Direct Nonlinear FET Parameter Extraction Using Large-Signal Waveform Measurements

A. Werthof, F. van Raay, and G. Kompa

***Abstract*—A new method is presented which permits a direct nonlinear FET parameter extraction of the drain current generator and the gate source capacitor from large-signal waveform measurements. For demonstration, the high frequency characteristics of the nonlinear drain current generator for a GaAs-MESFET and a MODFET are extracted. Significant differences between the dc and RF characteristics are observed and interpreted.**

I. Introduction

The SIMULATION and design of nonlinear microwave circuits require reliable large-signal FET models. The parameters for the nonlinear FET models which are implemented in commercially available nonlinear circuit simulators are usually extracted from the measured dc or pulsed dc characteristics and from the S-parameters [1]. The approximation of the nonlinear characteristics with analytical functions and the neglection of the differences between the dc and RF characteristics of the drain current generator can lead to inaccurate simulation results [2].

In [3], a method has been proposed which additionally takes into account the RF output power spectra measured under large-signal operating conditions. The coefficients of analytical functions used to model the FET nonlinearities are fitted to match not only the measured dc characteristics and S-parameters but also the RF output power spectra. This approach is based on the assumption that the analytical functions are appropriate to describe the S-parameters, the dc and the nonlinear RF characteristics simultaneously which often may suffer from the FET low frequency dispersion effects.

To overcome these limitations, we follow a new extraction concept that allows a direct nonlinear FET parameter extraction without the necessity of the previously mentioned assumptions. Precisely measured voltage and current spectra transformed from the outer to the inner FET reference planes are used for the analysis of the measured nonlinear RF characteristics of the voltage controlled drain current generator.

II. Nonlinear Deembedding Procedure

The fundamental data of the proposed extraction method are the dc characteristics, the S-parameters of different dc bias points and the voltage and current spectra in the outer FET gate and drain reference planes for different dc bias points, RF input power levels and fundamental frequencies. The FET voltage and current spectra ($\underline{V_{GS}}, \underline{I_{GS}}, \underline{V_{DS}}, \underline{I_{DS}}$) were measured in a large-signal waveform measurement system [4] with 40 GHz harmonic bandwidth. The FET small signal equivalent circuit elements were obtained by a highly consistent extraction method described earlier in [5]. The bias dependent small signal equivalent circuit elements (g_m, G_{ds}, C_{gs}, C_{gd}, τ, R_i) were extracted from the S-parameters of 320 different dc bias points, interpolated with 2-D splines and transformed to the inner FET voltage planes V_{gs} and V_{ds} shown in Fig. 1.

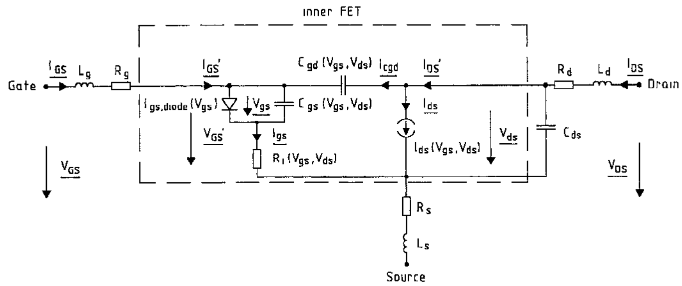

Fig. 1. Large-signal FET equivalent circuit model.

The transformation of the measured voltage and current spectra from the outer to the inner FET reference planes starts with a deembedding of the linear equivalent circuit elements (R_g, R_d, R_s, L_g, L_d, L_s, C_{ds}). The measured spectra are transformed for each dc bias point, RF input power level and frequency component through the linear elements. After the transformation, the measured spectra ($\underline{V_{GS}'}, \underline{I_{GS}'}, \underline{V_{ds}}, \underline{I_{DS}'}$) of the nonlinear inner part of the FET equivalent circuit model (Fig. 1) are available. The gate source diode is approximated with the PN diode model. The corresponding parameters are extracted from the complex signal spectra measured under gate forward operating conditions in a harmonic balance process considering bias dependent equivalent circuit elements C_{gs}, R_i, and C_{gd}.

With the parameters of the gate source diode and the bias dependent incremental values of C_{gs} and R_i known, the control voltage V_{gs} over the gate source capacitor C_{gs} can be derived from the measured gate voltage spectra $\underline{V_{GS}'}$ with a harmonic balance solution of the equation

$$0 = V_{gs} + R_i(V_{gs}, V_{ds})\, I_{gs} - V_{GS}' . \tag{1}$$

The current $I_{gs,C_{gs}}$ through the gate source capacitor C_{gs} can be calculated from the measured gate current spectra $\underline{I_{GS}'}$ with a deembedding of the gate drain capacitor C_{gd} and the gate

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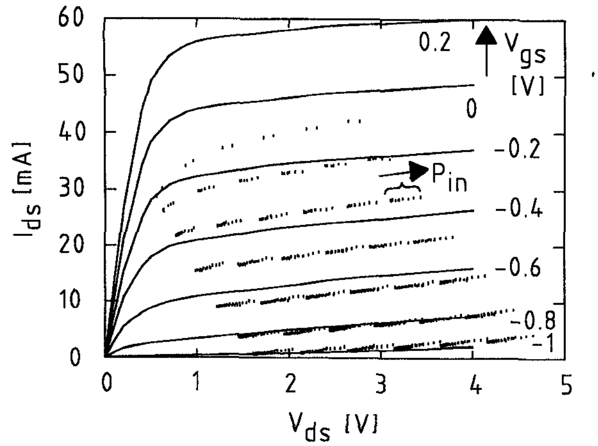

Fig. 2. Measured dc (—) and RF (··) characteristics of the nonlinear MESFET drain current generator (FSX03, $V_{GS,\mathrm{dc}} = -0.8$ V).

source diode,

$$I_{gs,Cgs} = I'_{GS}+C_{gd}(V_{gs}, V_{ds})\frac{d(V_{ds} - V'_{GS})}{dt}-I_{gs,\mathrm{diode}}\,. \quad (2)$$

The current of the gate drain capacitor is calculated as the product of the bias dependent incremental C_{gd} values with the derivative of the measured differences between the gate and drain voltages with respect to the time. The characteristic of the gate source capacitor is calculated from the deembedded measured gate voltage and current spectra using the equation

$$C_{gs}(V_{gs}, V_{ds}) = I_{gs,Cgs}/(d V_{gs}/dt)\,. \quad (3)$$

The measured drain current spectra $\underline{I'_{DS}}$ are corrected for the current through the feedback capacitor C_{gd},

$$I_{ds} = I'_{DS} - C_{gd}(V_{gs}, V_{ds})\frac{d(V_{ds} - V'_{GS})}{dt}\,. \quad (4)$$

The effect of the control voltage V_{gs} on the drain current generator is taken into account by a nonlinear time delay $\tau(V_{gs}, V_{ds})$. The control voltage

$$V_{gs}(t_i - \tau(V_{gs(t_i)}, V_{ds(t_i)})) = \mathcal{F}^{-1}(\underline{V_{gs}}\, e^{-j\omega\tau(V_{gs}(t_i),V_{ds}(t_i))}) \quad (5)$$

can be calculated in the time domain for each time sample t_i.

The construction of the nonlinear RF drain current generator characteristics has been accomplished by analyzing the deembedded signal waveforms for different input power levels and dc bias points. To permit a direct comparison with the measured dc characteristics, the evaluation has been carried out for defined values of the instantaneous gate control voltage V_{gs}. The corresponding values of the output voltage V_{ds} and the drain current I_{ds} are determined from the deembedded waveforms at the specific time points at which the gate control voltage has reached the defined values. The extracted characteristics are the real effective under large-signal operating conditions. They can be directly implemented in a large-signal FET model or utilized to analyze the validity not only of analytical but of arbitrary functions which are used to calculate the RF drain current characteristic as a function of the measured inner voltage spectra $\underline{V_{gs}}$ and $\underline{V_{ds}}$.

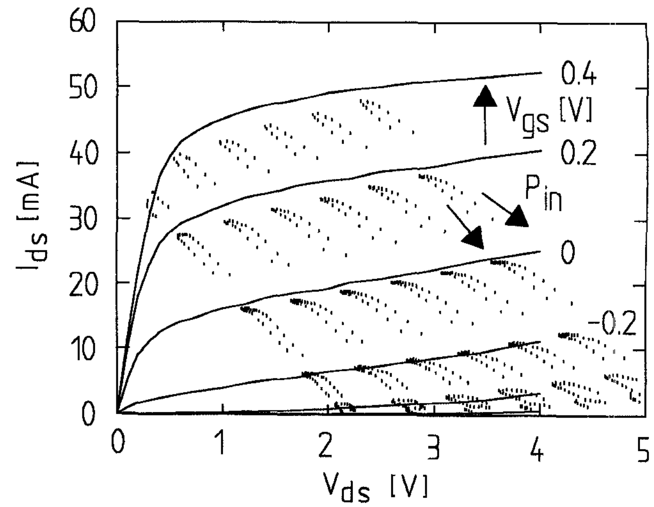

Fig. 3. Measured dc (—) and RF (··) characteristics of the nonlinear MODFET drain current generator (JS8902, $V_{GS,\mathrm{dc}} = 0$ V).

III. Measured Examples

The voltage and current spectra of a GaAs-MESFET of type Fujitsu FSX03 were measured for 102 different dc bias point/input power level combinations. The measurements are based on a fundamental frequency of 1 GHz, a constant dc gate bias voltage ($V_{GS,\mathrm{dc}}=-0.8$V), several dc drain bias voltages ($V_{DS,\mathrm{dc}}$ = 1.5 V, 2 V, 2.5 V, 3 V, 3.5 V, 4 V) and 17 RF input power levels ($P_{in} = -9$ dBm, $\cdots(1)\cdots$, 7 dBm). Fig. 2 shows the measured dc and RF characteristics of the nonlinear drain current generator for defined inner gate voltages. The grouping of I_{ds} values for every defined gate voltage follows from the selected six drain dc bias voltages. The widening of each group is a result of an input power dependent dc bias point shift. The RF behavior agrees with the dc characteristic only for instantaneous gate voltages in the vicinity of the gate bias value ($V_{gs} = -0.8$ V). An increasing deviation can be observed with growing difference between instantaneous and bias voltages which can be traced back to low frequency dispersion phenomena [2]. The measured RF characteristics of the nonlinear drain current generator result from a superposition of the dc current in the bias point and a RF current that can be calculated from an integral of the incremental bias dependent RF transconductance $g_{m,RF}$ and channel conductance $G_{ds,RF}$ in the V_{gs} and V_{ds} voltage plane [6]. The RF drain current characteristic of the GaAs-MESFET has a significant dependence on the dc bias point but shows only a small shift with the RF input power level.

Similar measurements were carried out on a MODFET of type Toshiba JS8902 for the operating conditions $f_0 = 1$ GHz, $V_{GS,\mathrm{dc}} = 0$ V, $V_{DS,\mathrm{dc}}$ = 1.5 V, 2 V, 2.5 V, 3 V, 3.5 V, 4 V, $P_{\mathrm{in}} = -10$ dBm, $\cdots(1)\cdots$, 6 dBm. Fig. 3 shows the measured dc and RF characteristics of the nonlinear drain current generator for defined inner gate voltages. The dc and RF currents agree for low RF input power levels ($V_{gs} = 0$ V) as it has been observed with the MESFET. Conversely to the MESFET results, the measured RF current of the MODFET nonlinear drain current generator is strongly dependent on the RF input power, it decreases with increasing input power levels. This behavior acts like a pinch-off voltage shift with increasing RF input power and is not implemented in large-signal FET models which are based on analytical functions or use the integral of $g_{m,RF}$ and $G_{ds,RF}$ to calculate the RF drain current. The simulations using a consistent dc to RF large-signal FET model [7] confirm the assumption, that the input power dependency results from the differences between the dc and RF transconductances of the drain current generator when the parasitic MESFET channel conduction occures.

IV. Conclusion

We presented a new method for the direct extraction of the voltage dependent nonlinear FET drain current generator and gate source capacitor from large-signal waveform measurements. The measured RF characteristics of the nonlinear drain current generator illustrated the differences between the dc and RF characteristics. It was demonstrated that the nonlinear RF drain current characteristic of a MODFET depends strongly on the RF input power level. The proposed method is a valuable instrument for the analysis of the real high-frequency FET nonlinearities and can be helpful in the improvement of large-signal FET models.

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