A NOVEL EXTRACTION METHOD FOR THE HIGHER ORDER COMPONENTS OF CHANNEL CURRENT IN A GaAs MESFET

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ABSTRACT: *A novel extractionion method has been proposed for direct extract of the higher order Taylor coefficients of the channel current I_{ds} (V_{gs}, V_{ds}) in a GaAs MESFET. Low-frequency (45 and 70 MHz) two-tone signals are employed to measure the harmonic component, and the load impedance was properly designed to find the cross terms. A Volterra series analysis is used for the formulation of Taylor series coefficients of the nonlinear channel current. This proposed parameter extraction procedure is simple and straightforward. The extracted current model is utilized successfully for intermodulation analysis.* © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 29: 114–117, 2001.

Key words: *MESFET; nonlinear model; channel current; Volterra series*

I. INTRODUCTION

Volterra series analysis has been a common technique used for the prediction of the distortion properties of weakly coupled nonlinear circuits. This analysis is superior, in terms of conversion efficiency in numerical simulation, to the harmonic balance or the time-domain methods [5].

In using the Volterra series method, the nonlinear components are represented by the Taylor series expansion form. In a GaAs MESFET, the most significant nonlinear source is the channel current I_{ds}. The Taylor expansion form of the channel current is given by Eq. (1). In this equation, all of the Taylor coefficients of the channel current are dependent on the bias voltages:

$$\begin{aligned} i_{DS}(v_{GS}, v_{DS}) = {} & I_{DS}(V_{GS}, V_{DS}) \\ & + G_m \cdot v_{gs} + G_d \cdot v_{ds} \\ & + G_{m2} \cdot v_{gs}^2 + G_{md} \cdot v_{gs} v_{ds} + G_{ds} \cdot v_{ds}^2 \\ & + G_{m3} \cdot v_{gs}^3 + G_{m2d} \cdot v_{gs}^2 v_{ds} \\ & + G_{md2} \cdot v_{gs} v_{ds}^2 + G_{d3} \cdot v_{ds}^3 \\ & + \cdots \end{aligned} \qquad (1)$$

where I_{DS} is the bias current and v_{GS}, v_{DS} are $V_{GS} + v_{gs}$, $V_{DS} + v_{ds}$, respectively. v_{gs}, v_{ds} are the small-signal gate and drain voltage, respectively, and V_{GS}, V_{DS} are the dc bias points of the MESFET. Many works for extracting the high-order Taylor coefficients of $I_{ds}(v_{gs}, v_{ds})$ in Eq. (1) have been reported [1–6]. A parameter set for Eq. (1) had been adjusted by a least square fit to the measured S-parameters at several bias points [4] or to microwave two-tone test data [2]. These methods are inaccurate due to the measurement error and insufficient data in the fitting process. Recently, more advanced methods based on the low-frequency harmonic measurements were proposed [1, 5]. These methods have the merits that the measurement errors are small, and the coefficient in Eq. (1) can be analytically extracted. However, the Maas method [5] cannot represent the cross terms of I_{ds}, i.e., a transconductance variation with v_{ds} and an output conductance variation with v_{gs}. To extract the cross terms, there should be a sufficient independent measurement. Pedro and Perez [1] reported a method of the more accurate harmonic component measurement technique. In this method, the independent measurement was performed by applying a signal to the gate side, and the other one to the drain side. But the Pedro method is very complex because the measurement system should have a high-power source at the drain side and a very high-performance duplexer to reject the leakage of harmonics generated from the large signal source. That is, this method has difficulties with the measurement of the intermodulation power from the drain side.

A new simple measurement system for the higher order channel current terms has been developed [2]. The experimental setup shown in Figure 1 is a usual two-tone test, composed of low-frequency two-tone signals, a power combiner, a bias circuit at the input port, and a load impedance at the output port. Here, the load impedance should be carefully designed to separate the cross terms. In the setup shown in Figure 1, $V_{s1}(\omega_1)$ and $V_{s2}(\omega_2)$ are low-frequency

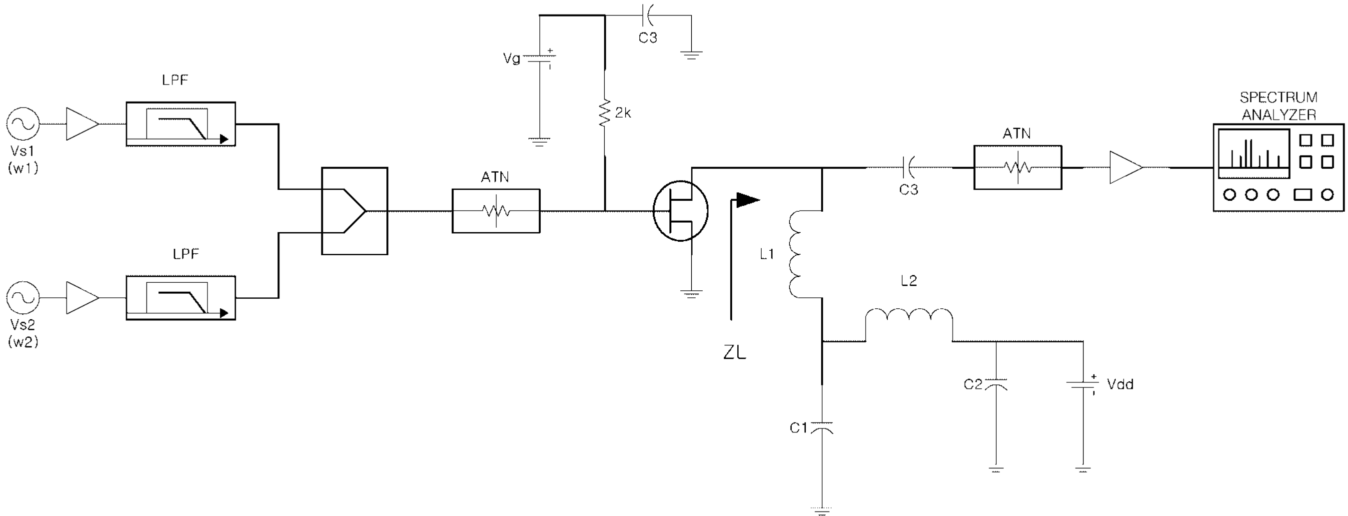

Figure 1 Experimental setup used for the low-frequency harmonic measurement

two-tone signals at 45 and 70 MHz. Using the system, all harmonic output power terms can be measured. From the terms, the coefficients in Eq. (1) can be accurately extracted.

II. EXTRACTION METHODOLOGY

Volterra series analysis [7] is used to calculate the harmonic distorted output power. The equivalent circuit shown in Figure 2 is used for the nonlinear analysis. At very low frequencies, the C_{gs} is basically an open circuit, and its nonlinearity is not important. Therefore, the major nonlinear component is the drain–source channel current, and the harmonic distorted output power can be expressed as a function of Taylor coefficients of the channel current in Eq. (1). Comparing the calculated and measured harmonic output power, these Taylor coefficients are extracted.

The channel current is modeled as a two-dimensional Taylor series of v_{gs} and v_{ds}. Since all capacitances (C_{gs}, C_{ds}, and C_{dg}) of the equivalent circuit can be treated as open circuits in these low frequencies, the circuit is quite simplified. From the simplified circuit, the relationships between (v_{gs}, v_{ds}) and V_s, I_n is given by

$$\begin{aligned} v_{gs}(\omega) &= K_{gs}(\omega)\cdot V_s(\omega) + K_{gn}(\omega) I_n(\omega) \\ v_{ds}(\omega) &= K_{ds}(\omega)\cdot V_s(\omega) + K_{dn}(\omega) I_n(\omega) \end{aligned} \tag{2}$$

$$\begin{aligned} K_{gn}(\omega) &= -\frac{R_s}{1 + G_m\cdot(R_s + G_d\cdot(R_s + R_d + Z_L(\omega))} \\ K_{dn}(\omega) &= -\frac{R_s + R_d + Z_L(\omega)}{1 + G_m\cdot(R_s + G_d\cdot(R_s + R_d + Z_L(\omega))} \\ K_{gs}(\omega) &= \frac{1 + G_d\cdot(R_s + R_d + Z_L(\omega))}{1 + G_m\cdot(R_s + G_d\cdot(R_s + R_d + Z_L(\omega))} \\ K_{ds}(\omega) &= \frac{-G_m(R_s + R_d + Z_L(\omega))}{1 + G_m\cdot(R_s + G_d\cdot(R_s + R_d + Z_L(\omega))}. \end{aligned} \tag{3}$$

In this equation, K_{gs}, K_{ds} are the voltage gain of the gate and drain terminals, respectively, and K_{gn} and K_{dn} are the transimpedences between I_{ds} and the terminal voltages. I_n is the nonlinear current component, which is generated by the device nonlinearities.

From the Eq. (2), the second-order harmonic components $I_n(\omega_2 - \omega_1)$, $I_n(2\omega_1)$, $I_n(\omega_1 + \omega_2)$, and $I_n(2\omega_2)$ can be obtained as

$$\begin{aligned} I_n(\omega_2 - \omega_1) = [&2\cdot K_{gs_1}^{*}\cdot K_{gs_2}\cdot G_{m2} \\ &+ (K_{gs_1}^{*}\cdot K_{ds_2} + K_{gs_2}\cdot K_{ds_1}^{*})\cdot G_{md} \\ &+ 2\cdot K_{ds_1}^{*} K_{ds_2}\cdot G_{d2}]\cdot \frac{V_{s1}^{*} V_{s2}}{2} \end{aligned} \tag{4}$$

$$\begin{aligned} I_n(2\omega_1) = \big[&K_{gs_1}^2\cdot G_{m2} + K_{gs_1}\cdot K_{ds_1}\cdot G_{md} \\ &+ K_{ds_1}^2\cdot G_{d2}\big]\cdot \frac{V_{s1}^2}{2} \end{aligned} \tag{5}$$

$$\begin{aligned} I_n(\omega_1 + \omega_2) = [&2\cdot K_{gs_1}\cdot K_{gs_2}\cdot G_{m2} \\ &+ (K_{gs_1}\cdot K_{ds_2} + K_{gs_2}\cdot K_{ds_1})\cdot G_{md} \\ &+ 2\cdot K_{ds_1}\cdot K_{ds_2}\cdot G_{d2}]\cdot \frac{V_{s1} V_{s2}}{2} \end{aligned} \tag{6}$$

$$\begin{aligned} I_n(2\omega_2) = \big[&K_{gs_2}^2\cdot G_{m2} + K_{gs_2}\cdot K_{ds_2}\cdot G_{md} \\ &+ K_{ds_2}^2\cdot G_{d2}\big]\cdot \frac{V_{s2}^2}{2} \end{aligned} \tag{7}$$

where $K_{gs_i} = K_{gs}(\omega_i)$, $K_{ds_i} = K_{ds}(\omega_i)$, and $V_{si} = V_s(\omega_i)$. The above equations can be represented in a more simple form using the matrix equation

$$\begin{bmatrix} I_n(\omega_2 - \omega_1) \\ I_n(2\omega_1) \\ I_n(\omega_1 + \omega_2) \\ I_n(2\omega_2) \end{bmatrix} = A_{N2}\cdot \begin{bmatrix} G_{m2} \\ G_{md} \\ G_{d2} \end{bmatrix} \tag{8}$$

where A_{N2} is directly obtained from Eqs. (4)–(7), and three unknowns of the second-order coefficients G_{m2}, G_{md}, G_{d2} can be extracted from the measured second-order intermodulation terms. In the same way, the third-order harmonic components $I_n(2\omega_2 - \omega_1)$, $I_n(3\omega_1)$, $I_n(2\omega_1 + \omega_2)$, and $I_n(3\omega_2)$ can be obtained $I_n(3\omega_1)$ is given by

$$\begin{aligned} I_n(3\omega_1) = \{&2G_{m2}\cdot K_{gs}(\omega_1)\cdot K_{gn}(2\omega_1) + G_{md} \\ &\cdot[K_{gs}(\omega_1)\cdot K_{dn}(2\omega_1) + K_{gn}(2\omega_1)\cdot K_{ds}(\omega_1)] \\ &+ 2G_{d2}\cdot K_{ds}(\omega_1) K_{dn}(2\omega_1)\}\cdot \frac{I_n(2\omega_1)\cdot V_s(\omega_1)}{2} \end{aligned}$$

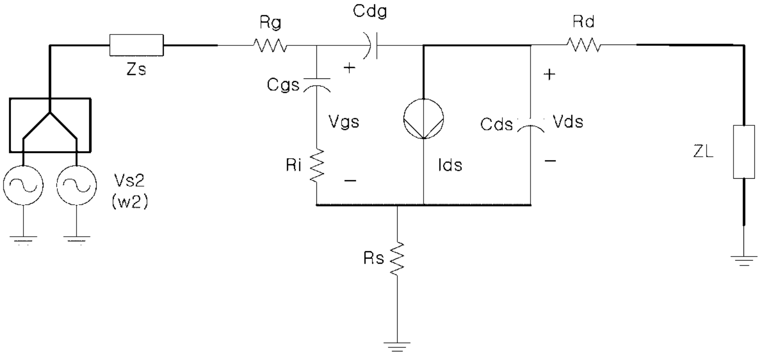

Figure 2 Equivalent circuit for nonlinear analysis (MESFET)

$$+\left\{G_{m3} + K_{ds}(\omega_1)G_{m2d} + K_{ds}(\omega_1)^2 G_{md2} + K_{ds}(\omega_1)^3 G_{d3}\right\}\frac{1}{4}(V_{S1}^3). \qquad (9)$$

In Eq. (9), the first term is generated by the second-order nonlinear current, and the later term from third-order nonlinearity. The third-order equations can be simplified in matrix form as

$$\begin{bmatrix} I_{n3}(2\omega_1 - \omega_2) \\ I_{n3}(2\omega_2 - \omega_1) \\ I_{n3}(3\omega_1) \\ I_{n3}(2\omega_1 + \omega_2) \\ I_{n3}(\omega_1 + 2\omega_2) \\ I_{n3}(3\omega_2) \end{bmatrix} = A_{N3} \cdot \begin{bmatrix} G_{m3} \\ G_{m2d} \\ G_{md2} \\ G_{d3} \end{bmatrix} + B_{N32} \cdot \begin{bmatrix} I_{n2}(\omega_2 - \omega_1) \\ I_{n2}(2\omega_1) \\ I_{n2}(\omega_1 + \omega_2) \\ I_{n2}(2\omega_2) \end{bmatrix} \qquad (10)$$

where A_{N3} can be obtained from the third-order nonlinear current equations, and B_{N32} is the current gain matrix which transfers from the second-order terms to the third-order currents.

In this equation, the matrix A_{N3} should be a well-conditioned matrix. The matrix singularity is strongly dependent on the load impedance. The optimum load for the nonsingular matrix is found by numerical optimization. The optimum load impedances at ω_1 and ω_2 should be a complex conjugate pair.

III. RESULT

In this experiment, the general two-tone tests are performed to measure the harmonic output power terms with the experimental setup shown in Figure 1. The source signals are $\omega_1 = 45$ MHz, $\omega_2 = 70$ MHz, and $P_{\text{in}} = -23$ dBm. In this test, an OKI KGF-1284 MESFET is used at the bias point $V_{ds} = 3.5$ V. To reduce the measurement system error, the harmonic power ratio with respect to the first-order output power, instead of absolute harmonic powers, is used in extracting the coefficients. Measured and calculated harmonic powers are compared to extract the Taylor coefficients. The extracted second- and third-order harmonic channel current coefficients in Eq. (1) are shown in Figures 3–5. With these extracted channel current coefficients and nonlinear capacitance model extracted from the measured bias-dependent S-parameters, a Volterra series model for an OKI KGF-1284 GaAs MESFET has been constructed. In order to verify this model, the two-tone test was carried out using an automatic tuner system at 1.75 GHz. The simulated and measured results are shown in Figure 6. The simulation results predict very accurately the nonlinear behavior of the MESFET.

IV. CONCLUSION

In this paper, we have proposed a very simple and straightforward method to measure the higher order Taylor series coefficients of the channel current of a GaAs MESFET. From this method, the harmonic components are successfully extracted. In order to obtain a proper solution, the load

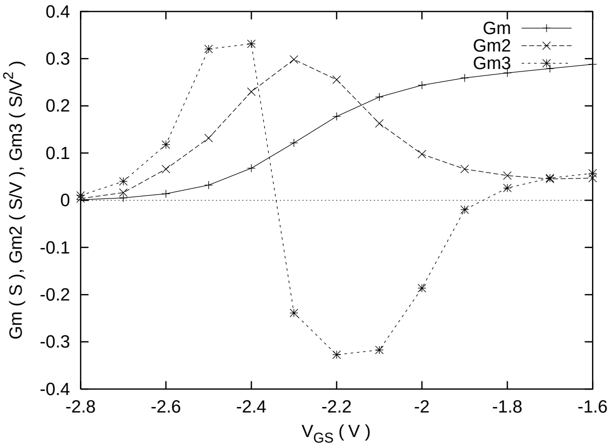

Figure 3 Measured G_m, G_{m2}, and G_{m3}

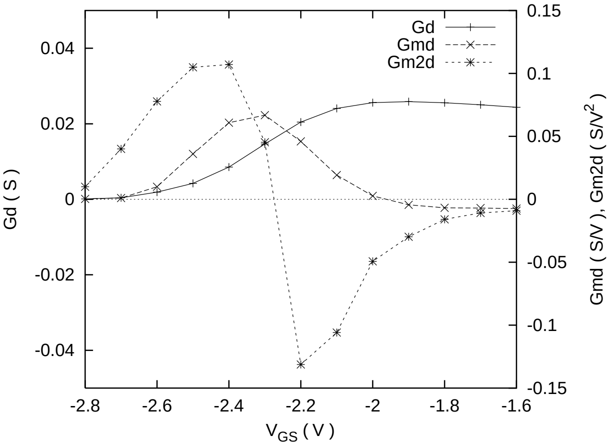

Figure 4 Measured G_d, G_{md}, and G_{m2d}

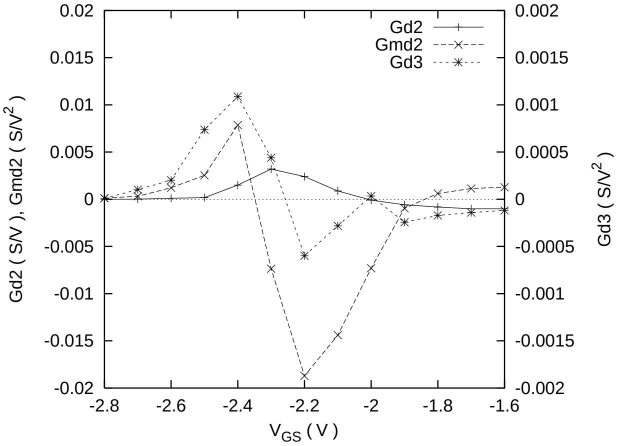

Figure 5 Measured G_{d2}, G_{md2}, and G_{d3}

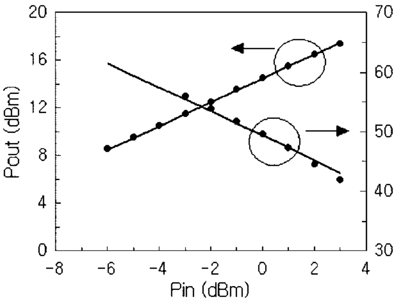

Figure 6 Comparison of simulated (lines) and measured (points) results of two-tone test

impedance should be properly designed. The MESFET model is constructed using the extracted higher order terms, and this model is verified by comparing the two-tone power performance measurements.

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2-D ANALYTICAL MODEL FOR CURRENT–VOLTAGE CHARACTERISTICS AND OUTPUT CONDUCTANCE OF AlGaN/GaN MODFET

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ABSTRACT: *A two-dimensional analytical model for an AlGaN/GaN MODFET is presented. The model assumes the velocity saturation of electrons in 2-DEG, which causes current saturation and accurately predicts the output conductance arising from the channel length modulation. The effects of spontaneous and piezoelectric polarization at the AlGaN/GaN heterointerface, the field-dependent mobility, and the parasitic source/drain resistances have been incorporated in the analysis. A good fit with the experimental data is obtained for an* $Al_{0.15}Ga_{0.85}N$/*GaN MODFET, thus proving the validity of our model.* © 2001 John Wiley & Sons, Inc. Microwave Opt Technol Lett 29: 117–123, 2001.

Key words: *AlGaN/GaN MODFET; sheet carrier concentration; output conductance*

1. INTRODUCTION

Modulation-doped field-effect transistors (MODFETs) have been the subject of intensive investigation since the first AlGaAs/GaAs MODFET was introduced in 1980 [1], and they have shown promising performance for high-frequency microwave applications [2–8]. Despite extensive applications, electronic devices based on Si, GaAs, and their alloys are intolerant of elevated temperature and caustic environments. The devices based on wide-bandgap semiconductors, such as III–V nitrides (GaN, AlN, InN), are, however, potentially free of these shortcomings [9]. Wide-bandgap GaN has long been sought for its applications to high-temperature/high-power electronic devices [10, 11]. The recent introduction of commercial blue and blue–green LEDs has led to a plethora of activity in the heterostructures based on GaN and its alloys with AlN and InN.

AlGaN/GaN MODFETs [Fig. 1(a)], also called high-electron-mobility transistors (HEMTs), have attracted increasing interest as a candidate for future microwave power devices. Although the electron effective mass in GaN is about three times higher than that in GaAs, resulting in smaller low-field electron mobility, GaN has a larger peak electron velocity, larger saturation velocity, higher thermal stability, and a larger bandgap, making it suitable for microwave power devices [12]. Further, in AlGaN/GaN-based MODFETs, significantly high spontaneous and piezoelectric polarization fields arising from material properties of AlGaN and GaN [13, 14] lead to the formation of two-dimensional electron gases (2-DEG) with very high sheet carrier concentrations of 10^{13} cm^{-2}, even without any intentional doping.

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