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# CIRCUIT DESIGN TO REDUCE 3rd ORDER INTERMODULATION DISTORTION IN FET AMPLIFIERS

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## ABSTRACT

Using a large-signal computer model for the MESFET with a modified harmonic balance technique the third-order intermodulation response of general amplifier circuits is found. The effect of device, bias, and impedance changes is investigated and compared with experimental results for a single-stage feedback amplifier. The method is useful for the design of microwave linearizers. A novel scheme for the reduction of intermodulation distortion in power amplifiers operating near compression is presented with experimental data.

## INTRODUCTION

GaAs MESFETS are increasingly finding application in power amplifiers, and particularly as solid-state replacements for TWT amplifiers, the output component in many microwave transmitters. Nonlinear behavior of the amplifier can result in intermodulation distortion, with distortion of existing frequency components within the transmission bandwidth, as well as the creation of spurious components outside it. Such behavior affects both the capacity and quality of communications links; its analysis is necessary to be able to control these parameters.

## MESFET MODEL

The FET model used in this analysis is a quasi-static modified implementation of Madjar and Rosenbaum [1]. For the basic model shown in Figure 1, the gate and drain displacement currents are derived from a three terminal nonlinear capacitance matrix, whose elements are calculated from the space charge capacitances of the channel region under the gate. The drain conduction current is given analytically by an expression similar to that derived by Curtice [2],

$$I_d(con)=(V_{SG}-V_p)^2\frac{[\beta \tanh(\eta V_{DS})+G_D V_{DS}]}{V_p^2} \qquad V_{SG}<V_p$$

$$=0 \qquad V_{SG}>V_p$$

where $\beta$ and $\eta$ are proportionality constants from the model [2]. External diode characteristics are also added to the model to allow for forward conduction and reverse breakdown at the gate-source and gate-drain junctions respectively.

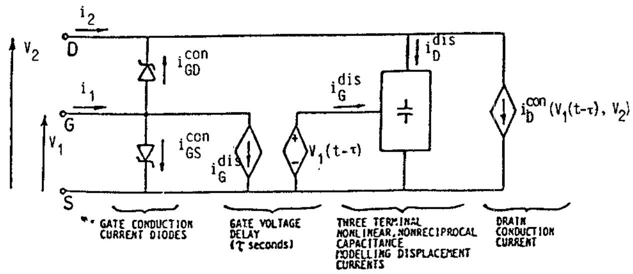


Figure 1 The nonlinear MESFET model

## THE MODIFIED HARMONIC BALANCE TECHNIQUE

The basic model is embedded in linear circuitry, composed of device parastics, matching elements, and terminations. Because the model is a time-domain one, the network is most efficiently solved by a harmonic-balance method, which uses Fourier theory to extract frequency components from time-domain samples obtained from the model. In the case of intermodulation distortion, in which two, nonharmonically related signals are applied as inputs, a modified harmonic balance approach [3] must be used to extract the closely spaced intermodulation sidebands from the complex waveform. This allows the efficient analysis of any general, linear matching circuit surrounding the MESFET, under different drive and circuit conditions.

## RESULTS

The simple resistive feedback amplifier shown in Figure 2 was modelled for $V_{GS}$ = -0.25 volts, $V_{DS}$ = +3 volts. The transistor used was an NEC72089, driven at 2 GHz, at power levels sufficient to saturate the device.

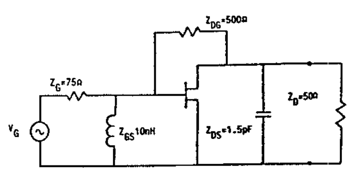


Figure 2 Lumped element AC equivalent circuit, showing the circuit external to the FET that was used to model the amplifier.



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The fundamental-frequency power response is illustrated in Figure 3a. Curves (i), (ii), and (iii) show the fundamental, reflected, and second harmonic output powers respectively; Curve (iv) shows the DC drain current. Simulations are shown as solid lines; experimental measurements are shown dashed. Figure 3b shows experimental and simulated results for two-tone (intermodulation) measurements. The top curves show the fundamental output power (per carrier) as a function of input power. The lower curves show the third-order intermodulation distortion.

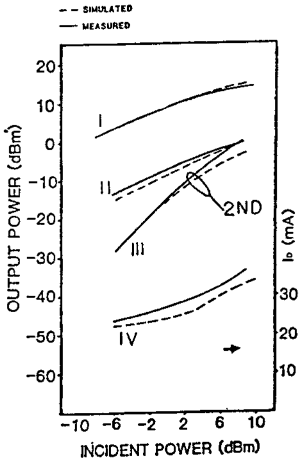


Figure 3a
Single tone measurements on a FET feedback amplifier. $V_{GS}$ =-0.25V, $V_{DS}$ = 3V, $R_{FB}$ =500Ω. From the top, the measured and simulated groups of curves show (i) fundamental, (ii) reflected and (iii)second harmonic output powers, and (iv) drain current, respectively.

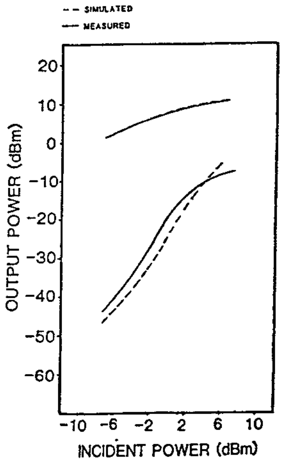


Figure 3b
Two tone measurements on the same FET amplifier, showing measured and simulated fundamental output (top) and third order intermodulation distortion (bottom) powers.

Agreement is good over the complete output range of the amplifier, even into saturation. Factors affecting the accuracy of the simulation are the choice for the second-harmonic termination, and the large dynamic range (60 dB) needed to numerically find a low level distortion signal in the presence of a much larger fundamental one. Furthermore, only small-signal measurements were taken to characterize the FET over its entire operating range.

Increasing the drain bias to $V_{DS}$ = +4V gives the fundamental, single-tone results shown in Figure 4a, and the two-tone measurements shown in Figure 4b. The effect of increased drain bias on the FET can be observed by comparison with Figures 3a and 3b. The gain and saturated output power are increased slightly, by 0.5 dB. The reflected power is essentially unchanged, and the DC drain current increased by only a few mA as we are beyond the "knee" of the FET current-voltage characteristic. Finally, at a constant output power, the level of the third-order IMD is reduced by up to 5 dB. This reduction is particularly noticeable for medium-signal levels, with outputs in the range of +5 to +10 dBm.

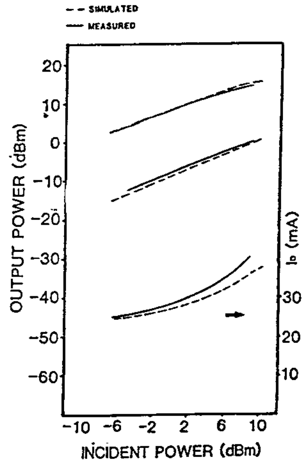


Figure 4a
Single tone measurements on the FET feedback amplifier $V_{GS}$=-.25V, $V_{DS}$=4V, $R_{FB}$=500 Ω. From the top, the measured and simulated groups of curves show fundamental output power, reflected power, and drain current, respectively.

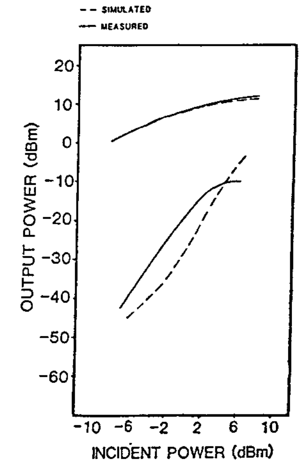


Figure 4b
Two tone measurements on the same FET amplifier, showing measured and simulated (top) fundamental output and (bottom) third-order intermodulation distortion power.

As an example of the effect of circuit variation on the distortion performance of the amplifier, the feedback resistor was reduced to 100 ohms, with $V_{GS}$ = -0.25V and $V_{DS}$ = 3V. The reflected power was reduced to more than 20 dB below the incident power. Figure 5a shows the measured and simulated fundamental output power and DC drain current for a single frequency tone.

Intermodulation measurements, in Figure 5b, show the reduction in power handling capability. Although behavior is now approximately third order, comparison with Figure 3b indicates that at a constant output power, an increase of between 10 and 15 dB in the level of the third-order product has resulted by reducing the feedback resistor to 100 ohms.

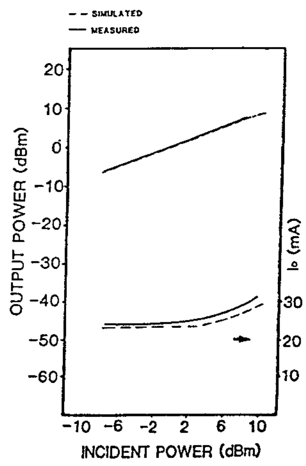


Figure 5a
Single tone measurements on the FET feedback amplifier, $V_{GS}$=-.25V, $V_{DS}$=3V, $R_{FB}$= 100Ω. The top curves show measured and simulated fundamental output power; the bottom curves show DC drain current.

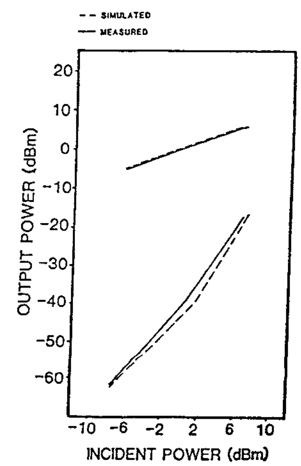


Figure 5b
Two tone measurements on the same FET amplifier. Curves are as for Figure 4b.

The technique can also be used to examine gain suppression in limiting amplifiers. As an example, Figure 6 shows measured and simulated results of the fundamental and intermodulation output powers in a saturated amplifier, driven by two tones, one of which is 5 dB stronger than the other. As shown in the Figure, the output tones differ by 5 dB at small signal levels. In saturation, gain suppression of the smaller signal can be observed, as the difference between the levels at the output has increased to 7.5 dB, where the smaller signal gain is now 2.5 dB below that of the strong signal.

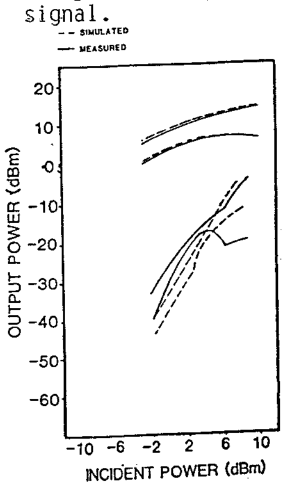


Figure 6
Two-tone tests of the FET feedback amplifier of Figure 2. Two unequal tones of level Pin and Pin -5 dB were applied to the amplifier.

The top set of measured and simulated curves show the output power in each fundamental carrier; the bottom set show the level of each third order intermodulation sideband.

LINEARITY IMPROVEMENT

The modified harmonic balance technique proves to be an invaluable tool in the design of linear amplifiers. Because the circuit impedances at each frequency can be specified independently of each other, the effect of second, third, and higher-order harmonics can be considered. The optimum second-harmonic source impedance was found to be a short circuit referred to the gate terminal of the deivce. Second-harmonic terminating impedances are important because third order intermodulation distortion can arise from any generated second-harmonic voltage remixing in the device with the fundamental. However, this is a higher order effect because the predominant intermodulation distortion arises directly from the fundamental inputs interacting via the third-order nonlinearity in the device, independently of any even-order harmonic currents or voltages. Nonetheless, by minimizing the generated second-harmonic voltage by means of a second-harmonic short circuit at the gate, intermodulation levels (for the amplifier of Figure 2) were obtained that were up to 5 dB lower than those for an open-circuit second-harmonic source termination. Third-harmonic terminating impedance made negligible difference to the third-order intermodulation distortion performance of the amplifier.

A further example motivating the use of computer simulations such as these in design is given by the amplifier modelled in Figure 7a. In this scheme, an external voltage is injected in series with the drain of the FET. Substantial improvement in linearity is achieved when the input drive and injected drain signal are driven in phase. This arises because reactive voltage swings associated with the output device are reduced, simultaneously improving both linearity and output power. Reinjection of a voltage swing of variable phase at the output is a form of load pull, and at certain phases can result in reduction of intermodulation distortion products. This results from reduction of the

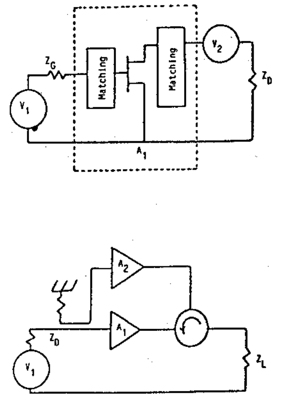


Figure 7
Novel intermodulation distortion improvement scheme. The top figure shows the configuration used in simulations; the FET and its matching elements make up amplifier $A_1$. The bottom figure gives a practical implementation: $V_2$ is added in series by the action of a second amplifier $A_2$ and the circulator.

voltage swing associated with the reactive part of the load trajectory . Output power can simultaneously increase as the output voltage and current are pulled closer in phase.

A practical implementation is given in Figure 7b. An NEZ5964-6 6-watt device was driven as part of a 50-dB gain amplifier chain. To supply the injected drain voltage, an 8 dB branch line coupler and NEZ5964-3 3-watt device was used with a microstrip circulator and delay line for phase adjustment. When the NEZ5964-6 was tuned for maximum 1-dB compressed output power without the injected signal and circulator assembly, and driven with two signals at 6 GHz of +34 dBm each at the output, the intermodulation spectrum of Figure 8a results. When combined with the injected signal, the spectrum of Figure 8b was achieved. The third-order products are reduced by 8 dB; the fifth-order products by over 20 dB. This is substantially greater than the reduction due solely to that possible by simply power combining the NEZ-3 with the NEZ-6 (which can achieve at most a 3.5 dB reduction in third-order product), and is attained with the additional circulator losses in this implementation. As shown in Figure 9, the improvement in performance is greatest at those power levels approaching saturation.

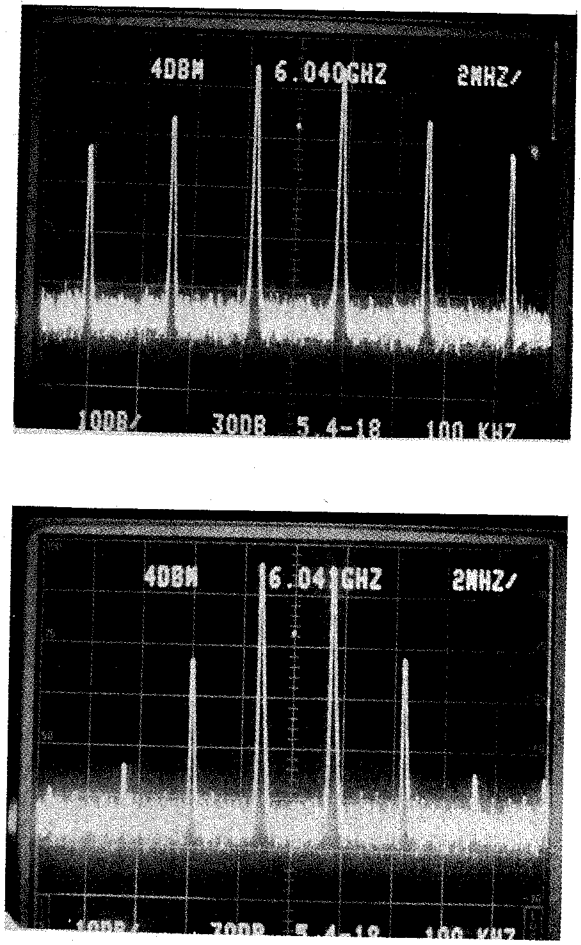


Figure 8 Intermodulation spectrum of 6-watt power amplifier with two signals of +34 dBm each at the output. a) without signal injection at drain b) with signal injection at drain. Vertical scale is 10 dB per division.

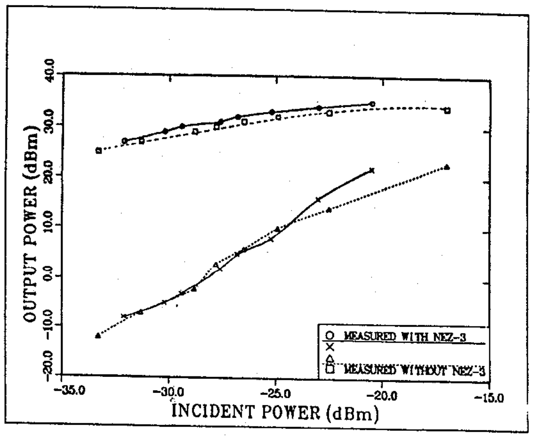


Figure 9 Measured level of fundamental and third-order intermodulation distortion products as a function of incident power for the amplifier of Figure 7 with (solid curve) and without (dotted curve) signal injection at the drain of the output FET (NEZ5964-6).

## CONCLUSION

A large-signal, circuit oriented design-technique has been presented which permits general analysis of arbitrary amplifiers excited by two, closely spaced, frequencies. This enables evaluation of intermodulation distortion response, gain suppression in limiting amplifiers, and the design of predistorters and linear amplifiers.

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