Intermodulation Analysis of FET Resistive Mixers Using Volterra Series[1]

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ABSTRACT

We have implemented the Volterra-series method to analyze intermodulation (IM) distortion in FET resistive mixers. The nonlinearities of the channel conductance of a NE71000 MESFET and a NE32400 HFET were first characterized using a low-frequency harmonic power measurement. The data was then used in a simulation program and results for two-tone IM distortion in X-band were compared with the measured data for both MESFET and HFET resistive mixer circuits. Very good agreement was achieved in each case. We have also shown by simulation that the two separate contributions to the third-order IM distortion from the mixing between the input signals themselves and the mixing between the input signals and the second-order mixing products have a very strong cancellation, which results in the low IM distortion in the FET resistive mixers observed in measurements.

INTRODUCTION

FET resistive mixers [1] have been gaining favor over their diode mixer counterparts due to their higher IP3, comparable conversion loss and noise figure, and easy realization in MMIC's. Because the demand for a wide dynamic range in today's microwave and millimeter-wave receivers results in strict IM performance requirements for the front-end mixers, FET resistive mixers have also become more preferable than the conventional type of FET gate mixers due to their superior IM performance. The superior IM performance of the FET resistive mixers has been experimentally demonstrated. Recently, a nonlinear drain-source current model [2] has been proposed specifically for the IM analysis of FET resistive mixers. The authors of [2] used a general-purpose, harmonic-balance program for their single-tone IM analysis and good agreement between the simulation and measurement data was obtained. However, there are several drawbacks of using the general-purpose harmonic-balance technique for the IM analysis of mixers. The long simulation time and narrow simulation dynamic range are the two main concerns. Therefore, most of the simulations and studies of IM distortion in mixers as in [2] were performed for the single-tone case.

The utilization of the harmonic-balance technique for the large-signal analysis and the Volterra-series method for the small-signal conversion efficiency and IM analysis has been demonstrated [3],[4] as the optimal technique for multi-tone IM analysis of mixers. In this work, we extend the Volterra-series method given in [4] to calculate the small-signal IM distortion in FET resistive mixers. We first characterized the nonlinearities of the channel resistance of a NE71000 MESFET and a NE32400 HFET using a low-frequency harmonic power measurement. The nonlinear coefficients obtained from this characterization were then numerically implemented into a FET mixer IM analysis program based on the Volterra-series method [4], and simulation results of two-tone IM distortion in X-band were compared with measurement data for both MESFET and HFET resistive mixers.

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METHOD OF ANALYSIS: THE NONLINEAR CURRENT METHOD

In FET resistive mixers the local oscillator (LO) is applied to the gate of the FET, at zero drain bias, to modulate the channel resistance (conductance). The RF signal is applied to the drain, and the frequency mixing occurs between the RF and LO due to the nonlinear channel conductance. The incremental drain current expanded in Taylor's series for the RF small signals applied to the drain terminal can be written as:

$$i_{ds}(t) = \frac{\partial I_{ds}}{\partial V_d} v_d(t) + \frac{1}{2}\frac{\partial^2 I_{ds}}{\partial V_d^2} v_d^2(t) + \frac{1}{6}\frac{\partial^3 I_{ds}}{\partial V_d^3} v_d^3(t) + \dots$$

$$\equiv g_d(t) v_d(t) + g_{d2}(t) v_d^2(t) + g_{d3}(t) v_d^3(t) + \dots \quad \text{(EQ 1)}$$

where I_{ds} is the drain-source current, which is a function of both gate and drain voltages, g_d is the channel conductance, and g_{d2} and g_{d3} are the second and third derivatives of the drain-source current with respect to the drain voltage, respectively. Due to the LO pump at the gate terminal, these coefficients are also time-dependent and have to be evaluated for each large signal LO pumping waveform.

The small-signal drain voltage, $v_d(t)$, can be expanded into a summation of different orders with respect to the input small-signal voltage, which is considered as first order,

$$v_d(t) = v_{d1}(t) + v_{d2}(t) + v_{d3}(t) + \dots \quad \text{(EQ 2)}$$

After the expansion, the original small-signal nonlinear circuit is divided into a combination of subcircuits of each order and each subcircuit is simply a linear circuit with an excitation current dependent on the voltages of previous orders (except for the first-order excitation current, which is the input small signal). Restricting our consideration up to third-order components, we have the second-order excitation current, I_{s2},

$$I_{s2} = g_{d2}(t) v_{d1}^2(t) \quad \text{(EQ 3)}$$

and the third-order excitation current, I_{s3},

$$I_{s3} = 2g_{d2}(t) v_{d1}(t) v_{d2}(t) + g_{d3}(t) v_{d1}^3(t) . \quad \text{(EQ 4)}$$

By solving each subcircuit in order, the IM distortion at the frequencies of interest can be determined [4].

NONLINEAR CHARACTERIZATION

The key factor in obtaining realistic IM simulation results is the accurate characterization of the functional dependence of the coefficients (g_d, g_{d2} and g_{d3}) in the Taylor's series on the gate voltage. The most accurate way to obtain these dependences is to extract them from measurement. Therefore, we followed the method of low-frequency harmonic power measurement [5],[6] to derive the dependences of the coefficients g_{d2} and g_{d3} on the gate voltage. The channel conductance, g_d, and other linear circuit elements were first obtained from fitting the small-signal equivalent circuit to measured S-parameter data (500MHz-26GHz). The coefficients g_{d2} and g_{d3} were then easily determined from harmonic power measurements by a simple Volterra-series analysis. We applied this technique to characterize a MESFET (NE71000) and a HFET (NE32400) at various gate voltages. The results of these characterizations for the MESFET and HFET are shown in Figures 1 and 2, respectively.

TWO-TONE IM RESULTS

We numerically implemented the measured data of the coefficients in (EQ 1) into a FET mixer IM analysis program [4] and obtained a two-tone IM simulation for both the MESFET and HFET mixers in X-band. We also performed measurements to have a comparison with the simulation results. For simplicity, both mixer circuits had a 50 Ω resistive gate and a 50 Ω resistive drain impedance for all frequencies in this work. The LO frequency was chosen to be 10.8 GHz, and the RF 11.1 GHz and 11.2 GHz with power levels -15 dBm per tone. The conversion gain and IM3 output at 500 MHz ($2f_{RF2}-f_{RF1}-f_{LO}$) were measured at the drain terminal. The measured and calculated results are shown in Figure 3 for the MESFET resistive mixer and Figure 4 for the HFET mixer. Very good agreement between the calculated

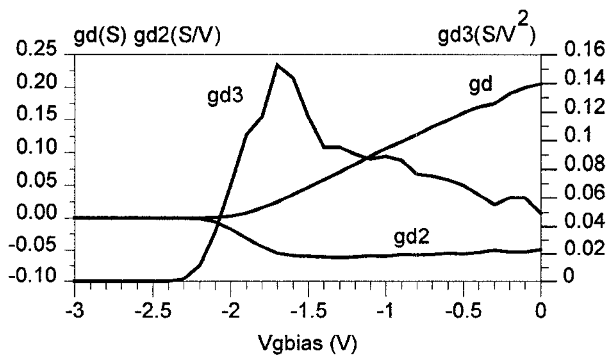

Figure 1. Measured g_d, g_{d2} and g_{d3} of a NE71000 MESFET.

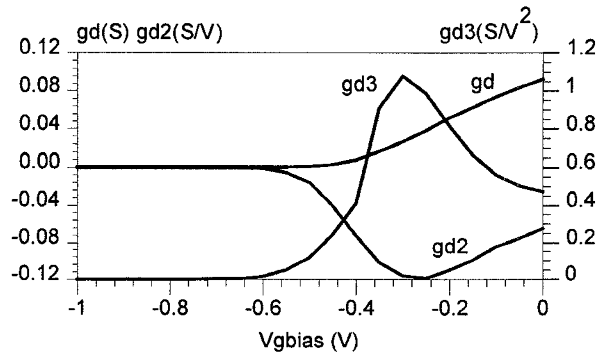

Figure 2. Measured g_d, g_{d2} and g_{d3} of a NE32400 HFET.

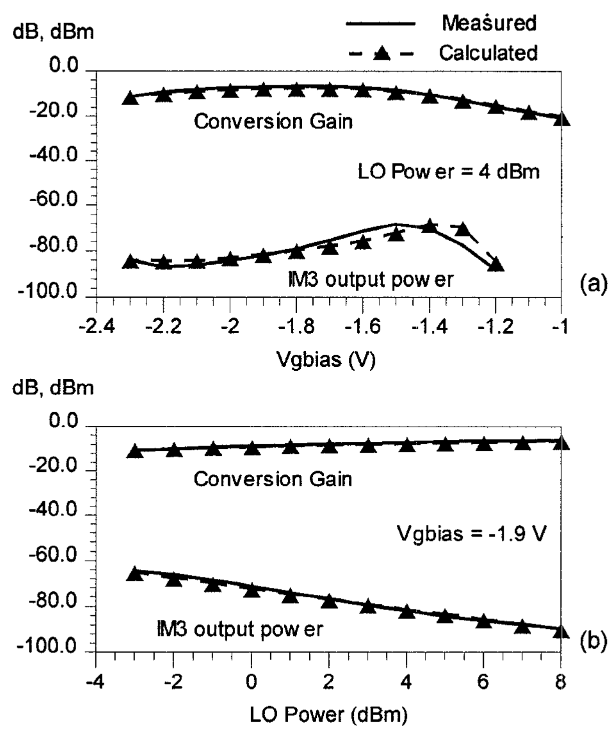

Figure 3. Conversion gain and IM3 level of the NE71000 MESFET resistive mixer as a function of (a) gate-bias voltage and (b) LO power level. The LO frequency is chosen to be 10.8 GHz, and the RF 11.1 and 11.2 GHz with power levels -15 dBm per tone. IF and IM3 power levels are measured at 300 and 500 MHz, respectively.

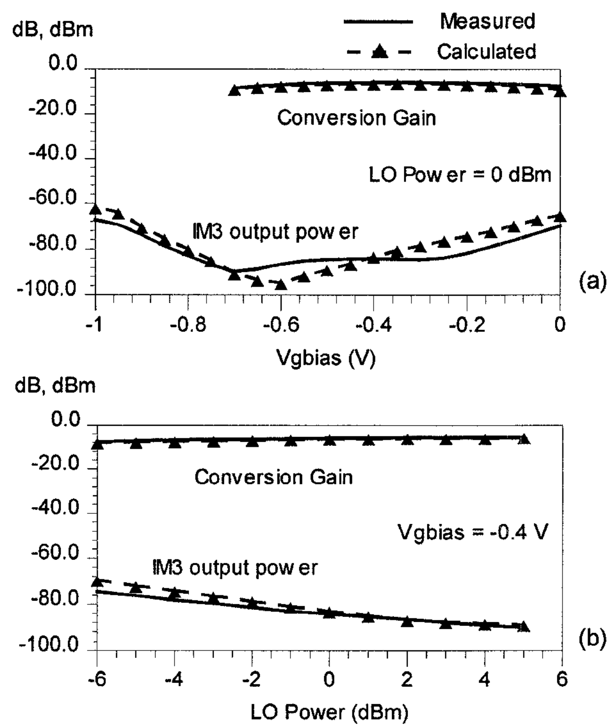

Figure 4. Conversion gain and IM3 level of the NE32400 HFET resistive mixer as a function of (a) gate-bias voltage and (b) LO power level. The LO frequency is chosen to be 10.8 GHz, and the RF 11.1 and 11.2 GHz with power levels -15 dBm per tone. IF and IM3 power levels are measured at 300 and 500 MHz, respectively.

and measured data for both the conversion gain and IM3 output power level of both mixers is evident.

The third-order IM products are generated by the third-order excitation current source, I_{s3} (EQ 4). This current consists of two terms: (1) $2g_{d2}v_{d1}v_{d2}$, which represents the third-order products created by frequency mixing between the second-order mixing signals (v_{d2}) and the first-order input signals (v_{d1}), and (2) $g_{d3}v_{d1}^3$, which represents the third-order products created by frequency mixing between the first-order input signals themselves (v_{d1}^3). An examination of the separate contribution from these two terms to the IM3 output current was performed in the simulation and the results are shown in Figures 5 and

6 for the MESFET and HFET resistive mixers, respectively. As can be seen for both mixers, the contributions from $2g_{d2}v_{d1}v_{d2}$ and $g_{d3}v_{d1}^3$ are approximate 180-degree out of phase throughout the range of gate bias. Furthermore, their magnitudes are comparable (especially in the case of HFET resistive mixer). As a result, there is always a strong cancellation between the contributions from $2g_{d2}v_{d1}v_{d2}$ and $g_{d3}v_{d1}^3$. This phenomenon provides another explanation of the low IM distortion observed experimentally in FET resistive mixers since most FET's have not been optimized for resistive channel operation. (For instance, both of the devices in this work have quite large values of g_{d2} and g_{d3} at some gate bias voltages which indicates the channel conductance is not very linear with respect to the drain voltage in these devices, especially the NE32400 HFET.) This also suggests a very feasible way to improve the IM performance in FET resistive mixers by tailoring the embedded drain impedance at the second-order frequencies, which in turn tailors the value of v_{d2}, to cause even stronger cancellation between the contributions from $2g_{d2}v_{d1}v_{d2}$ and $g_{d3}v_{d1}^3$ without affecting the conversion efficiency of the mixers.

CONCLUSIONS

We have demonstrated that the Volterra-series method can accurately predict two-tone IM distortion levels in FET resistive mixers and that the method requires much less computational time than the general-purpose harmonic-balance technique. Each calculated data point of the results shown in this paper requires less than one minute to compute on a Sun Sparc20 workstation with 12 harmonics included. Moreover, contributions to the IM distortion from each order products can be easily monitored in the Volterra-series analysis.

REFERENCES

[1]. S. A. Maas, "A GaAs MESFET Mixer with Very Low Intermodulation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp.425-429, April 1987

[2]. Robinder S. Virk and S. A. Maas, "Modeling MESFETs for Intermodulation Analysis of Resistive FET Mixers," *IEEE MTT-S Digest*, pp. 1247-1250, 1995

[3]. S. A. Maas, "Two-Tone Intermodulation in Diode Mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 307-314, April 1987

[4]. Solti Peng, Patrick J. McCleer, and George I. Haddad, "Nonlinear Models for the Intermodulation Analysis of FET Mixers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-43, pp. 1037-1045, May 1995

[5]. S.A. Maas and D. Neilson, "Modeling MESFET's for Intermodulation Analysis of Mixers and Amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 1964-1971, Dec. 1990

[6]. José Carlos Pedro and Jorge Perez, "An Improved MESFET Model for Prediction of Intermodulation Load-Pull Characterization", *IEEE MTT-S Digest*, pp. 825-828, 1992

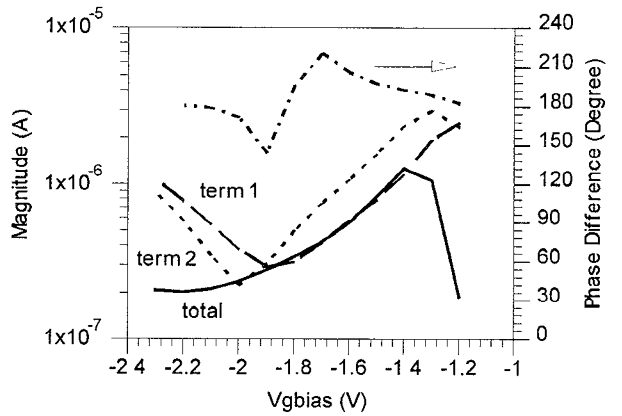

Figure 5. Magnitude and phase difference of the separate contributions to the IM3 output current from $2g_{d2}v_{v2}v_{v1}$ (term 1) and $g_{d3}v_{v1}^3$ (term 2) in (EQ 4) for the NE71000 MESFET resistive mixer.

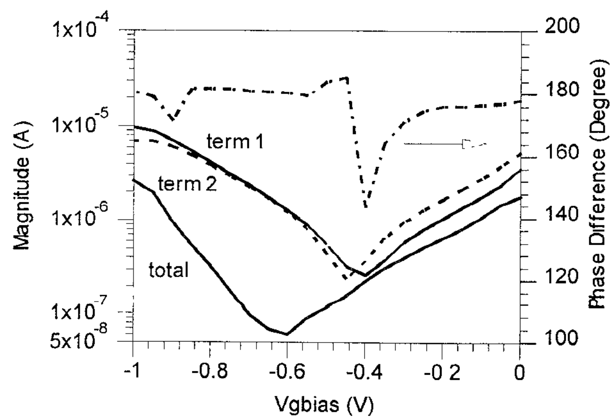

Figure 6. Magnitude and phase difference of the separate contributions to the IM3 output current from $2g_{d2}v_{v2}v_{v1}$ (term 1) and $g_{d3}v_{v1}^3$ (term 2) in (EQ 4) for the NE32400 HFET resistive mixer.