# SIMULATION OF INTERMODULATION DISTORTION IN MESFET CIRCUITS WITH ARBITRARY FREQUENCY SEPARATION OF TONES

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## ABSTRACT

Design and simulation of microwave integrated circuits requires computer aided analysis tools that can accurately predict a variety of nonlinear distortion effects including gain compression and intermodulation distortion. This paper applies a new frequency domain approach to the simulation of a MESFET amplifier with multifrequency excitation. The unique attributes of the simulation method are that it can be used with general active circuits having multiple input tones of arbitrary amplitude and frequency separation. As an example, gain compression and two-tone intermodulation distortion in a MESFET amplifier are simulated.

## INTRODUCTION

Active circuits are inherently nonlinear When large signals or multifrequency tones are present gain compression and intermodulation distortion result deteriorating system performance. In a receiver system, multiple tones may result from the finite bandwidth of a communication signal (especially spread spectrum communication signals); the return echo of a radar signal; nearby transmitters; or jamming. In general the multitone signals are of arbitrary frequency spacing and in some cases an undesired component, such as a jamming signal, could have an amplitude much larger than that of the desired signal. Consequently, computer aided design of active circuits generally requires simulation of gain compression and intermodulation distortion responses. While several methods are available for characterizing the gain compression performance of a system, until recently there has been no general method for evaluating the response of an active circuit to large amplitude multi-frequency excitation. In this paper we apply the novel frequency domain method we have previously presented, termed the *generalized power series method* to the numerical simulation of gain compression and intermodulation distortion in a MESFET amplifier.

The purpose of this paper is to demonstrate the applicability of the generalized power series method to the simulation of gain compression and intermodulation distortion in a MESFET amplifier circuit. First, the existing methods for calculating intermodulation distortion are reviewed. Then, the generalized power series method is presented A MESFET model is developed, and gain compression and intermodulation distortion results from a common source amplifier simulation presented. Our simulated gain compression results are compared to previously reported experimental results. We present intermodulation distortion results for the case with two tones input of varying amplitude and frequency separation.

## REVIEW

Currently, powerful programs exist for use in simulation and design of linear microwave circuits. However, existing nonlinear analysis programs are not so advanced. Generally, simulations can predict gain compression and the generation of harmonic signals. Intermodulation distortion is more difficult to predict and no general simulation technique has previously been available. Existing methods for the numerical simulation of intermodulation distortion can be categorized as

- those that use Volterra series representations [3, 4].
- those based on a modified harmonic balance technique [5, 6].
- those based on time domain analyses [7].

In this section, these techniques are briefly reviewed and evaluated.

Volterra series analysis is one of the most popular techniques for analyzing nonlinear circuits having multifrequency excitation. This method is attractive because it can be applied to a broad range of nonlinear element types and because a complex frequency spectrum can be considered. A major limitation is that the complexity of the analysis makes it useful only for mildly nonlinear systems. Typically the nonlinearities are described using the equivalent of third order power series. With MESFET circuits it has been shown that higher order terms must be included to accurately predict the intermodulation distortion as the signal levels increase. Thus, Volterra series analysis can only be used for small signals.

There are several methods of calculating intermodulation distortion using modified harmonic balance approaches. In the basic harmonic balance analysis, linear circuit elements are treated in the frequency domain while



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nonlinear elements are treated in the time domain. The solutions are interfaced using Fourier techniques. The use of Fourier techniques has traditionally limited this approach to situations involving only signals that are harmonically related. A modification of this technique to adapt it to work with nonharmonic signals is presented in [5]. This method uses a discrete Fourier transform and undersampling which results in aliasing. By shifting the frequency of the input signals several times, the resulting spectra can be used to approximately calculate the intermodulation distortion. This assumes that the input frequencies can be shifted without affecting the voltages in the circuit. The technique is thus limited to wide bandwidth circuits and to small separations of the input frequencies.

Another modified harmonic balance approach was presented in [6]. This approach calculates the frequency components using a least squares analysis that is essentially a generalized discrete Fourier transform. The disadvantage is that as the number of frequencies considered in the analysis increases, the number of time steps must increase along with the associated matrix dimensions. In addition, derivative information is required which must be either calculated numerically or provided by an analytical formula that would have to be programmed specially for each individual nonlinear element.

A strictly time domain analysis can also be used to simulate nonlinear circuits. This technique becomes impractical however when the signals are not periodic or their frequency separation is not negligible. In such cases, the time samples must be chosen small enough to accurately simulate the high frequencies and at the same time enough samples must be used to retain the low frequency information. This results in extremely long computation times and possible convergence problems.

This paper discusses the simulation of intermodulation distortion using the nonlinear analysis technique, termed *generalized power series analysis* which avoids the problems just described. This technique has the following attributes:

(1) the analysis is done entirely in the frequency domain. This allows the input frequencies to be separated by an arbitrary amount.

(2) the analysis is valid for large signals and strong nonlinearities.

(3) the analysis is easily applied to different circuit configurations.

(4) the terminating impedances at the harmonic frequencies and at the sum and difference frequencies can be varied independently.

As a demonstration of this method, results are presented for a MESFET amplifier simulation. The results with a single tone input are compared with previously published experimental results.

## METHOD OF ANALYSIS

The generalized power series method used here solves a nonlinear circuit by minimizing an error function derived from application of Kirchoff's current law. Nonlinear elements are described by generalized power series (power series with complex coefficients and time delays) relating the current through the elements to voltages in the circuit. Formulae are available to calculate the various frequency components of the currents through the elements given their generalized power series descriptions and the frequency components of the circuit voltages. These currents are used to formulate the error function. The solution is found by minimizing the error as a function of the circuit voltages. Because this technique operates entirely in the frequency domain, there are no constraints on the relationships of the frequencies considered. Thus, in simulations of intermodulation distortion, the two input signals can be arbitrarily spaced in frequency.

The use of generalized power series analysis requires separation of an active circuit into linear and nonlinear subcircuits. In the case of MESFET circuits, the nonlinear subcircuit is a collection of nonlinear resistors, capacitors, and a transconductance used to model the nonlinear behavior of the transistor. Such a circuit is shown in Figure 1. Each nonlinear element is described by a generalized power series in voltage. This type of model can predict a wide range of behavior including forward bias gate conduction and gate-to-drain breakdown, as well as the typical drain current characteristics.

The linear subcircuit consists of parasitic elements necessary for the complete MESFET model along with source and load networks. These networks can be specified

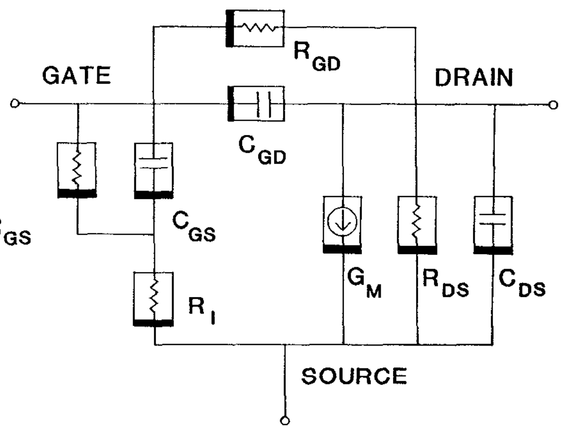


Figure 1
Circuit used to model the nonlinear behavior of the MESFET. Each element is in general nolinear and is described by a generalized power series.

separately for each frequency considered in the simulation. This enables investigation of intermodulation distortion as a function of fundamental and harmonic impedances.

## MESFET MODEL

For the simulations described in this paper, the MESFET model of Figure 1 was used. The generalized power series descriptions for the elements of the model were chosen to match the transistor discussed in [7]. wherein it is characterized and experimental results are available for the device in an amplifier circuit. This section describes the derivation of the transistor's power series model. The results of an amplifier simulation using this model are presented in the following section.

In [7], a MESFET amplifier is simulated using a time domain analysis and the results compared to experimental performance. The transistor is characterized at dc and by s-parameter measurements made at various bias conditions. The variation of the circuit elements of the transistor model as a function of bias were found by optimizing the model to fit the measured s-parameters. This data was in turn used with the method of least squares fit to determine generalized power series representations for the nonlinear capacitors transconductance and output resistance of the model shown in Figure 1.

The linear element values were chosen based on optimization to s-parameters measured at the bias point used in the simulations. The following section presents the results of the amplifier simulation using the generalized power series analysis and the model just developed.

## AMPLIFIER SIMULATION

The analysis method described in the previous section is illustrated through the simulation of the common source MESFET amplifier of [7]. The circuit considered is shown in Figure 2. The results of a simulation of the circuit of Figure 2 with a fundamental frequency of 2 GHz and two harmonics present are shown in Figures 3 and 4. The experimental results of [7] are shown for comparison. Figure 3 shows the output power at the fundamental as a function of input power. The simulated results are seen to agree well with the experimental performance. The amplifier has a small signal gain of 8.4 dB and is simulated with input powers up to 16 dBm corresponding to gain compression of approximately 4 dB. Figure 4 shows the output power at the first harmonic frequency as a function of input power. Again, agreement with experimental performance is good.

The results of an intermodulation distortion simulation are shown in Figure 5. In this simulation, signals were input at 2 and 2.5 GHz. The third order intermodulation product at 1.5 GHz is shown as a function of input power. The third order intercept occurs at an input power of 17.9 dBm corresponding to an output power of 26.3 dBm.

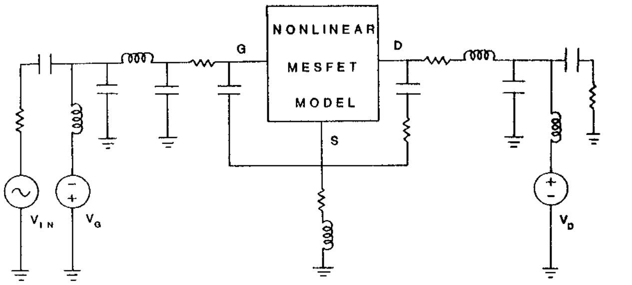


Figure 2
Common source MESFET amplifier considered in the simulations. The nonlinear MESFET model is the circuit shown in Fig. 1.

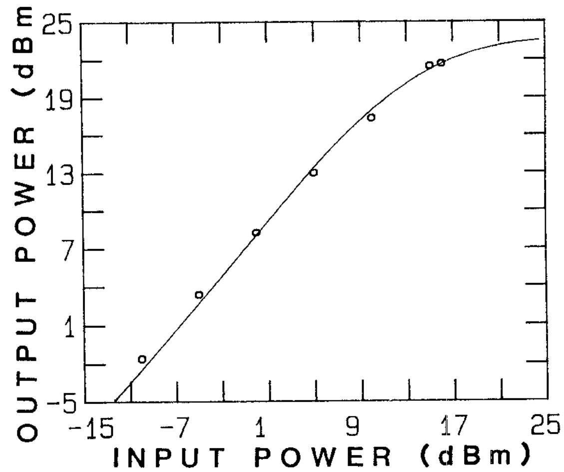


Figure 3
Power output at the fundamental frequency versus input power for the common source MESFET amplifier of Fig. 2 with a single input at 2 GHz. The simulated output power ( o ) is shown along with the experimental results (-) from [7].

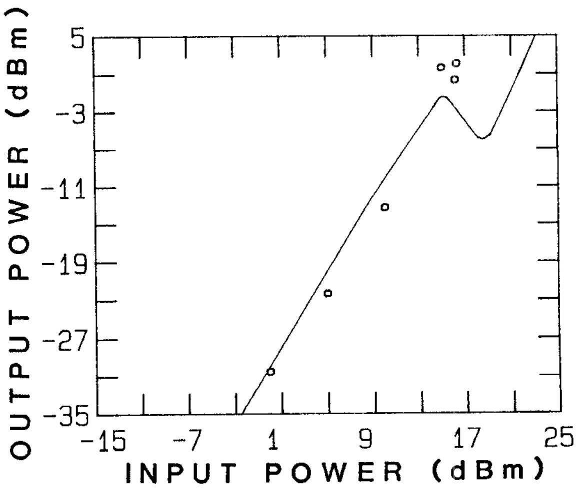


Figure 4
Power output at the second harmonic (4 GHz) versus input power for the common source MESFET amplifier of Fig. 2 with a single input at 2 GHz. The simulated output power ( o ) is shown along with the experimental results (-) from [7].

Figure 6 shows the level of the third order intermodulation product as a function of the separation of the input signals for a constant input power of 5 dBm One input is kept at 2 GHz while the other input frequency is varied over a wide range.

## CONCLUSIONS

In this paper we have discussed a novel approach to the simulation of intermodulation distortion in MESFET circuits. This approach is unique in that it is applicable to general circuits and places no restrictions on the amplitude or the frequency separation of the input signals. The terminating impedances are also unconstrained. The method was demonstrated through the simulation of a MESFET amplifier and agreement with experimental gain compression results.

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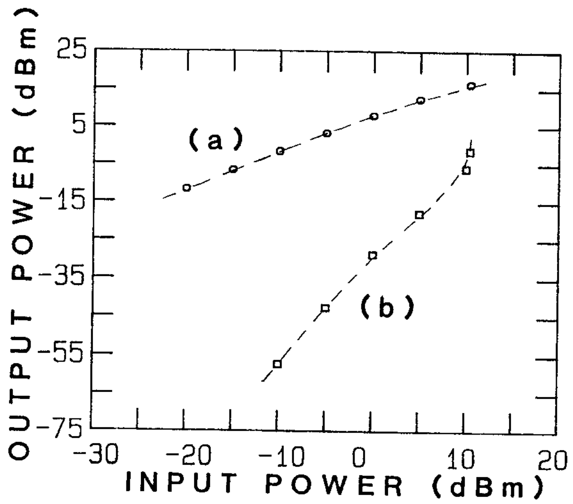


Figure 5
Simulated power output at the fundamental (a) and the third order intermodulation frequency (b) for the amplifier of Fig. 2 with inputs at 2 GHz and 2.5 GHz. The intermodulation frequency shown is at 1.5 GHz.

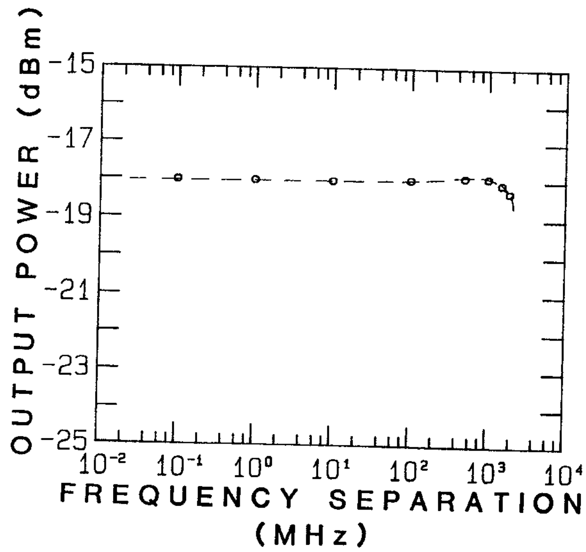


Figure 6
Simulated power output at the third order intermodulation frequency for the amplifier of Fig. 2 as a function of the separation of the input signals. One signal is fixed at 2 GHz. The input power of each signal is 5 dBm.