GENERALIZED POWER SERIES ANALYSIS OF INTERMODULATION DISTORTION IN A MESFET AMPLIFIER: SIMULATION AND EXPERIMENT

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ABSTRACT

Design of microwave integrated circuits requires accurate simulation tools capable of predicting a variety of nonlinear distortion effects including gain compression and intermodulation distortion. This paper uses the recently developed generalized power series analysis to simulate a MESFET amplifier. For the first time, the simulations are compared to experimental results for single-tone and two-tone inputs. Good agreement is seen. This analysis is suited to any complex analog circuits having arbitrary input frequency spacing.

INTRODUCTION

Interest is rapidly growing in the computer-aided design of microwave circuits. While a variety of powerful design tools have been developed for linear circuits, few tools are available for the analysis and design of nonlinear circuits. Currently available simulators fall into two categories: time-domain methods (e.g. SPICE [1]) and harmonic-balance methods (e.g. N-FET [2]).

Time-domain simulators enjoy a wide range of application including both analog and digital circuits having either steady-state or transient responses. Several factors, however, limit the applicability of these methods to microwave circuit analysis. Distributed circuits are particularly difficult to model in the time domain. Convergence of the numerical methods is a problem when the circuit contains widely varying time constants or when widely spaced frequency components are present, resulting in lengthy computation times. The time-domain simulation of systems with mult-frequency excitation requires multidimensional signal processing to determine intermodulation levels. Both time domain simulations and multidimensional transform techniques have severe dynamic range limitations so that intermodulation levels even 30 dB below the fundamental signal level cannot be resolved adequately.

Simulators based on harmonic balance can more efficiently analyze microwave circuits since the linear portion of the circuit is modeled in the frequency domain. Because the nonlinear portion of the circuit is still modeled in the time domain, Fourier techniques must be used to interface the models. This restricts all frequencies considered to be harmonically related (in special cases closely spaced frequencies may be considered [3]). Thus, these methods are very limited in their ability to simulate mixing or intermodulation.

We have recently presented a frequency-domain technique for simulating nonlinear analog circuits having arbitrary input spectra [4], [5]. This technique, termed generalized power series analysis, is used here to simulate a common source MESFET amplifier with single-tone and with two-tone inputs. The simulated results are in good agreement with experimental results verifying that the generalized power series analysis technique is useful in predicting the behavior of nonlinear circuits under a variety of operating conditions including intermodulation.

DEVICE CHARACTERIZATION

The device used in this paper is a low noise medium power GaAs MESFET (Avantek AT8250). The circuit shown in Fig. 1 was chosen to model the transistor. This model was developed from dc measurements and small signal microwave measurements and contains a number of linear elements as well as nonlinear voltage-dependent elements.

The magnitude of the transconductance, G_m, was found from dc measurements of the drain current at varying gate-source voltages with the drain-source voltage fixed at the chosen operating point ($V_{ds} = 3V$, $V_{gs} = -0.1V$).

Small signal s-parameters were measured over the frequency range 0.5-15.0 GHz at a variety of bias voltages. In particular, measurements were made with V_{ds} fixed at 3 V and V_{gs} allowed to vary, and with V_{gs} fixed at -0.1 V and V_{ds} varying. Measurements were also made with $V_{ds} = V_{gs} = 0V$.

With zero drain-source voltage, the equivalent circuit becomes much simpler and is useful in determining the various parasitic elements [6], [7] TOUCHSTONE [8] was used to optimize the simplified circuit to match the measured zero bias s-parameters over the frequency range 0.5-10.65 GHz. With the parasitic elements determined, the model of Fig. 1 was then optimized to match the measured s-parameters at each bias setting, resulting in a table of element values as a function of bias voltage. Figures 2 and 3 show a comparison of the measured s-parameters and the s-parameters of the transistor model.

The nonlinear simulation requires that the element values be described by generalized power series in voltage. A least squares routine was used to fit power series to the data determined from the TOUCHSTONE optimizations. As an example of the results, Fig. 4 shows the optimized values of G_m along with it's power series representation, while Fig. 5 shows the values of C_{gs}.

COMPUTER SIMULATION

The simulations described in this paper were done using a program we have developed called FREDA (FREquency Domain Analysis) which is based on generalized power series analysis [4], [5] . Generalized power series analysis is a technique similar to harmonic balance techniques except that the entire circuit is analyzed in the frequency domain so that no Fourier transforms are needed. (The term harmonic balance is commonly used to refer to techniques that iterate between the time domain solution of a nonlinear circuit and the frequency domain solution of a linear circuit.) This allows the method to be applied to nonlinear circuits with multi-frequency inputs where the input frequencies can be arbitrarily separated. It is more appropriately termed a spectral balance technique since the frequencies considered are generally not harmonically related.

The circuit to be analyzed is input to FREDA along with information about the frequencies and power levels to be considered. In addition, FREDA requires an initial estimate of the circuit voltages. This estimate can be made for a low value of input power where it can be almost arbitrary. FREDA solves the circuit at this power level and then increments the input power level and uses the previous solution, appropriately scaled, as the next initial estimate. This continues until the desired range of input powers has been covered.

The circuit of Fig. 1 (with 50 Ω source and load impedances and bias circuitry added) was simulated using FREDA. Simulations were performed for the case of a single tone input as well as for two input tones.

EXPERIMENTAL SETUP

For the single tone test, an input frequency of 3 GHz was used and the output power measured at 3, 6, and 9 GHz using a spectrum analyzer. (The input power level and the spectrum analyzer were computer controlled.) The transistor was biased at $V_{ds} = 3V$ and $V_{gs} = -0.1V$. The input power was varied from -35 dBm to 10 dBm. The small signal gain was observed to be approximately 10 dB and the power output in the fundamental saturated at 16 dBm.

For the two-tone intermodulation test, the transistor was again biased at $V_{ds} = 3V$ and $V_{gs} = -0.1V$. Two equal amplitude signals were input, one at 2.35 GHz and one at 2.40 GHz. The input power was varied from -35 dBm to 5 dBm and the output power measured at the fundamental frequencies, their harmonics, and the third order intermodulation frequencies. (The frequencies and power levels used were chosen entirely for experimental convenience and not for ease of simulation.)

COMPARISON OF SIMULATED AND EXPERIMENTAL RESULTS

Fig. 6 shows the results of the simulation with one input tone compared to the experimental results. The simulation is continued until the gain is compressed by 3 dB from its small signal value of 10.1 dB. Shown are the fundamental and first two harmonics.

The results of the two-tone intermodulation test are shown in Fig. 7. The power output in one of the input tones (2.35 GHz) is shown along with the power output in one of the third-order intermodulation frequencies (2.3 GHz).

The agreement between the simulated results and the experimental results is seen to be quite good, particularly for the fundamentals and the third order products. The agreement can be improved however and the range of input power expanded by improving the power series representations of the nonlinear elements through more extensive device characterization.

CONCLUSION

In this paper, we have for the first time compared circuit simulations using generalized power series analysis to experimental results for a MESFET amplifier circuit with a single tone input as well as for a two-tone intermodulation test. The simulated results were seen to be in good agreement with the measured results. The agreement for the two-tone test is particularly significant as these simulations cannot be arbitrarily performed using currently available software. Thus, generalized power series analysis is a useful tool in simulating and designing nonlinear microwave circuits having complex multi-frequency inputs.

ACKNOWLEDGMENTS

The authors would like to acknowledge the assistance of Mr. Wes Lawrence in the measurement of device s-parameters.

REFERENCES

[1] L.W. Nagel and D.O. Pederson, "SPICE (Simulation Program with Integrated Circuit Emphasis)," University of California, Electronics Research Laboratory Memorandum ERL-M382, April 12,1973.

[2] W.R. Curtice and M. Ettenberg, "N-FET, a New Software Tool for Large-Signal GaAs FET Circuit Design," *RCA Review*, vol. 46, pp. 321-340, Sept. 1985.

[3] R.J. Gilmore and F.J. Rosenbaum, "Modelling of Nonlinear Distortion in GaAs MESFETS," *IEEE MTT-S International Microwave Symp. Digest*, pp. 430-431, 1984.

[4] G.W. Rhyne and M.B. Steer, "A New Frequency Domain Approach to the Analysis of Nonlinear Microwave Circuits," *IEEE MTT-S International Microwave Symp. Digest*, pp. 401-404, 1985.

[5] G.W. Rhyne and M.B. Steer, "Simulation of Intermodulation Distortion in MESFET Circuits with Arbitrary Frequency Separation of Tones," *IEEE MTT-S International Microwave Symp. Digest*, pp. 547-550, 1986.

[6] W.R. Curtice and R.L. Camisa, "Self-Consistent GaAs FET Models for Amplifier Design and Device Diagnostics," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1573-1578, Dec. 1984.

[7] F. Diamond and M. Laviron, "Measurement of the Extrinsic Series Elements of a Microwave MESFET Under Zero Current Conditions," *Proc. 12th European Microwave Conf.*, Sept. 1982.

[8] TOUCHSTONE, EEsof Inc., Westlake Village, CA.

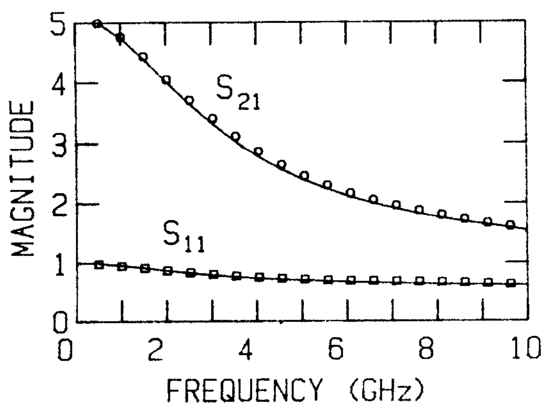

Figure 2
Magnitude of S_{11} and S_{21} as a function of frequency. The points are measurements and the curves are simulations using the optimized circuit of Fig. 1. ($V_{gs} = -0.1V$,$V_{ds} = 3.0V$)

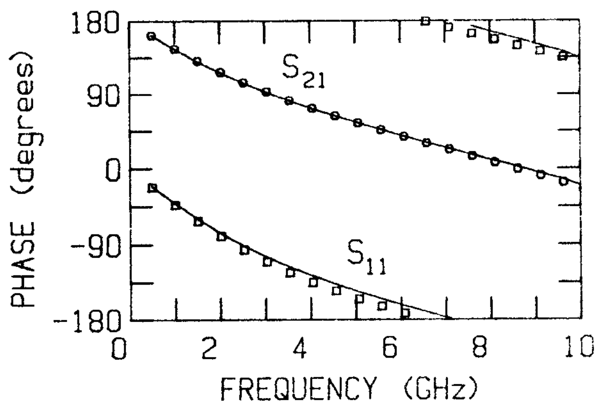

Figure 3
Phase of S_{11} and S_{21} as a function of frequency. The points are measurements and the curves are simulations using the optimized circuit of Fig. 1. ($V_{gs} = -0.1V$,$V_{ds} = 3.0V$)

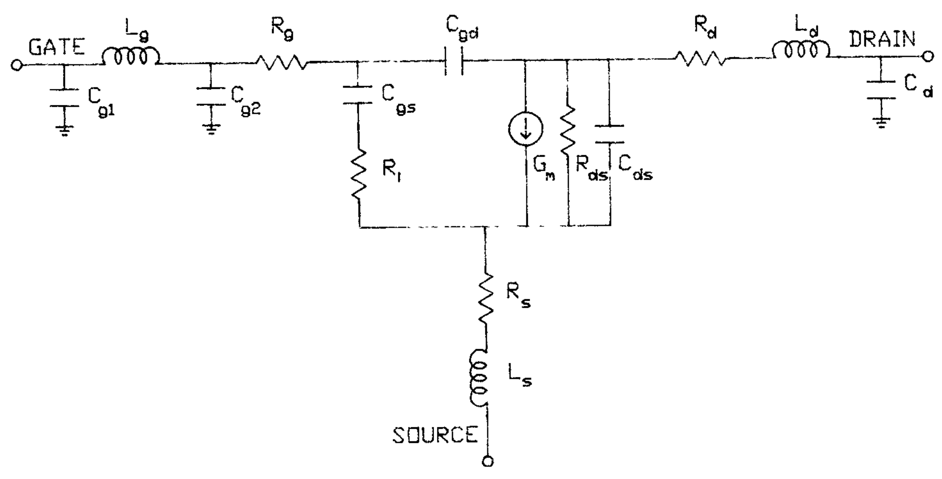

Figure 1
Circuit used to model the transistor.

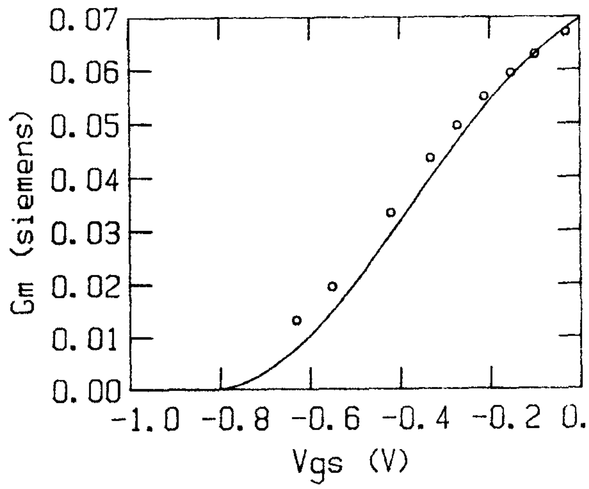

Figure 4
Optimized values of the transconductance, G_m, as a function of gate-source voltage. The points are the optimized values and the curve is the power series representation.

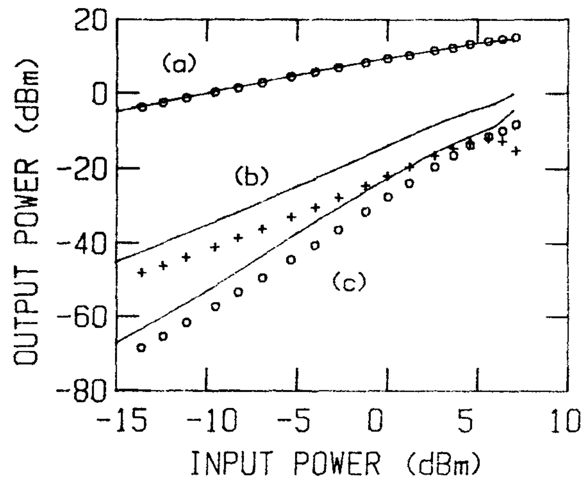

Figure 6
Results of the single-tone test. Power output in the fundamental (a), the second harmonic (b), and the third harmonic (c) are shown as a function of input power. The points are measurements and the curves are simulated results.

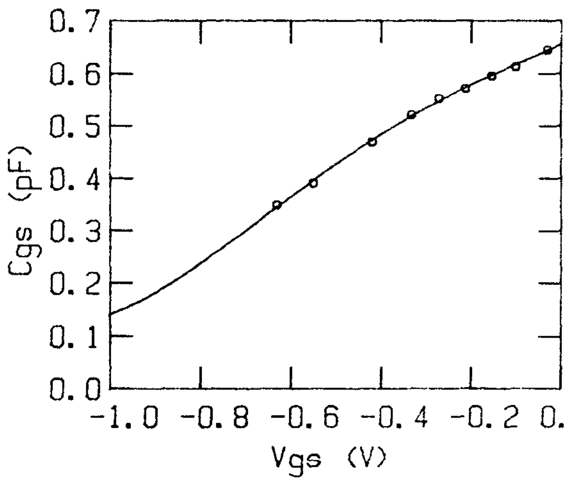

Figure 5
Optimized values of the gate-source capacitance, C_{gs}, as a function of gate-source voltage. The points are the optimized values and the curve is the power series representation.

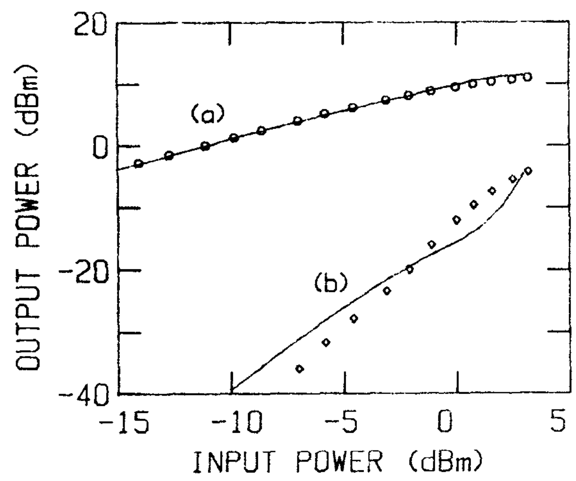

Figure 7
Results of the two-tone test. Power output in one of the fundamentals (a), and in one of the third order intermodulation frequencies (b) is shown as a function of input power. The points are measurements and the curves are simulated results.