Microwave Noise Characterization of GaAs MESFET's: Determination of Extrinsic Noise Parameters

MADHU S. GUPTA, SENIOR MEMBER, IEEE, AND PAUL T. GREILING, FELLOW, IEEE

***Abstract*—The noise equivalent circuit model for a GaAs MESFET proposed previously [1] is supplemented with a model for device parasitics, in order to calculate the noise parameters of a mounted GaAs MESFET. The calculated parameters are in good agreement with measured noise parameters from 2 to 18 GHz. The model is thus established as a valid representation of the noise properties of the device. The utility of the model lies in the fact that, compared with the measured and tabulated noise parameters, its elements are easier to obtain, and it serves as a simpler, more compact description of the noise characteristics of the MESFET.**

I. Introduction

A. Motivation

IT IS WELL KNOWN in the theory of linear noisy networks [2] that a complete characterization of the noise in a linear two-port at one frequency requires a knowledge of four noise parameters. The most convenient parameters from the circuit design point of view are the minimum noise figure $F_{\min}$ of the two-port (minimized with respect to the generator admittance Y_g), the optimum value of the generator admittance $Y_{g,\mathrm{op}} = G_{g,\mathrm{op}} + jB_{g,\mathrm{op}}$, and a coefficient R_n, having the units of resistance, which measures how rapidly the noise figure degrades when the generator admittance Y_g deviates from its optimum value. The noise figure for any generator admittance can be expressed in terms of these four parameters as follows [3]:

$$F(Y_g) = F_{\min} + \frac{R_n}{G_g}\left[(G_g - G_{g,\mathrm{op}})^2 + (B_g - B_{g,\mathrm{op}})^2\right]. \quad (1)$$

A noise equivalent circuit for a GaAs MESFET in common-source configuration was presented in [1]. This equivalent circuit employs only four lumped circuit elements and a noise source; these five elements are dc-bias-dependent but frequency-independent, and their values can be found by on-wafer measurements which require no circuit tuning. Fig. 1(a) shows the noise equivalent circuit of the intrinsic device, along with the idealized model for the external circuit that has been used in [1]. The four noise parameters were calculated for this circuit model at a frequency ω under several simplifying assumptions [1], leading to the following results:

$$F_{\min} = 1 + 2R_n(G_c + G_{\mathrm{in}}) + 2\sqrt{R_n(G_c + G_{\mathrm{in}}) + R_n^2(G_c + G_{\mathrm{in}})^2} \quad (2)$$

$$Y_{g,\mathrm{op}} \equiv G_{g,\mathrm{op}} + jB_{g,\mathrm{op}} = \left[(G_c + G_{\mathrm{in}})^2 + \frac{G_c + G_{\mathrm{in}}}{R_n}\right]^{1/2} - j[B_c + B_{\mathrm{in}} + B_{\mathrm{cor}}] \quad (3)$$

$$R_n = \frac{S_{io}/4kT_{\mathrm{ref}}}{g_m^2/(1+\omega^2 C_{gs}^2 R_T^2)} \quad (4)$$

where $G_{\mathrm{in}} + jB_{\mathrm{in}}$ is the input admittance Y_{in} of the intrinsic MESFET defined in Fig. 1(a), S_{io} is the power spectral density of the output noise current i_o at ω, T_{ref} is the reference temperature of 290 K, jB_{cor} is the purely imaginary correlation admittance relating the noise voltage i_o/g_m to the correlated part of the input noise current i_{in}, k is Boltzmann's constant, and all other symbols have been defined in Fig. 1(a).

The noise model of Fig. 1(a) was validated in [1] by on-wafer experimental measurements, which demonstrated that the model is capable of predicting the minimum noise figure $F_{\min}$ of the device embedded in a linear circuit over a range of microwave frequencies and dc bias conditions. The present paper generalizes the results of [1] in the following two ways:

(i) It shows how the MESFET noise model can be extended so that it applies not only to on-wafer devices, but also to devices that are mounted and bonded in circuits.

(ii) It shows, by comparing calculated and experimental results, that the device noise model presented in [1] is useful for predicting not only the minimum noise figure $F_{\min}$, as demonstrated in [1], but other noise parameters as well.

B. The Problem

While the ability to determine $F_{\min}$ entirely from on-wafer measurements is a major advantage of the proposed

Manuscript received March 3, 1987; revised September 24, 1987.

The authors are with the Hughes Research Laboratories, Malibu, CA 90625. M. S. Gupta is also with the Department of Electrical Engineering and Computer Science, University of Illinois at Chicago, Chicago, IL 60680.

IEEE Log Number 8719196.

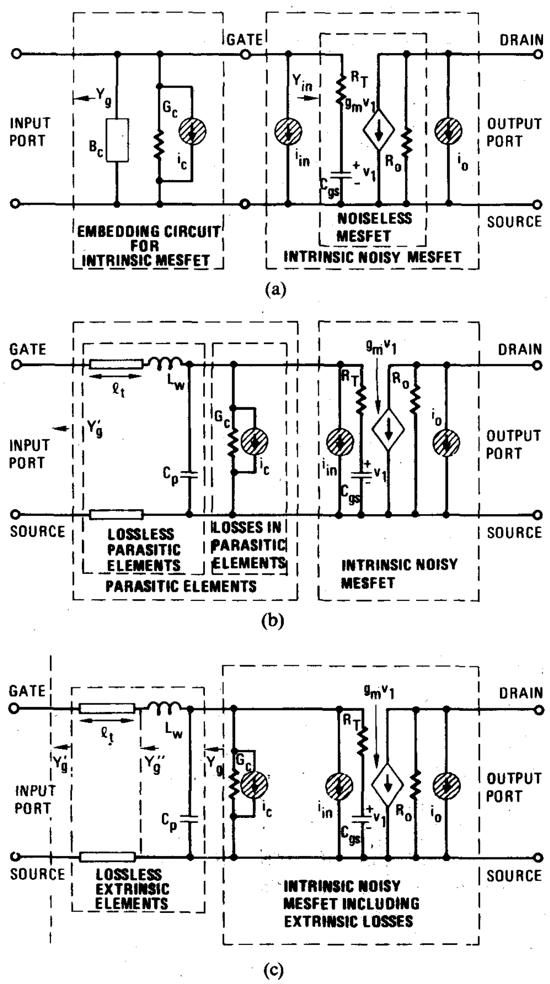

Fig. 1. Noise equivalent circuits for the MESFET, its parasitics, and its circuit. (a) The noise model for the intrinsic device, and the representation of external circuit, as used in deriving the noise parameters in Part I of this paper. (b) The noise model for the intrinsic device, and for the parasitic elements included within the reference planes at which the device noise characterization is carried out. Together, these define the "extrinsic MESFET." (c) The inclusion of the losses of the parasitic elements along with intrinsic device for simplifying the calculation of noise parameters.

model and technique, the noise model should be equally applicable to MESFET's that are not on-wafer, e.g., packaged devices or chips mounted and bonded on a carrier. The electromagnetic nature of the packaging and bonding region can usually be represented by some parasitic elements, such as the bonding wire inductance and bonding pad capacitance. The inclusion of parasitics was not necessary in [1], where only the expression for $F_{\min}$ in (2) was verified by actual measurement. This is because the package or the chip carrier contributes to the device some parasitic elements which are largely lossless, and $F_{\min}$ is invariant with respect to lossless transformations at the input and output ports of a two-port [4]. By contrast, the other three noise parameters $G_{g,\mathrm{op}}$, $B_{g,\mathrm{op}}$, and R_n are *not* invariant to lossless transformations and therefore change as a result of the parasitics introduced by device mounting and packaging. Since the experimental measurement of the noise parameters in practice is usually carried out on mounted devices which incorporate the parasitics, the values of the four noise parameters as obtained by experimental measurement, and as contained in manufacturers' data sheets, are normally defined at reference planes which are physically separate from the terminals of the intrinsic MESFET in general. On the other hand, the four noise parameters calculated from (2)–(4) are "intrinsic noise parameters," since the noise equivalent circuit of Fig. 1(a) represents only the intrinsic elements of the MESFET (shunted by Y_c at the input), and does not account for the device parasitics. A proper accounting of these parasitics is essential before the measured (extrinsic) and the calculated (intrinsic) noise parameters can be compared.

In most circuit applications, the device is typically embedded in the circuit along with its mounting and bonding parasitics. Therefore, in order to optimize the noise performance of the circuit, the circuit designer needs the extrinsic noise parameters of the MESFET, which include the effect of the parasitics. Moreover, the reference plane at which these parameters are defined must be precisely known for the noise parameters to be useful in any actual design optimization.

C. Objectives

The primary purpose of this paper is to (a) extend the noise model of MESFET to include the parasitics introduced by mounting and packaging, (b) develop transformations relating the noise parameters at the terminals of the intrinsic device to those at the terminals of the extrinsic device and vice versa, (c) compare the calculated extrinsic noise parameters with the experimentally measured noise parameters, and (d) thereby establish the validity of the noise model of [1] for predicting noise parameters other than $F_{\min}$.

A noise equivalent circuit model for the MESFET including the parasitics is given in Section II, and it is shown how the value of each circuit element in this model is deduced from experimental data taken on the MESFET. The noise parameters are then calculated from the model, and are compared with experimentally measured noise parameters in Section III.

As a by-product, this paper also serves the following secondary purposes:

(a) Normally, the noise parameters of the MESFET are reported on the device data sheets in tabular form, listing the values of $F_{\min}$, $G_{g,\mathrm{op}}$, $B_{g,\mathrm{op}}$, and R_n as a function of frequency. This paper suggests a method of summarizing the measured device noise data very compactly in the form of the values of a few model circuit elements, from which the tabulated data can be calculated using simple closed-form expressions.

(b) The usual method of determining the equivalent circuit parameter values of the MESFET (and its parasitics) is by numerically optimizing the equivalent circuit element values for which the S parameters of the equivalent circuit best match the S parameters of the device over a wide frequency range. In an analogous manner, if the noise parameters have already been measured over a wide frequency range, the technique of this paper can be used to determine the values of the MESFET noise equivalent circuit parameters and parasitic elements by fitting them to the measured noise parameters of the device.

(c) The experimental data used in [1] to verify the noise model were obtained on developmental devices, which are not publicly available. In this paper, commercially available MESFET and noise parameter data are used for modeling and verification, so that the readers can verify the validity of the noise models for themselves.

TABLE I
MEASURED VALUES OF THE NOISE PARAMETERS OF NE045 MESFET AS A FUNCTION OF FREQUENCY

	Packaged Device [5]			Unpackaged Device [7]		
f_0 (GHz)	F_{min} (dB)	$\Gamma_{g,op}$	R_n (Ω)	F_{min} (dB)	$\Gamma_{g,op}$	R_n (Ω)
2.0	0.45	0.78∠29°	33.5	0.45	0.77∠16°	42.5
4.0	0.5	0.85∠58°	32.5	0.5	0.75∠29°	40
6.0	0.6	0.73∠90°	20.0	0.6	0.72∠43°	38.5
8.0	0.8	0.65∠122°	19.0	0.8	0.68∠53°	37.5
10.0	1.1	0.61∠152°	13.0	1.1	0.64∠65°	30
12.0	1.45	0.60∠−169°	10.0	1.45	0.60∠75°	25
14.0	1.7	0.59∠−136°	5.5	1.7	0.56∠90°	20
16.0	—	—	—	1.9	0.53∠110°	15
18.0	2.2	0.57∠−83°	4.5	2.2	0.53∠125°	10

II. NOISE MODEL FOR THE EXTRINSIC MESFET

A. The Device Parasitics

Although many parasitic elements are usually included in a broad-band representation of the MESFET (see, for example, [1, fig. 4]), the noise analysis can be simplified if some of these can be combined together to yield the effective values for a few essential parasitic elements. Such a model of parasitics, reduced to its simplest form, is shown in Fig. 1(b), and includes the following elements:

(i) The net capacitance C_p in shunt at the input port of the MESFET. The largest contribution to C_p is usually due to the bonding pads on the semiconductor chip.

(ii) The net inductance L_w in series at the input port of the MESFET. Much of L_w is due to the bonding wires leading from bonding pads to the transmission line of the fixture in which the measurements are made.

(iii) The net loss in the parasitics, represented by a shunt conductance G_c at the input port. This manner of modeling the loss has been motivated by the simplicity of subsequent calculation that it allows, as will be shown in Section III.

(iv) The net electrical length l_t of a lossless uniform nondispersive section of transmission line representing the physical separation of the plane of measurement from the intrinsic device. This line has a characteristic admittance Y_0, and it introduces a time delay $\tau_d = v_p/l_t$, where v_p is the speed of electromagnetic waves on the transmission line.

This model will be referred to as "extrinsic MESFET" in the subsequent discussions. This model is one of the many that could be constructed to represent the MESFET along with its parasitics, and was selected due to its intuitive appeal, since each element in it can be given a direct physical interpretation in terms of the device structure.

The parasitics at the output port of the MESFET have been ignored in this model for the following reason. In general, the parasitics at the output port will also consist of the lossy and the lossless elements, and will therefore have two effects. The thermal noise in lossy elements will contribute to the noise figure, while the impedance of all the elements will serve to transform the load impedance. Consider first the thermal noise due to the losses in the output parasitics. If the gain of the MESFET is large, the contribution of the lossy parasitics to the overall noise figure is negligible. Next consider the impedance transformation due to the parasitics at the output. Since the four noise parameters are each independent of the load impedance of the two-port, they are unaffected by the parasitics.

B. The Device and Its Noise Parameters

All circuit element values, calculated noise parameters, and measured noise data reported in this paper pertain to the NE045 microwave GaAs MESFET's manufactured by the NEC Corporation. These devices are designed for low-noise, high-gain applications, and are available in chip form. They are fabricated by a triple epi layer self-aligning process and have recessed aluminum gate which is 0.3 μm long and 200 μm wide. These devices were chosen for two reasons:

(i) Unlike the developmental devices reported in [1], the NE045 MESFET's are commercially available in quantity, so that our results can be verified in other laboratories.

(ii) Detailed specifications for this device are available from the manufacturer in the form of a data sheet [5], which includes broad-band noise parameters of the MESFET.

The data sheet specifies the microwave small-signal and the noise parameters for this MESFET under one operating condition, in which the device is maintained at room temperature, and is dc biased at a drain-to-source voltage $V_{DS} = 3$ V and a drain current $I_D = 10$ mA. All parameters and calculations mentioned in this paper therefore also refer to this same operating point.

The measured values of the four noise parameters for this MESFET packaged in a standard 70 mil microstrip package [6], at the above operating point and over the frequency range 2 to 18 GHz, are shown in Table I, which is taken from the manufacturer's data sheet [5]. In place of $Y_{g,op}$ the data sheet provides the optimum generator reflec-

TABLE II
EQUIVALENT CIRCUIT PARAMETERS FOR INTRINSIC MESFET AND EXTRINSIC PARASITICS DETERMINED BY MEASUREMENTS

Intrinsic Elements	Extrinsic Elements
(a) Determined from S parameter fitting: $C_{gs} = 160$ fF $R_T = 7.1\ \Omega$ $g_m = 36.5$ mS $R_0 = 450\ \Omega$.	(d) Determined from S parameter fitting: $C_p = 20$ fF $L_w = 0.1$ nH.
(b) Determined from output noise current spectrum measurement: $S_{io} = 7.1\times10^{-22}\ \mathrm{A^2/Hz}$.	(e) Estimated from low-frequency noise parameter measurement: $G_c = 0.7\times10^{-4}$S.
(c) Assumed to be negligible (compared to B_n): $B_{cor} = 0.0$ mS.	(f) Estimated from broadband noise parameter data: $\tau_d = 3.5$ ps.

tion coefficient $\Gamma_{g,op}$ on a transmission line of characteristic admittance $Y_0 = 20$ mS, from which $Y_{g,op}$ can be determined, if desired. The right half of Table I contains a more recent set of noise parameter data, also available from the device supplier [7], for the same device in chip (unpackaged) form and at the same operating point. The second set is measured with the input port reference plane at the gate bonding pad of the device, and will therefore be used in all of the following calculations. The first set is nevertheless included in this table because it will subsequently help clarify the role of a parasitic element τ_d, to be introduced later.

C. Equivalent Circuit Parameter Evaluation

The NE045 MESFET chip was mounted in the fixture that has been described in the literature [8], and the values of the four equivalent circuit elements C_{gs}, R_T, g_m, and R_0 were determined from the broad-band S parameters of the device. The measured S parameters for the device are not reported here, because they are in very good agreement with the S parameters contained in the data sheet mentioned above [5]. The equivalent circuit elements were found by fitting the MESFET equivalent circuit to the measured S parameters, as described in [1]. At the operating point of interest, the element values thus found have the values listed in Table II. In addition to these element values, the S parameter fitting also yields the values of some of the parasitic elements associated with the device; these are discussed in Section II-D.

The fifth parameter, S_{io}, obtained through the output noise power measurement method described in [1], is also listed in Table II. The only intrinsic equivalent circuit parameter not determined is B_{cor}. Of the four noise parameters, only $B_{g,op}$ is influenced by B_{cor}. If the correlated input noise current is small, B_{cor} will also be small. It will be assumed to be negligible compared to B_{in} in the following. This assumption should be valid for the lower frequencies (up to 18 GHz), for which the noise parameter expressions of Section I-A hold.

The remainder of Section II describes a method for determining each of the circuit elements appearing in the model of Fig. 1(b) and illustrates this method by an actual determination of the element values for a commercial MESFET.

D. Determination of Parasitics

The S parameter fitting procedure mentioned in Section II-C yields the values of the parasitic elements C_p and L_w along with the values of the intrinsic MESFET parameters. These values are also listed in Table II.

The third parasitic element G_c can be determined in one of several ways. Since the device noise parameter data are available for NE045 MESFET in Table I, the simplest way of estimating G_c is through the measured values of the device noise parameters at a low frequency f_L. This frequency should be sufficiently low that the device input conductance G_{in} becomes negligible compared to G_c, but should be sufficiently high that the noise parameters are not influenced by the low-frequency noise sources such as $1/f$ and $g-r$ noise in the device. At such a frequency, each of the noise parameters F_{min}, R_n, and $G_{g,op}$ of the intrinsic MESFET becomes independent of frequency, and this fact can be used as a check of the correct choice of f_L. For devices with submicrometer gate lengths, a frequency of approximately 1 GHz is a suitable choice for f_L in most normal cases.

The value of G_c can be found by solving (2) in the low-frequency limit, which yields

$$G_c = \frac{(F_{min}-1)^2}{4R_n} \quad \text{at } f_L. \tag{5}$$

Alternatively, (3) in the low-frequency limit could be solved for G_c, which leads to

$$G_c = \frac{\sqrt{1+(2R_nG_{g,op})^2}-1}{2R_n} \quad \text{at } f_L. \tag{6}$$

Although the measured parameter values in Table I apply at the reference plane of measurement, they can be used in place of the intrinsic parameter values appearing in (5) and (6) since the parasitics have a vanishing effect in the limit of low frequencies, where (5) and (6) apply.

From the data in Table I, the values of F_{min}, R_n, and $G_{g,op}$ at 1 GHz can be extrapolated as 0.4 dB, 43 Ω, and 2.3 mS, respectively. The estimated value of G_c is thus found to be 0.07 mS from (5), and 0.18 mS from (6). While this scatter implies either a discrepancy in the measured data or a weakness in the noise model at low frequencies, or both, it has little effect on the accuracy of modeling at microwave frequencies, where G_c is small compared to G_{in}. The value of G_c is therefore taken as 0.07 mS in Table II; this will result in a circuit model which will have a better match with F_{min} data than with $G_{g,op}$ data at low frequencies, since (5) is used and (6) is ignored.

The last parasitic value τ_d depends on the exact location of the reference plane at which noise parameters were defined and measured. This will therefore be treated as an unknown, and will be determined from the noise parameter data themselves.

III. Calculation of Noise Parameters

Having determined the value of every element (except τ_d and B_{cor}) in the noise equivalent circuit model of Fig. 1(b), the noise parameters for the extrinsic MESFET can be calculated. In principle, this calculation can be carried out in three steps:

(i) The four noise parameters for the intrinsic MESFET in the right half of Fig. 1(b) can be calculated directly from (2)–(4), by setting $Y_c = 0$.

(ii) The noise parameters of the passive two-port consisting of the parasitic elements alone, as shown in the left half of Fig. 1(b), can be calculated from a knowledge of the Z parameters of this two-port [9].

(iii) The relationships for the noise parameters of a cascade of two two-ports [10] can be employed to determine the overall noise parameters for the complete extrinsic MESFET of Fig. 1(b).

However, the results can be obtained by a simpler technique as follows. Since the lossy part of the parasitics has been modeled as a shunt conductance G_c at the input port of the intrinsic MESFET, its effect on the noise parameters can be included in (2)–(4), by setting $Y_c = G_c$, which accounts for the loss in the parasitic elements. The quantities F_{min}, $Y_{g,op}$, and R_n thus determined are the noise parameters for the combination of intrinsic MESFET plus parasitic losses, while Y_g and Γ_g are the generator admittance and reflection coefficient connected to this combination, as indicated in Fig. 1(c). The noise parameters and the generator admittance for the complete extrinsic MESFET of Fig. 1(b) will be denoted by the corresponding symbols with primes. These can be calculated from the unprimed quantities as follows:

(i) The remainder of the parasitics form a lossless transformation at the input port, and therefore leave the minimum noise figure invariant. Therefore, F'_{min} for the entire extrinsic MESFET is the same as the F_{min} for the combination of intrinsic MESFET plus extrinsic losses:

$$F'_{min} = F_{min}. \tag{7}$$

(ii) The generator admittance Y'_g at the input port of the extrinsic MESFET is related to the generator admittance Y_g (seen at the input port of the intrinsic MESFET plus extrinsic losses combination) by

$$Y_g(\omega) = j\omega C_p + \frac{1}{j\omega L_w + \dfrac{1}{Y''_g(\omega)}} \tag{8a}$$

$$Y''_g(\omega) = Y_0 \frac{1-\Gamma''_g(\omega)}{1+\Gamma''_g(\omega)} \tag{8b}$$

$$\Gamma''(\omega) = e^{-j\omega\tau_d}\Gamma'_g(\omega) \tag{8c}$$

$$\Gamma'_g(\omega) = \frac{Y_0 - Y'_g(\omega)}{Y_0 + Y'_g(\omega)} \tag{8d}$$

where Y''_g and Γ''_g are defined at the reference plane defined in Fig. 1(c). Since the noise figure remains invariant with respect to lossless transformation, the optimum values of Y_g and Y'_g occur together. Therefore, the noise parameter $Y'_{g,op}$ for the extrinsic MESFET can be found by inverting the set of eqs. (8) as

$$Y'_{g,op}(\omega) = Y_0 \frac{1-\Gamma'_{g,op}(\omega)}{1+\Gamma'_{g,op}(\omega)} \tag{9a}$$

$$\Gamma'_{g,op}(\omega) = e^{j\omega\tau_d}\Gamma''_{g,op}(\omega) \tag{9b}$$

$$\Gamma''_{g,op}(\omega) = \frac{Y_0 - Y''_{g,op}(\omega)}{Y_0 + Y''_{g,op}(\omega)} \tag{9c}$$

$$Y''_{g,op}(\omega) = \left[-j\omega L_w + \frac{1}{Y_{g,op}(\omega) - j\omega C_p}\right]^{-1}. \tag{9d}$$

(iii) The value of the last noise parameter R'_n for the extrinsic MESFET can be found by the use of a theorem due to Lange [11], which states that the product $R_n G_{g,op}$ is also invariant with respect to lossless transformation. Therefore, the value of R'_n for the extrinsic MESFET is given by

$$R'_n = \frac{R_n G_{g,op}}{G'_{g,op}}. \tag{10}$$

The four noise parameters for the extrinsic MESFET are thus calculated in two steps. First, the noise parameters for the intrinsic MESFET plus extrinsic losses combination are calculated from (2)–(4). Then the four noise parameters F'_{min}, R'_n, and $Y'_{g,op}$ are obtained from (7), (9), and (10).

The one unknown τ_d is treated as an adjustable parameter. Since it influences only the values of R'_n and the angle of $\Gamma'_{g,op}$, it is selected to obtain a good fit between the calculated and measured values of R'_n and the angle of $\Gamma'_{g,op}$. The value of τ_d was thus estimated to be approximately 3.5 ps, which is included in Table II.

The four noise parameters for NE045 MESFET, found in this manner, are plotted as a function of frequency in Fig. 2. The optimum generator reflection coefficient $\Gamma'_{g,op}$ on a transmission line of characteristic admittance $Y_0 = 20$ mS is calculated from, and is plotted instead of, $Y'_{g,op}$. For the purpose of comparison with experimental data, the

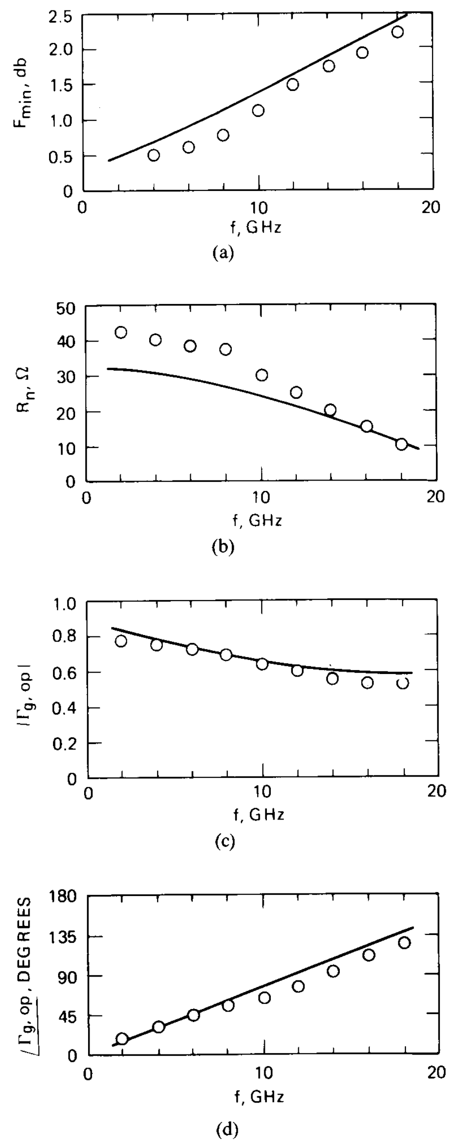

Fig. 2. Noise parameters for the NE045 MESFET as calculated from the noise equivalent circuit (solid curve) and measured values provided by the device supplier (circles).

chip noise parameters from Table I are also plotted in Fig. 2 as circles. It is apparent that there is good agreement within the uncertainty of measurements. A good agreement can also be obtained with the noise parameter data in Table I for the packaged device by a suitable choice of τ_d. In this case, the value of τ_d is estimated to be approximately 10 ps for good agreement with the measured R_n' data, and 25 ps for good agreement with measured angles of $\Gamma_{g,op}'$ over the entire frequency range. Thus the process of model parameter determination helps understand exactly how the two data sets in Table I differ from each other with respect to the reference plane used during the measurement of noise parameters.

IV. Conclusions and Significance

The principal conclusions of this paper can be summarized as follows:

(i) The noise equivalent circuit of the extrinsic MESFET can be used for predicting not only the minimum noise figure of the MESFET, as shown in [1], but also the other noise parameters $G_{g,op}$ and R_n as a function of frequency.

(ii) The noise parameters for the intrinsic GaAs MESFET, calculated from the noise equivalent circuit, can be transformed to the accessible reference planes of the MESFET by including the effect of the extrinsic parasitics.

(iii) If the small-signal and package parasitic elements have already been determined for the MESFET, one additional measurement of the noise current spectral density S_{io} is sufficient to determine the noise parameters F_{min}, $G_{g,op}$, and R_n.

The practical significance of these results lies in the following possible uses of the technique of this paper:

(i) The results of this paper show that the device parasitics can be helpful in the design of low-noise circuits. At low frequencies, the parasitics have little effect, so that the value of $R_n'(\omega)$ is nearly equal to the frequency-independent value of R_n. At higher frequencies, the parasitics cause $R_n'(\omega)$ to fall below R_n, and must at the same time increase $G_{g,op}'(\omega)$ above $G_{g,op}$, since the $R_n G_{g,op}$ product remains invariant. Both of these changes are helpful. The increase of $G_{g,op}'(\omega)$ makes it easier to provide an optimum termination at the input port of the device, since $G_{g,op}$ is typically smaller than the most commonly encountered value of $G_g = 20$ mS in practice. At the same time, a smaller $R_n'(\omega)$ implies that the noise figure is less sensitive to degradation caused by nonoptimal input termination. Indeed, controlled amount of on-chip parasitics may be added to simplify the design of the circuit at a given frequency.

(ii) The noise behavior of the MESFET in a linear circuit, and under given dc bias and temperature conditions, can be compactly summarized in a small set of parameters (the five intrinsic device parameters, and a few parasitics), from which the noise performance can be readily calculated at any desired frequency. This eliminates the need for graphical or tabulated noise data, such those in Table I, which are cumbersome and require interpolation for a frequency not present in the table. All but one of the parameters in this small set are typically already determined for small-signal characterization of the MESFET, so that only one additional number, the noise current spectral density S_{io}, is needed for complete noise characterization. This set of parameters can be used for such purposes as device specification, circuit design, and optimization. In particular, this parameter set can be efficiently used in the device parameter libraries that usually accompany some of the commonly available computer software for circuit analysis and simulation.

(iii) The measured values of the noise parameters over a range of frequencies can be used to estimate the values of the several elements in the noise equivalent circuit and the parasitic elements, by requiring best fit. This is analogous to the determination of the device equivalent circuit elements by broad-band S parameter measurement followed by model fitting to the measured data.

ACKNOWLEDGMENT

The authors thank R. Mencik of California Eastern Laboratories, Inc., Santa Clara, CA, for providing the more recent data on NE045 MESFET's, and O. Pitzalis, Jr., of EEsof, Inc., Westlake Village CA, who carried out the measurement and fitting of S parameters.

REFERENCES

[1] M. S. Gupta, O. Pitzalis, Jr., S. E. Rosenbaum, and P. T. Greiling, "Microwave noise characterization of GaAs MESFETs: Evaluation by low-frequency output noise current measurement," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 1208–1218, Dec. 1987.

[2] H. Rothe and W. Dahlke, "Theory of noisy fourpoles," *Proc. IRE*, vol. 44, no. 6, pp. 811–818, June 1956.

[3] IRE Subcommittee 7.9 on Noise (H. A. Haus, Chairman), "Representation of noise in linear twoports," *Proc. IRE*, vol. 48, no. 1, pp. 69–74, Jan. 1960.

[4] H. A. Haus and R. B. Adler, *Circuit Theory of Linear Noisy Networks.* New York: Wiley, 1959.

[5] NEC Corporation, *NE045 MES Field Effect Transistor Preliminary Data Sheet*, California Eastern Laboratories, Inc., Santa Clara, CA, June 1985, 6 pp.

[6] D. W. Hughes, H. M. Harris, and C. T. Rucker, "An equivalent circuit for a 70 mil microstrip package," *Microwave J.*, vol. 29, no. 8, pp. 97–102, Aug. 1986.

[7] R. Mencik (California Eastern Laboratories, Inc., Santa Clara, CA), private communication, 1987.

[8] O. Pitzalis, J. Marzan, and S. E. Rosenbaum, "A DC to 26.5 GHz coaxial test fixture for MMICs and transistors," in *27th Automatic RF Technol. Group Conf. Dig.*, (Baltimore, MD), June 1986, pp. 135–147.

[9] S. M. Bozic and S. G. Emmett, "Evaluation of equivalent external noise generators for passive networks," *Int. J. Electron.*, vol. 29, no. 6, pp. 597–599, Dec. 1970.

[10] K. Hartmann and M. J. O. Strutt, "Changes of the four noise parameters due to general changes of linear two-port circuits," *IEEE Trans. Electron Devices*, vol. ED-20, pp. 874–877, Oct. 1973.

[11] J. Lange, "Noise characterization of linear twoports in terms of invariant parameters," *IEEE J. Solid-State Circuits*, vol. SSC-2, no. 2, pp. 37–40, June 1967.

Madhu Sudan Gupta (S'68–M'72–SM'78) received the master's and Ph.D. degrees in 1968 and 1972, respectively, from the University of Michigan, Ann Arbor.

While at the University of Michigan, he was a member of the Electron Physics Laboratory, and carried out research on the large-signal and noise characteristics of microwave semiconductor devices. During the years 1973–1979, he was first an Assistant Professor and then an Associate Professor of Electrical Engineering at the Massachusetts Institute of Technology, Cambridge. There he was a member of the M.I.T. Research Laboratory of Electronics, and conducted research on microwave and millimeter-wave semiconductor devices, related high-field transport properties, and thermal fluctuations. Since 1979, he has been at the University of Illinois at Chicago, where he is presently a Professor of Electrical Engineering, and works on the materials, design, characteristics, limitations, and noise of high-frequency, nonlinear, active, and/or very small electron devices. During 1985–86, he was a Visiting Professor at the University of California, Santa Barbara.

Dr. Gupta is a member of Eta Kappa Nu, Sigma Xi, and Phi Kappa Phi. He is a registered Professional Engineer, and has served as the chairman of the Boston and Chicago chapters of the IEEE Microwave Theory and Techniques Society. He is the editor of *Electrical Noise: Fundamentals and Sources* (IEEE Press, 1977), *Noise in Circuits and Systems* (IEEE Press, 1988), and *Teaching Engineering: A Beginners Guide* (IEEE Press, 1987), and was the recipient of a Lilly Foundation Fellowship.

Paul T. Greiling (S'64–M'69–SM'82–F'85) received the B.S.E.E. and B.S. Math. degrees in 1963, the M.S.E.E. degree in 1964, and the Ph.D. degree in 1970 from the University of Michigan, Ann Arbor.

He joined the faculty of Electrical Engineering at Northeastern University, Boston, MA, in 1970. While at Northeastern he consulted for Lincoln Laboratory, M.I.T., in the area of IMPATT diodes. In 1972, he joined the faculty of Electrical Sciences and Engineering at the University of California, Los Angeles, where he did research on the theoretical analysis and experimental characterization of microwave solid-state devices. He consulted for local industry on millimeter-wave semiconductor devices. In 1976, he was a Visiting Faculty Member at Sandia Laboratory, Albuquerque, NM, working on GaAs FET's. In 1976 he joined the staff at Hughes Research Laboratory, Malibu, CA, where he has been responsible for the design, modeling, and testing of GaAs digital IC's.

Dr. Greiling was selected as a Distinguished Microwave Lecturer by the MTT-S for 1984–85 and presented a lecture entitled "High-Speed Digital IC Performance Outlook" to MTT chapters throughout the U.S., Europe, and Japan. At present he is Manager of the GaAs Devices and Circuits Department at Hughes Research Laboratories, working on high-speed GaAs logic circuits and is an Adjunct Professor in the Electrical Sciences and Engineering Department at UCLA. Dr. Greiling is a member of MTT-S ADCOM, Eta Kappa Nu, Tau Beta Pi, and Sigma Xi.