Improved FET Noise Model Extraction Method for Statistical Model Development

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Abstract

An analytic method is presented for extracting gate-source leakage resistance, R_{gs}, from S-parameter measurements ≥500 MHz. Subsequent noise source parameter extraction is frequency independent. Consequently, model parameter optimization is eliminated and physical correlations between parameters preserved. Compact statistical noise models can then be developed using the Principal Component method. R_{gs} also improves modeled low-frequency stability characteristics.

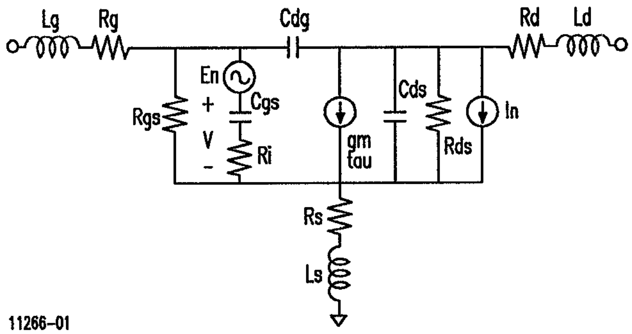

Figure 1. Hybrid-Noise Model Schematic Diagram

Introduction

Statistical yield analysis and optimization capabilities have been available in the commercial RF/microwave simulation tools for several years.[1] This has enabled yield analysis, based on the Monte Carlo method. This method is efficient and capable of accurate assessments, provided the engineer adheres to the inherent assumptions. Two key Monte Carlo assumptions are:

- All parameter distributions are Gaussian
- Parameters are mutually independent.

Generally, all parameters representing MMIC process variation can be described by or transformed to Gaussian distributions. However, parameter independence does not hold for active device Equivalent Circuit Parameters (ECPs). Resolution of this issue has been demonstrated for linear ECP models through application of analytic parameter extraction and the Principal Component method.[2] Previously, these linear models have not included the gate-to-source leakage resistance, R_{gs}, and the noise source parameters (V_N, I_N, Re[ρ], and Im[ρ]) necessary to simultaneously account for FET noise characteristics (Figure 1).

Since the Principal Component method is a linear transformation of variables, this method is extensible to noise models, provided analytic methods are used to extract R_{gs}, V_N, I_N, Re[ρ], and Im[ρ] values. Analytic methods for de-embedding noise model parameters have been reported previously.[3-5] Ikalainen[6] developed a method for directly extracting each of the noise source parameters from measurements. Ikalainen also demonstrated frequency independence of the resulting noise source parameters, provided the low-frequency Johnson noise, represented by R_{gs}, was accurately de-embedded. However, Ikalainen's method did not define an analytic R_{gs} extraction method.

Direct extraction of R_{gs} is desired for statistical model development to ensure parameter statistical distributions reflect physically-based variation. However, previous methods required optimization unless S-parameter measurements below 100 MHz were used. The proposed analytic R_{gs} extraction method does not require S-parameter measurements below 500 MHz.

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Noise parameter optimization is eliminated with this method since the noise contribution of R_{gs} is de-embedded from noise parameter data prior to application of Ikalainen's analytic noise parameter extraction method. Thus, physical statistical distributions and correlations are preserved. This enables generation of compact statistical noise models using the Principal Component method.[2]

In addition, FET models incorporating R_{gs} maintain a finite input impedance at low frequencies, consistent with physical devices. Consequently, the accuracy of low-frequency stability predictions are also improved by incorporating R_{gs}.

Hybrid-Noise Model

The hybrid-noise model used to represent the FET was illustrated in Figure 1. Figure 2 illustrates typical values for V_N and I_N, extracted by Ikalainen's analytic noise source extraction method[6] for $R_{gs} = \infty$. Note the frequency dependence of the parameter values obtained by analytic extraction.

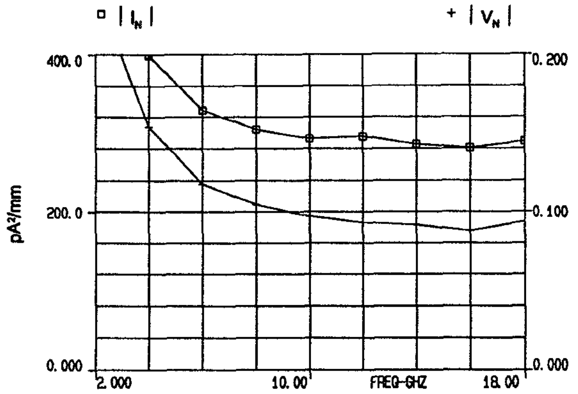

Figure 2. Typical Noise Voltage, and Current Source, Values Obtained by Analytic Extraction ($R_{gs} = \infty$)

The origin of this dependence can be identified by comparing measured versus modeled Γ_{OPT}, illustrated in Figure 3. By inspection, for $R_{gs} = \infty$, low-frequency $Re[\Gamma_{OPT(Model)}]$ is significantly larger than the corresponding values for $Re[\Gamma_{OPT(Meas.)}]$. The $R_{gs} = 1{,}250\ \Omega/mm$ curve illustrates the agreement between $\Gamma_{OPT(Meas.)}$ and $\Gamma_{OPT(Model)}$ achievable when R_{gs} is extracted prior to application of Ikalainen's method.

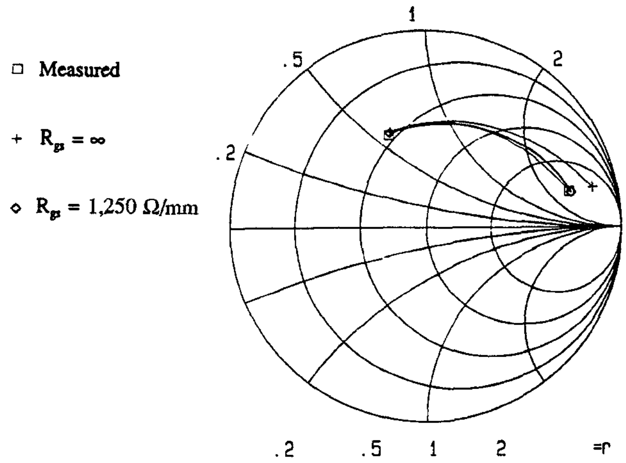

Figure 3. Measured Versus Modeled Γ_{OPT} Comparison

G-S Leakage Resistance, R_{gs}, Extraction

Previous methods for extracting the gate-source leakage resistance, R_{gs}, from S-parameter measurements above 500 MHz resulted in excessive uncertainty, and thus reliance on optimization. An accurate R_{gs} extraction method is obtained by analysis of the real part of the intrinsic input admittance $[Y_{11}]$ associated with the circuit in Figure 1. By inspection:

$$Re[Y_{11}] = \frac{1}{R_{gs}} + \frac{\omega^2 R_i C_{gs}^2}{1 + \omega^2 R_i^2 C_{gs}^2} \quad (1)$$

However, when $\omega R_i C_{gs} < 0.1$ (typically valid for $f < 10$ GHz), $Re[Y_{11}]$ can be approximated by

$$Re[Y_{11}] \approx \frac{1}{R_{gs}} + \omega^2 R_i C_{gs}^2 \quad (2)$$

This expression can be written as a linear function of ω^2 with slope m and intercept b, such that

$$Re[Y_{11}] \cong b + m(\omega^2) \quad (3)$$

where $m = R_i C_{gs}^2$ and $b = 1/R_{gs}$. Thus, R_{gs} can be obtained by fitting a line to the data for $Re[Y_{11}(\omega^2)]$ and extracting the value for R_{gs} from the intercept of that line. Linearization of $Re[Y_{11}]$ in terms of ω^2 eliminates the dependence of R_{gs} on R_i and C_{gs}. Consequently, measurements where

$$f < \frac{1}{2\pi\sqrt{R_i R_{gs} C_{gs}^2}} \tag{4}$$

are not necessary. Typically this frequency is less than 100 MHz.

Modeled Versus Measured Results

Figure 4 illustrates the noise source parameters extracted by Ikalainen's[6] method subsequent to extracting and de-embedding R_{gs} using the intercept method described above. The frequency dependence of these parameters is virtually eliminated. The frequency dependence associated with the real part of the correlation coefficient was also eliminated as illustrated in Figure 5.

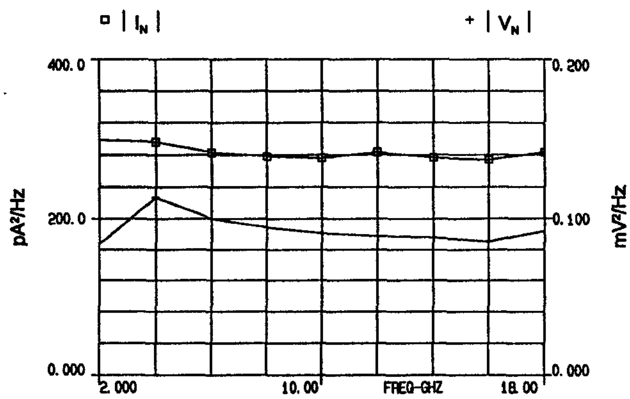

Figure 4. Noise Voltage Source and Current Source Values Obtained by Analytic Extraction (R_{gs} < 2,000 Ω/mm)

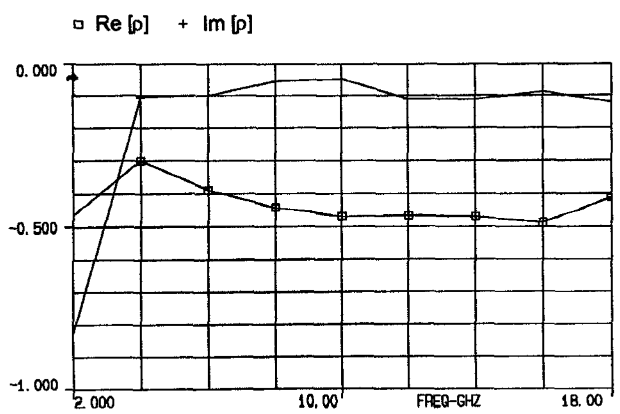

Figure 5. Noise Source Correlation Coefficients, Re[p] and IM[p], Obtained by Analytic Extraction (R_{gs} < 2,000 Ω/mm)

The low-frequency agreement between model and measured noise figure is also improved. In addition, this method significantly improved the agreement between measured and modeled stability factor, K, illustrated in Figure 6.

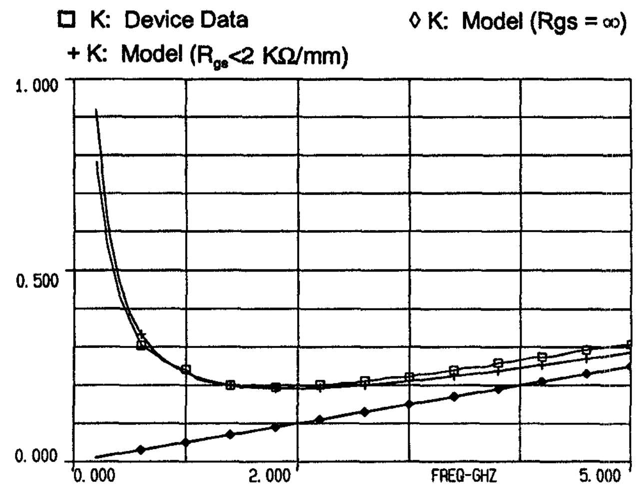

Figure 6. Stability Factor, K, Comparison

Summary

An improved procedure is presented for analytic extraction of gate-source leakage resistance, R_{gs}. This procedure reduces extracted R_{gs} uncertainty and eliminates the frequency dependence of analytically extracted noise source parameters. This approach assures the analytic solution obtained provides the best physical model representation. As a result, Principal Component ECP (PC-ECP) models demonstrated previously for linear models,[2] can be extracted from a population of noise models. Thus enabling incorporation of noise characteristics into MMIC yield analysis during the design process.

REFERENCES

[1] M. Meehan and J. Purviance, Yield and Reliability in Microwave Circuit and System Design, Boston: Artech, 1993.

[2] J. Carroll, K Whelan, S Pritchett, and D. Bridges, *FET Parameter Orthogonalization with Principal Components,* IEEE MTT-S, 1994.

[3] H. Hillbrand and P.H. Russer, "An Efficient Method for Computer-Aided Noise Analysis of Linear Amplifier Networks," *IEEE Trans. on Circuits and Systems*, Vol. 23, No. 4, April 1976.

[4] R.A. Pucel, W. Strubble, R. Hallgren, and U.L. Rohde, "A General Noise De-embedding Procedure of Packaged Two-Port Linear Active Devices," *IEEE Trans. Microwave Theory & Tech.*, Vol 40, No. 11, November 1992.

[5] A. Riddle, "Extraction of FET Model Noise-Parameters from Measurement," *IEEE MTT-S Digest*, 1991.

[6] P. Ikalainen, "Extraction of Device Noise Sources from Measured Data Using Circuit Simulator Software," *IEEE Trans. Microwave Theory & Tech.*, Vol. 41, No. 2, February 1993.