Modeling MESFETs for Intermodulation Analysis of Resistive FET Mixers

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Abstract: **This paper describes a new method for calculating intermodulation distortion in resistive FET mixers. By utilizing an expression for the *I/V* characteristics of the MESFET device whose parameters are fit to the static *I/V* and its derivatives, this model accurately predicts distortion and is the first of its kind to be shown valid for resistive FET mixers.**

I. Introduction

In recent years, as part of a general effort towards improving the design of nonlinear circuits, engineers have labored to understand intermodulation distortion (IM) in mixers. An outgrowth of this work was the proposal of a new type of mixer, called a resistive FET mixer [1], that uses the resistive channel of a MESFET to provide frequency conversion with substantially less distortion than either diode or active FET mixers. Although this idea has gained popularity in the past few years, very little work has been done in calculating distortion in these mixers.

The availability of general-purpose harmonic-balance and Volterra-series simulators has generated a need for accurate nonlinear models of GaAs MESFETs, and many FET models have been proposed. Most of these models are not valid for passive FETs [2], [3], and missing from those that do apply is an assessment of the properties of a model that are necessary for the accurate calculation of IM [4], [5]. Models are usually designed to reproduce the FET's static current-voltage (*I/V*) and charge-voltage (*Q/V*) characteristics when, in fact, the derivatives of those characteristics are dominant in determining IM levels. A recently introduced model for the MESFET gate *I/V* characteristic (the dominant nonlinearity in most FETs) is accurate through at least the third derivative [6] and can be utilized in the distortion analysis of resistive FET mixers.

II. Modeling GaAs MESFETs

The modeling of intermodulation distortion in mixers is beset by a number of subtle problems that largely do not occur in the distortion analysis of amplifiers or conversion analysis of mixers. It was shown recently that modeling *n*th-order IM in mixers requires that the device's model reproduce accurately the first *n* derivatives of its *I/V* and *Q/V* characteristics over its entire voltage or current range of operation [2]. In a resistive FET mixer, the channel is used as a gate-voltage-controlled resistor, and its *I/V* characteristic is necessarily a function of two voltages, the gate-to-source and drain-to-source voltages. In this case it is necessary that the model reproduce not only the derivatives of the drain current with respect to these control voltages, but also the partial derivatives of the current with respect to both voltages. The fundamental difficulty lies in accurately modeling all of the terms in a two-dimensional Taylor-series expansion of the drain current.

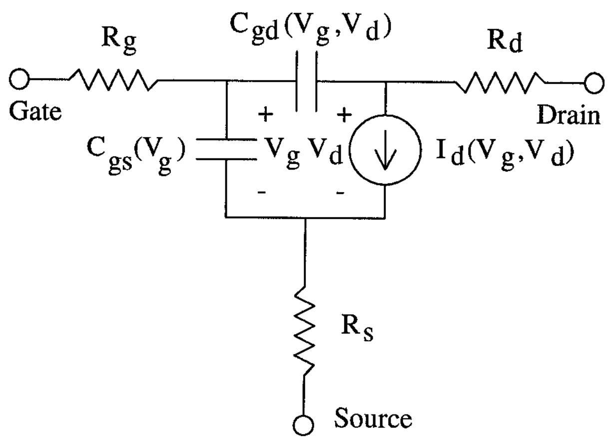

Figure 1 Equivalent circuit of a GaAs MESFET operated at zero drain voltage.

In the formulation of an accurate model to predict distortion in RF FET switches, a new technique for modeling a passive FET's drain current was introduced [6]. This model is based upon measurements performed on the nonlinearity of the FET conductive channel as discussed in

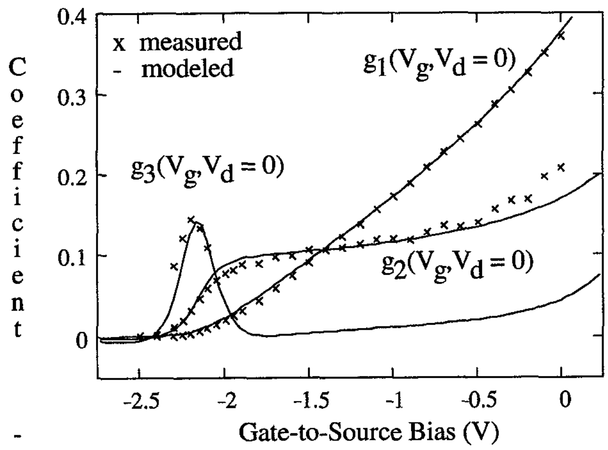

Figure 2 Measured (x) and modeled (-) Taylor-series expansion coefficients of the *I/V* characteristic of an NEC NE72084 MESFET. The device parameters are I1 = 0.49 A, V_p = 2.94 V, ϕ = 0.8 V, $R_d = R_s$ = 0.55 Ω, α = 4, β = 1.5, γ = 0.0093, δ = -0.0023 and ε = 0.0014.

[2], [7], and how these measurements relate to the Taylor-series expansion coefficients ($g_1(V_g,V_d)$, $g_2(V_g,V_d)$, and $g_3(V_g,V_d)$) of the drain current. Figure 1 shows the resulting equivalent circuit of a MESFET without drain bias voltage. R_g is the gate resistance, and R_d and R_s are the parasitic drain and source resistances. The drain current is $I_d(V_g,V_d)$, a function of both the gate and drain voltages:

$$Id(Vg,Vd) = I1\left[\frac{3\beta\ Vd}{Vp} - 2\left[\left[\frac{\beta\ Vd - Vg + \phi}{Vp}\right]^{\frac{3}{2}} - \left[\frac{-Vg+\phi}{Vp}\right]^{\frac{3}{2}}\right]\right]F(Vg,Vd) + \gamma\, Vd + \delta\, Vd^2 + \varepsilon\, Vd^3$$

where

$$F(Vg,Vd) = \frac{1}{2}\left[1 + \frac{2}{\pi}\,\mathrm{atan}\left[\alpha\,(Vg - Vd + Vp - \phi)\right]\right]$$

Because the drain is unbiased, the gate-to-channel capacitance is divided approximately equally between the gate-to-source and gate-to-drain capacitances. These are modeled as ideal Schottky-barrier capacitances, with uniform epitaxial doping:

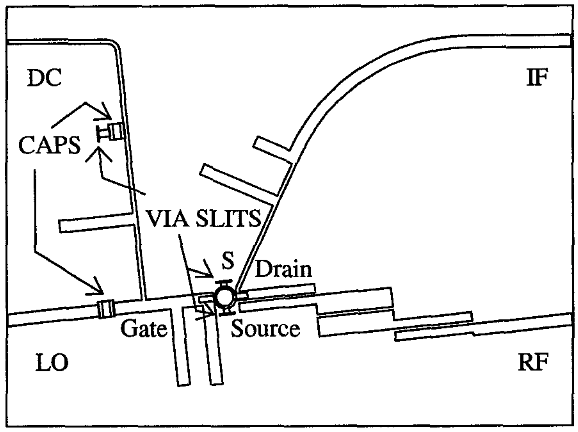

Figure 3 Drawing of the single-ended resistive FET mixer circuit.

$$Cgs(Vg) = Cgd(Vg,Vd=0) = \frac{Cgo}{\sqrt{1 - \frac{Vg}{\phi}}}$$

where

$$Cgo \cong Cgso \cong Cgdo$$

Figure 2 compares the measured and modeled Taylor-series expansion coefficients of the *I/V* characteristic of an NEC NE72084 MESFET. In order to obtain an accurate representation of the *I/V* expression and all its derivatives, we fit this model to the measured $I_d(V_g,V_d)$ and its derivatives by adjusting the parameters of the device (I1 = 0.49 A, V_p = 2.94V, ϕ = 0.8 V, $R_d = R_s$ = 0.55 Ω, α = 4, β = 1.5, γ = 0.0093, δ = -0.0023, and ε = 0.0014). Note that the sensitivity of the test set-up limits the measurable power levels and thus the measurable data points for g_3.

III. Results

We installed this model into HP's general-purpose, harmonic-balance program Microwave Design System (MDS) to simulate the performance of the single-ended resistive FET mixer shown in Figure 3. The mixer was realized on microstrip substrate (RT Duroid 5870) utilizing the layout option available on MDS. Note that the package parasitic components as provided by the manufacturer were also included in the simulations. The LO and RF frequencies of 6.3 and 7.3 GHz, respectively, when applied to the mixer provided IF output power at 1, 2, and 3 GHz. These single-tone IM products are relatively easy to measure, and they test the properties of the model as well as more conventional two-tone measurements. Because the sole purpose of this circuit was to obtain experimental verification of the model's

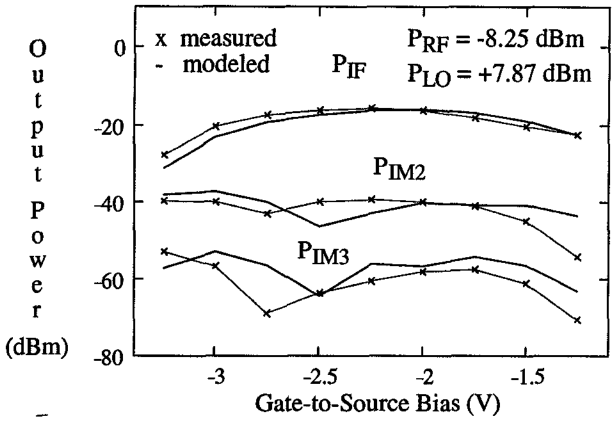

Figure 4 Intermodulation levels in the resistive FET mixer as a function of gate bias. The RF and LO frequencies are 6.3 and 7.3 GHz. The FET model parameters are as shown in the caption of Figure 2. The IF, IM2, and IM3 power levels are measured at 1, 2, and 3 GHz, respectively.

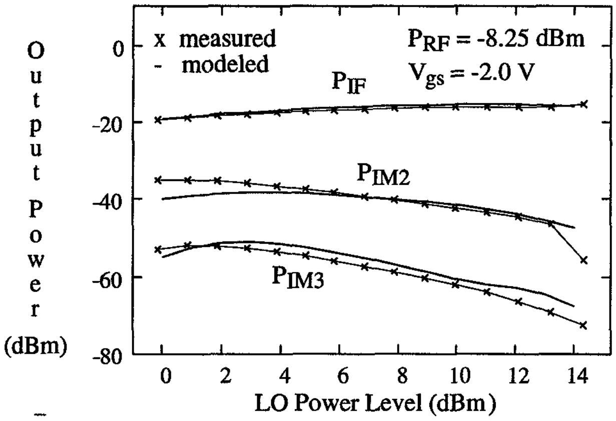

Figure 5 Intermodulation levels in the resistive FET mixer as a function of LO power level. The RF and LO frequencies are 6.3 and 7.3 GHz. The FET model parameters are as shown in the caption of Figure 2. The IF, IM2, and IM3 power levels are measured at 1, 2, and 3 GHz, respectively.

validity, no attempt was made to achieve any particular performance goals.

Figures 4 and 5 show the measured and modeled power levels at the IF output as a function of the gate bias (with P_{LO} = +7.87 dBm) and the LO power level (with V_{gs} = -2.0 V), respectively, at an RF input power of -8.25 dBm. The agreement between measured and calculated data shown in these figures is probably within the combined effects of experimental error and the calculations' convergence errors. The worst agreement exists in Figure 4 where we notice that the two sets of curves consistently appear shifted with respect to the gate bias. A closer look at Figure 2 reveals that a similar difference exists for

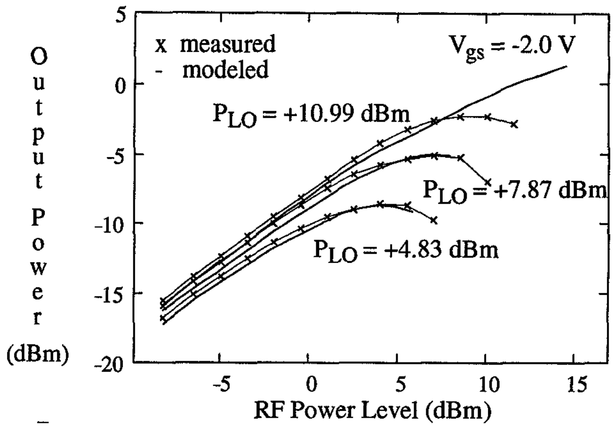

Figure 6 IF output power in the resistive FET mixer as a function of RF input power at several LO drive levels. The RF and LO frequencies are 6.3 and 7.3 GHz, respectively. The FET model parameters are as shown in the caption of Figure 2. The IF output power is measured at 1 GHz.

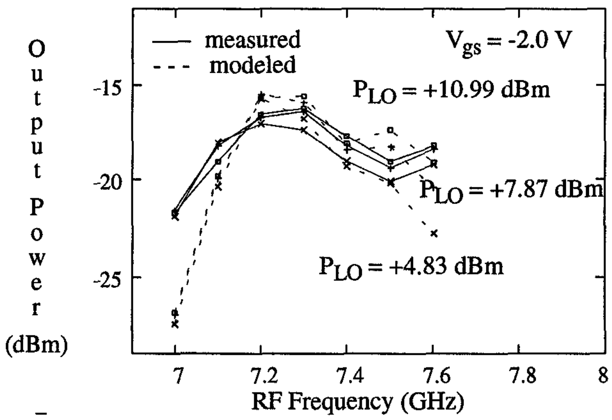

Figure 7 IF output power in the resistive FET mixer as a function of RF frequency at several LO drive levels. The RF and LO frequencies are 6.3 and 7.3 GHz, respectively. The FET model parameters are as shown in the caption of Figure 2. The IF frequency is held constant at 1 GHz.

g_3, the third Taylor-series expansion coefficient. This model is also capable of providing a description of additional frequency components observed at the IF output; the largest of which are located at the LO, RF, LO+RF, and 3LO frequencies.

The model is also capable of providing additional important performance data. Figure 6 shows the mixer's response to an increase in RF input power for several LO drive levels (with V_{gs} = -2.0 V). The agreement between measured and modeled data verifies that the model is capable of calculating the 1-dB compression point except at large RF and LO power levels (when our modeling assumption of $V_{ds} \cong 0$ is no longer valid). Figure 7 compares the measured and modeled bandwidth performance of the mixer when the IF frequency is held constant at 1 GHz (with V_{gs} = -2.0 V and P_{RF} = -8.25 dBm). Additional information about the mixer was also calculated including: isolation, return loss, and bandwidth (for constant LO frequency). The correlation for these performance characteristics was definite but not as impressive.

IV. Conclusion

A new method for calculating intermodulation distortion in resistive FET mixers has been described. This technique utilizes an expression for the *I/V* characteristics of the MESFET device whose parameters are fit to the static *I/V* and its derivatives. The results show that this model is not only useful for distortion calculations but also provides a means to calculate other mixer characteristics such as: compression, bandwidth, isolation, and return loss.

Acknowledgment

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