\lambda = 0.0486$/V, and $k = 7.8 \times 10^{-6}$, with $V_t = -0.9$ V. In the first example, the objective was to compare the simulation time of the present model with those of Statz and TriQuint models using an inverter circuit and the PSPICE circuit simulation tool. The total simulation times, using a Digital DECstation 5000, taken by Statz, TriQuint, and the current model were 1.57, 1.73, and 1.65 seconds, respectively. It is evident that the new model results in a minor reduction in the simulation times compared to the TriQuint model. This advantage could be more significant as the number of transistors increase in the simulated circuit. In the second example, a single-ended gate mixer was simulated using the conversion matrices approach proposed by by Maas [10]. In Fig. 3, the values of the simulated conversion gain at $V_{ds} = 3$ V are shown for several

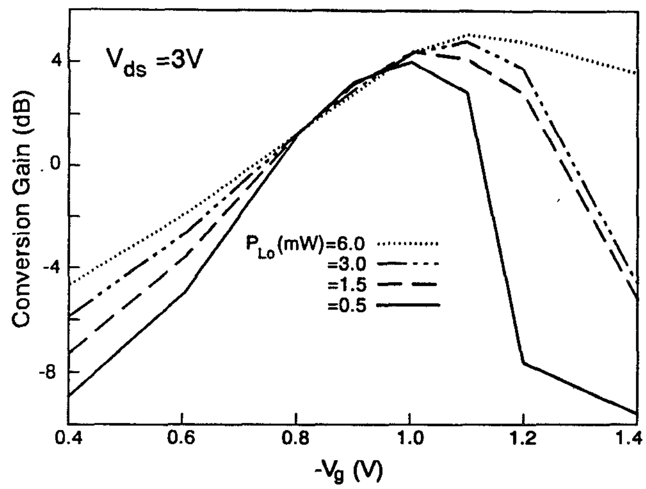

Fig. 3. Single-ended gate mixer conversion gain as a function of gate voltage for different local oscillator power drive ($\omega_{lo} = 7$ GHz, $\omega_{RF} = 8$ GHz, $\omega_{IF} = 1$ GHz).

values of gate voltage, and local oscillator power, P_{LO}. It can be seen that for optimum conversion gain, the device should be biased near pinch-off ($V_g = -0.9$ V). This result confirms the conclusion reported previously by Maas [10] and the model accuracy. The full assessment of the present model's ability to predict correct intermodulation distortion levels is beyond the intended scope of this letter.

IV. Conclusion

We have presented a new MESFET large-signal model that provides better fit to measured I-V data compared to the Curtice quadratic model and is capable of accurately predicting the transconductance and conductance dependence on the bias voltages. Furthermore, compared to the TriQuint model, the present model has a compact form with a minor improvement in simulation times by about 5%. A simple procedure for determining the model parameters from the bias dependence of the small-signal elements was described. Model based circuit simulation examples using PSPICE with the present model were also discussed.

Acknowledgment

The authors are thankful to Drs. J. Beyer, J. O'Callaghan, N. S. Dogan, S. Maas, and D. Schrader for their useful discussions and assistance.

References

[1] A. Materka, T. Kacprzak, "Computer calculation of large-signal GaAs FET amplifier characteristics," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 129–135, Feb. 1985.
[2] W. R. Curtice, "A MESFET model for use in the design of GaAs integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 448–456, May 1980.
[3] H. Statz *et al.*, "GaAs FET device and circuit simulation in SPICE," *IEEE Trans. Electron Devices*, vol. ED-34, pp. 160–169, Feb. 1987.
[4] A. J. McCamant, G. D. McCormack, and D. H. Smith, "An improved GaAs MESFET model for SPICE," *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 822–824, June 1990.
[5] S. A. Maas, "Modeling MESFET's for intermodulation analysis of mixers and amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 12, pp. 1964–1971, 1990.
[6] C. Rausher and H. A. Willing, "Simulation of nonlinear FET performance using a quasistatic model," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 834–840, Oct. 1979.
[7] A. K. Jastrzebski, "Non-linear MESFET modeling," *Proc. 17th European Microwave Conf.*, 1987, pp. 599–604.
[8] P. H. Ladbrooke, *MMIC Design: GaAs FET's and HEMT's.* Norwood, MA: Artech House, 1989.
[9] J. M. O'Callaghan and J. B. Beyer, "A large-signal nonlinear MODFET model from small signal *s*-parameters," *IEEE Microwave Theory Tech. Symp. Dig.*, 1989, pp. 347–350.
[10] S. A. Maas, "Theory and analysis of GaAs MESFET mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1402–1406, Oct. 1984.