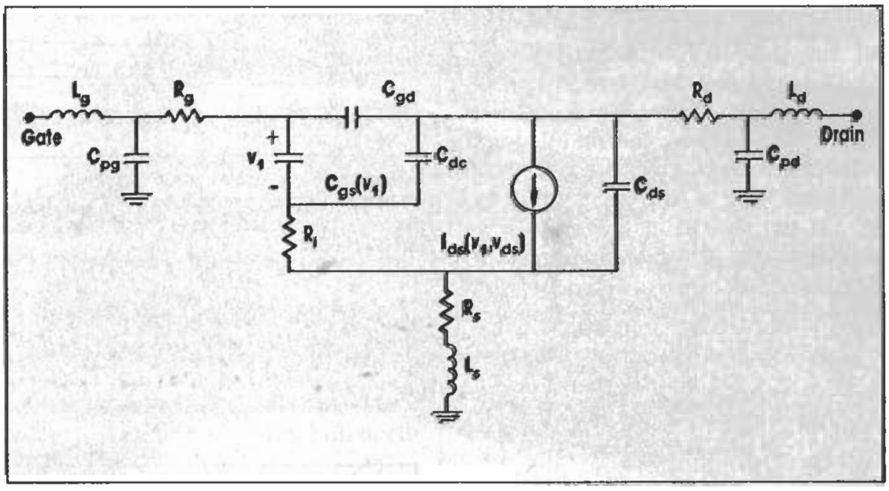
MODEL PREDICTS LARGE-SIGNAL MODFET PERFORMANCE

Small-signal measurements at various bias points yield a useful nonlinear equivalent circuit.

MODULATION doped FETs (MODFETs) provide low-noise performance in many medium- and high-power microwave applications. Unfortunately, there are few large-signal models available for MODFETs, and determining the parameters of these models at high power levels is often difficult. A good large-signal model can be obtained from small-signal measurements that require relatively common microwave instrumentation.



1. In the equivlent circuit used to model MODFETs, only C_{gs} and I_{ds} are considered nonlinear.

MODFETs are useful for class B amplifiers because their transfer characteristics can be approximated by piecewise linear curves. This feature yields large-signal transconductances that are relatively independent of the input signal level. Unfortunately, many MODFET models cannot be conveniently used in common CAD programs. However, simple modeling and measurement techniques yield polynomial expressions for nonlinear elements. These expressions can be used with most CAD programs to design matching networks for maximum gain and output power.

The modeling and measurement techniques necessary to obtain a

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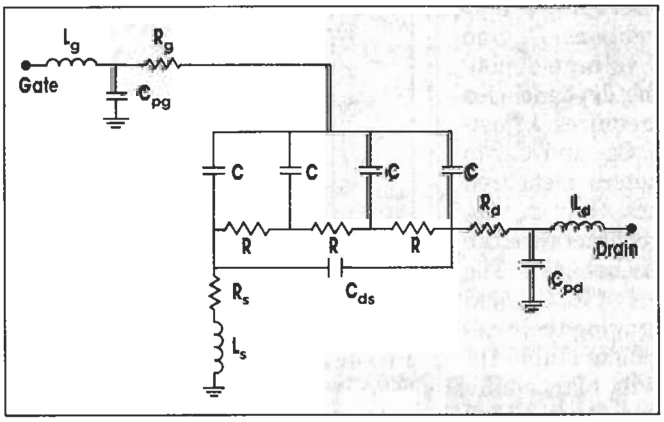
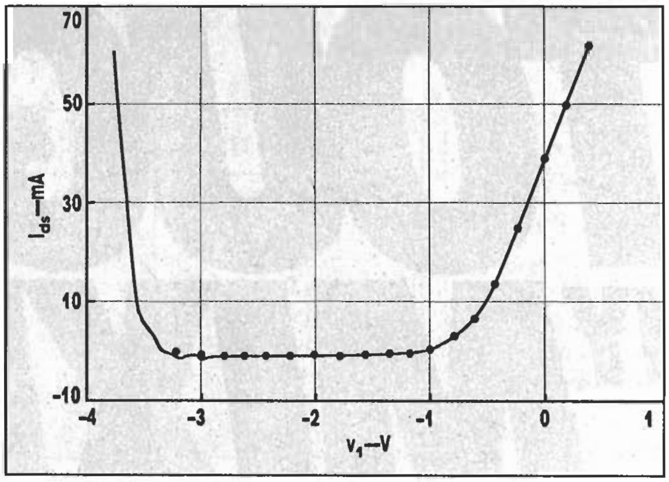
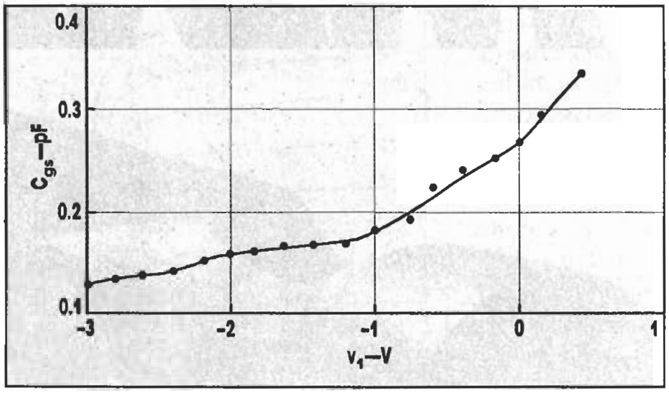


2. The circuit used to model the MODFET under zero-bias conditions yields C_{ds} and the device's extrinsic elements.



5. A 10-degree polynomial curve was fitted to the data with a maximum RMS error of 5.4 μA.



6. The dependence of C_{gs} is simulated by an 8-degree polynomial with a maximum RMS error of 3.8 fF.

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A similar procedure is used to determine $p_d(v_{ds})$, which is the dependence of I_{ds} on v_{ds}. From Eqs. 1 and 3, it is known that:

$$G_0\,(V_{GSQ},\,v_{ds}) = p_g\,(V_{GSQ})[p_d\,(v_{ds})]' \qquad (6)$$

where:

$[p_d(v_{ds})]' = d\,p_d(v_{ds})/d\,v_{ds}$.

Since $p_g(V_{GSQ}) = I_{ds}(V_{GSQ},V_{DSQ})$, it follows that:

$$[p_d\,(v_{ds})]' = G_0\,(V_{GSQ},\,v_{ds}) \div I_{ds}\,(V_{GSQ},\,V_{DSQ}) \qquad (7)$$

Eq. 7, together with the condition that $p_d(V_{DSQ}) = 1$, yields an expression for $p_d(v_{ds})$:

$$p_d\,(v_{ds}) = 1 + [I_{ds}\,(V_{GSQ},\,V_{DSQ})]^{-1} \times \int_{V_{DSQ}}^{v_{ds}} G_0\,(V_{GSQ},\,u)\,du \qquad (8)$$

Normally, p_d approaches zero for $v_{ds} = 0$. Using values of $G_0(V_{GSQ}, v_{ds})$ and performing the integration indicated in Eq. 8, $p_d(v_{ds})$ was found for v_{ds} ranging from 0.5 to 4.0 V, with $V_{GSQ} = -0.2$ V (Table 2).

CURVE FITTING

After determining the one-variable functions that describe the voltage dependencies of C_{gs} and I_{ds}, these functions must be expressed in a form that can be handled by a CAD program. If the model is to be used in SPICE, user-defined nonlinearities must be expressed in polynomial form.

There are several methods to fit a polynomial to a set of data. One such algorithm minimizes the sum of the squared residual errors using a set of orthogonal polynomials.[4] Other algorithms, including those found in commercially available math programs, can be used for this purpose.

For simulating class A operation, curves for $p_g(v_1)$ and $C_{gs}(v_1)$ are required for the entire range of v_1 in which the device operates. Similarly, these parameters should be characterized for $v_1 < V_T$ for class B or C operation. However, it may not be neccessary to measure $p_g(v_1)$ and $C_{gs}(v_1)$ for $v_1 < V_T$ because in this range $p_g(v_1) = 1$ and $C_{gs}(v_1)$ is generally a smooth function. Extrapolation of these parameters from values measured for $v_1 > V_T$ can reduce the number of measurements required.

The MODFET is characterized as

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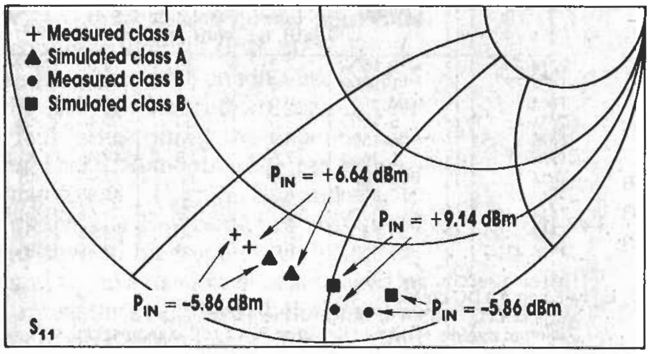
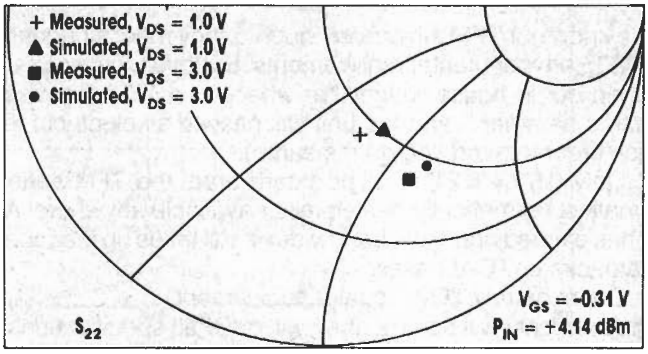


7. The MODFET's input impedance was measured and compared to calculated values for class A and B operation. The results enable rapid design of optimum input-matching networks.



8. Output impedance was measured for class B operation at two different bias points with constant input power. The sensitivity of S_{22} to drive level was relatively small.

Table 2: Numerical calculations

V_{ds} (V)	G_0 (mS)	P_d
0.5	18.9751	0.4408
1.0	8.2583	0.7215
2.0	5.2548	1.0000
3.0	3.7447	1.1855
4.0	3.4330	1.3334

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having $V_T = -1.0$ V with maximum $v_1 = +0.4$ V. Therefore, v_1 ranges from –2.4 to +0.4 V during class B operation at full drive. Extrapolation of p_g below V_T requires adding zeros at discrete values of v_1 (Fig. 5). The curve obtained using a least-squares algorithm and a 10-degree polynomial for I_{ds} has a 5.4-μA RMS error.

At low values of v_1, the polynomial approximation for $p_g(v_1)$ deviates considerably from zero. This is a typical characteristic of polynomial curve fitting, i.e., the absolute error tends to be high at the extremes of the fitting interval.

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Therefore, the highest relative errors can be expected at the leftmost extreme of the transfer characteristic, where current is small. To lessen this effect, a few zeros were added to the data at values of v_1 less than –2.4 V.

Extrapolation of $C_{gs}(v_1)$ at values below V_T is more involved. The coefficient, m, must be found to fit the measured values of C_{gs} to the following expression:

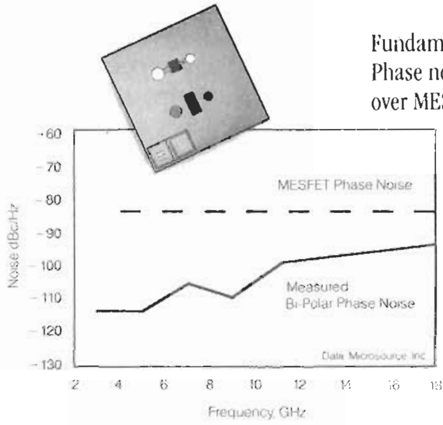
$$C_{gs}(v_1) = C_0 (1 - v_1/0.8)^{-m} \quad (9)$$

where:

C_0 = zero-bias capacitance, and
v_1 is in volts.

Eq. 9 is used to find C_{gs} for $v_1 < V_T$. For the 2SK677H5 MODFET, m = 0.474. Using an 8-degree polynomial, the curve for $C_{gs}(v_1)$ has a 3.8-fF maximum RMS error (Fig. 6).

The final step in modeling the MODFET is to interpolate the calcu-



lated values of $p_d(v_{ds})$, including the point $p_d(0) = 0$. Because interpolation is simply a particular case of polynomial fitting, the same software that is used to fit $p_g(v_1)$ and $C_{gs}(v_1)$ can be employed to interpolate $p_d(v_{ds})$.

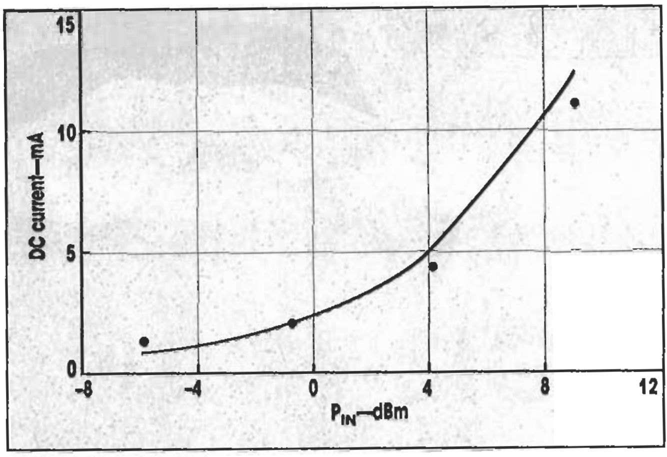
EXPERIMENTAL RESULTS

Large-signal measurements of a 2SK677H5 MODFET at 10 GHz were used to confirm the accuracy of the model's nonlinear elements, C_{gs} and I_{ds}. Simulations of the device's input reflection coefficient, S_{11}, are comparable to measured values (Fig. 7). Two values of incident power (P_{IN}) were used for both class A and B operation to show the variation of S_{11} with the drive level.

Similarly, the large-signal behavior of S_{22} is expected to be sensitive to the nonlinear dependence of I_{ds} on v_{ds}. Fig. 8 shows comparative results of this parameter at two bias levels. (S_{22} demonstrated low sensitivity to the incident power level).

The accuracy in the simulated transfer characteristic was also checked by comparing the measured DC current generated in class B operation to that calculated using the model (Fig. 9). Again, there is good agreement between measured and simulated values.

The data shows that MODFETs can be accurately modeled for large-signal operation using small-signal data and common software. The resulting model does not make any assumptions about the transistor's physical structure, and CAD simulations are in good agreement with large-signal measurements. The technique should be accurate for most MODFETs if v_{ds} is limited to values where V_T is essentially constant. ••



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9. The DC current through a MODFET operating class B was predicted with good accuracy using the large-signal model.

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Note

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References

1. W. Curtice, "GaAs MESFET modeling and nonlinear CAD," *IEEE Transactions on Microwave Theory and Techniques*, Feb. 1988.
2. F. Diamond and M. Laviron, "Measurement of extrinsic series elements of a microwave FET under zero current conditions," *Proceedings of the 12th European Microwave Conference* (Finland), Sept. 1982.
3. C. Rausher and H.A. Willing, "Simulation of nonlinear FET performance using a quasi-static model," *IEEE Transactions on Microwave Theory and Techniques*, Oct. 1979.
4. J.C. Hayes, Editor, *Numerical Approximation to Functions and Data*, Athlone Press, 1970.

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large-signal model include a program to fit an equivalent circuit to S-parameter data. A simple least-squares polynomial approximation program, as well as a CAD program such as SPICE to perform nonlinear time-domain simulations, are also required. Hardware requirements are basically limited to an automatic network analyzer to perform small-signal S-parameter measurements.

NONLINEAR MODEL

The nonlinear circuit used to model the MODFET is an extension of a widely used small-signal equivalent circuit. However, the nonlinearities of the gate-to-source capacitance, $C_{gs}(v_1)$, and the drain-to-source current, $I_{ds}(v_1,v_{ds})$, are taken into account (Fig. 1). In the small-signal equivalent circuit, $I_{ds}(v_1,v_{ds})$ is substituted with a transconductance, g_m, in parallel with an output conductance, G_0. The nonlinear nature of I_{ds} is manifested in the dependencies of g_m and G_0 on bias voltages:

$$G_0(v_1, v_{ds}) = dI_{ds}(v_1, v_{ds})/dv_{ds} \quad (1)$$

$$g_m(v_1, v_{ds}) = dI_{ds}(v_1, v_{ds})/dv_1 \quad (2)$$

where:

v_1 = voltage across C_{gs}, and
v_{ds} = drain-to-source voltage.

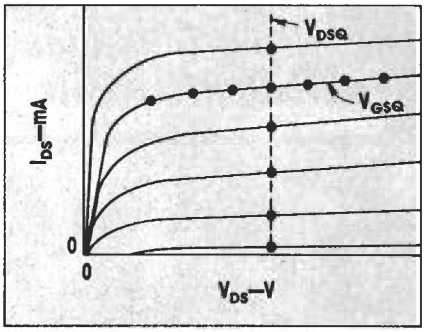
Values for C_{ds} and the extrinsic elements in the nonlinear model were determined for a 300-μm MODFET, model 2SK677H5 (Sony Corp., Cypress, CA). The device's S-parameters were measured at $v_{ds} = 0$ and $v_{gs} = 0$ to determine a zero-bias equivalent circuit (Fig. 2).[1,2]

For other bias conditions, C_{gs} and I_{ds} are considered voltage-dependent.[3] Describing the dependencies of these elements requires adjusting g_m, G_0, C_{gs}, R_i, C_{gd} and C_{dc} to match the S-parameters measured at several bias points. Only g_m, G_0, and C_{gs} are used to characterize the transistor's nonlinear behavior. The linearized equivalents of R_i, C_{gd}, and C_{dc} are found by averaging their values at several bias points (Table 1).

The distribution of bias points used to determine the small-signal equivalent circuit includes points along the lines corresponding to $v_{ds} = V_{DSQ}$ and $v_{GS} = V_{GSQ}$ (Fig. 3). These are the DC voltages at the drain and gate.

Table 1: Linear elements

L_d	0.0741 nH
L_g	0.0478 nH
L_s	0.0588 nH
R_d	1.39 Ω
R_g	1.36 Ω
R_s	1.22 Ω
C_{ds}	0.0219 pF
C_{pg}	0.0267 pF
C_{pd}	0.0371 pF



3. The distribution of bias points used to determine the nonlinear variations of C_{gs} and I_{ds} lie on curves corresponding to constant gate and drain voltages.

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It is assumed that $I_{ds}(v_1, v_{ds})$ can be expressed as the product of two single-variable functions:

$$I_{ds}(v_1, v_{ds}) = p_g(v_1)\,p_d(v_{ds}) \quad (3)$$

where:

$p_g(v_1)$ = variation with v_1, and
$p_d(v_{ds})$ = variation with v_{ds}.

The function $p_g(v_1)$ is found from the transistor's transfer function at $v_{ds} = V_{DSQ}$:

$$p_g(v_1) = I_{ds}(v_1, v_{ds})/p_d(V_{DSQ}) \quad (4)$$

By setting $p_d(V_{DSQ}) = 1$, $p_g(v_1)$ is forced to take the values of the transfer characteristic. From Eq. 2, and knowing that $I_{ds}(V_T,V_{DSQ}) = 0$, $p_g(v_1)$ can be expressed as:

$$p_g(v_1) = \int_{V_T}^{V_1} g_m(u, V_{DSQ})\,du \quad (5)$$

where:

V_T = pinch-off voltage.

Eq. 5 enables the calculation of I_{ds} as a function of v_1 for $v_{ds} = V_{DSQ}$ from measured values of g_m at several bias points. For the 2SK677H5 MODFET, g_m was measured for v_1 ranging from −1.4 to +0.4 V with $v_{ds} = V_{DSQ} = 2$ V. The corresponding values of p_g, or equivalently, $I_{ds}(v_1, V_{DSQ})$, were calculated using Eq. 5 (Fig. 4).

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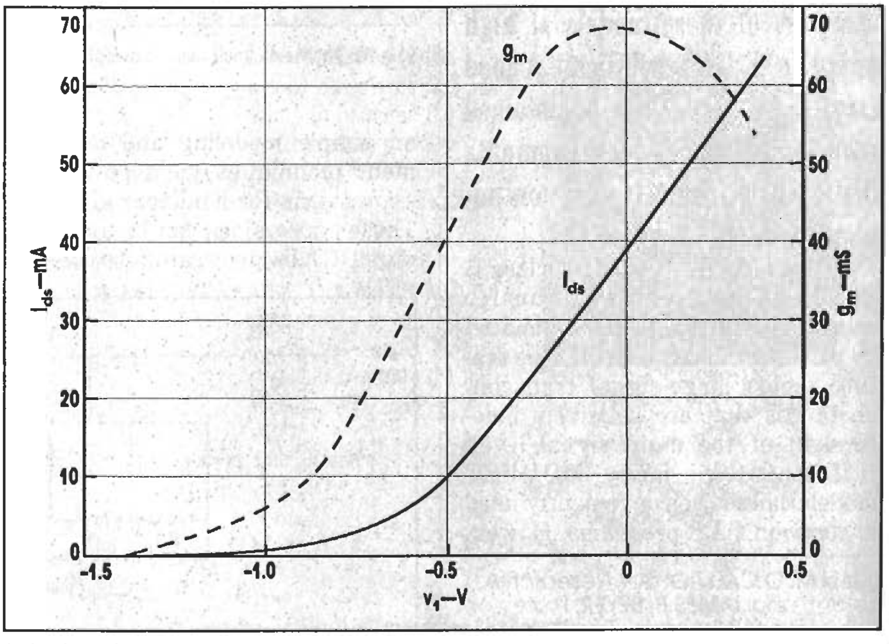

4. The dependence of I_{ds} and g_m on gate voltage was calculated from small-signal measurements at various bias points.

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