A New Method for On Wafer Noise Measurement

Gilles Dambrine, Henri Happy, Francois Danneville, and Alain Cappy

***Abstract*—A new method for measuring the noise parameters of MESFET's and HEMT's is presented. This new method is based on the fact that only three independent noise parameters are sufficient to fully describe the device noise performance. It is shown that two noise parameters (R_n and $|Y_{\mathrm{opt}}|$) can be directly obtained from the frequency variation of the noise figure F_{50} corresponding to a 50 Ω generator impedance. By using a theoretical relation between the intrinsic noise sources as additional data, the F_{50} measurement only can provide the four noise parameters. A good agreement with more conventional techniques is obtained.**

I. Introduction

It is well-known in the theory of linear noisy networks that a complete characterization of the noise in a linear two-port at one frequency requires the knowledge of four noise parameters [1]. From the circuit design point of view, the most convenient parameters are the minimum noise figure $F_{\min}$, the optimum value of the generator admittance Y_{opt} (or reflection coefficient Γ_{opt}) and the equivalent noise resistance R_n. For measuring the noise parameters of MESFET's and HEMT's several techniques are possible [2]. In the most wide usage, the noise parameters are determined by presenting a range of generator impedances to the Device Under Test (DUT) and measuring the noise figure (or the noise power) corresponding to each impedance [3]. On-wafer microwave probing system associated together with automatic variable admittance generator and automatic noise figure meter is generally used since it enables the noise performance evaluation without the need for dicing and mounting of individual chips in microwave packages. However, this method presents some drawbacks even if fully automatic commercial systems are used. First, the development of a complete test bench is not simple. The bench calibration and the choice of the admittance values are critical parameters highly influencing the results. Second, the measurement accuracy is not easy to specify since a numerical analysis is used to determine the noise parameters. Last but not least, commercial systems are rather expensive since a good repeatability needs a high performance admittance generator. As a consequence, there is a need to develop methods for rapidly and efficiently determining the noise performance of MESFET's and HEMT's. It should be pointed out that such a method has been already proposed [4]. The aim of this paper is to propose a new method for determining the noise parameters of MESFET's and HEMT's constituting thus an alternative approach to the previously published works.

Manuscript received April 27, 1992; revised June 29, 1992. This work was partially supported by C.E.C. under Contract ESPRIT 2035 GIANTS and by D.R.E.T. under Contract 89501.

The authors are with the Institut d'Electronique et de Microélectronique du Nord U.M.R. C.N.R.S., no. 9929, Département Hyperfréqences es Semiconducteurs, Batiment P4, Universite des Sciences et Technologies de Lille, 59655 Villeneuve D'Ascq, Cedex, France.

IEEE Log Number 9205446.

Basically, the method presented here is based on the fact that the number of noise parameters in MESFET's and HEMT's can be reduced if simple theoretical considerations are taken into account. Therefore, some important theoretical results of the MESFET and HEMT noise modeling will be recalled in the first section of this paper. In the second section, the new method for measuring the noise parameters will be described while the test bench and experimental results will be presented in the third section.

II. Theoretical Analysis

Following the pioneering work of A. Van Der Ziel [5], [6], the noise properties of MESFET's and HEMT's have been studied by several groups [7], [8], [9]. The aim of these theoretical approaches is to calculate the drain and gate noise sources $\langle i_d^2 \rangle$ and $\langle i_g^2 \rangle$ and their correlation coefficient C. The noise modeling is usually restricted to the intrinsic part of the device (i.e. the active channel under the gate) and the noise properties of the extrinsic device are easily deduced after adding the source and gate resistance and their associated Nyquist noise source (Fig. 1(a)). Although the modeling assumptions and approximations are very different, all these models show two important features of the noise behavior of any field effect device:

(i) The power spectral density of the drain noise current source $\langle i_d^2 \rangle$ is frequency-independent. (ii) The real part of the correlation between the gate and drain noise sources, $\langle i_g i_d^* \rangle$, is small as compared with the imaginary part. So, the complex correlation coefficient C is mainly imaginary. In addition $\langle i_g i_d^* \rangle$ increases linearly versus frequency.

The first property is simply due to the fact that the diffusion noise power spectrum is white in the microwave frequency range [6] while the second property results from the capacitive coupling between the conductive channel and the gate electrode [5]. Therefore, these two properties are valid for any kind of MESFET and HEMT.

Let us now consider the noise correlation matrix of FET's using the chain representation (Fig. 1(b)) [10]. For the extrinsic device 2-2' (without series inductance and pad capacitance) and three parameters $\langle u^2 \rangle, \langle i^2 \rangle$ and $\langle u^* i \rangle$ of this matrix can be expressed as:

$$\langle u^2 \rangle = \frac{\langle i_d^2 \rangle}{|Y_{21}|^2} + 4 \cdot kT_o \cdot (R_s + R_g) \cdot \Delta f \tag{1}$$

$$\langle i^2 \rangle = \langle i_g^2 \rangle + \frac{|Y_{11}|^2 \cdot \langle i_d^2 \rangle}{|Y_{21}|^2} - 2 \cdot \mathrm{Real}\left(\frac{Y_{11} \cdot \langle i_g^* i_d \rangle}{Y_{21}}\right) \tag{2}$$

0018–9480/93$03.00 © 1993 IEEE

$$\langle u^* i\rangle = \frac{Y_{11}\cdot\langle i_d^2\rangle}{|Y_{21}|^2} - \frac{\langle i_g i_d^*\rangle}{Y_{21}^*} \tag{3}$$

From these equations, we can define the equivalent noise resistance R_n and the correlation admittance Y_{cor} by:

$$\begin{aligned} Rn &= \frac{\langle u^2\rangle}{4\cdot kT_o\cdot\Delta f} \\ &= (R_s + R_g) + \frac{\langle i_d^2\rangle}{4\cdot kT_o\cdot|Y_{21}|^2\cdot\Delta f} \end{aligned} \tag{4}$$

$$\begin{aligned} Y_{\mathrm{cor}} &= \frac{\langle u^* i\rangle}{\langle u^2\rangle} \\ &= \frac{(Y_{11}\cdot\langle i_d^2\rangle - Y_{21}\cdot\langle i_g i_d^*\rangle)}{4\cdot kT_o\cdot R_n\cdot|Y_{21}|^2\cdot\Delta f} \end{aligned} \tag{5}$$

using (4), Y_{cor} can be approximated by:

$$Y_{\mathrm{cor}} \sim Y_{11} - \frac{\langle i_g i_d^*\rangle}{4\cdot kT_o\cdot R_n\cdot Y_{21}^*\cdot\Delta f} \tag{6}$$

In these expressions, R_s and R_g are the source and gate parasitic resistances, k the boltzmann consant, T_o is the reference temperature 290K and Δf the frequency bandwidth. Y_{11} and Y_{21} are the device admittance parameters while $*$ denotes complex conjugate, $\langle\,\rangle$ denotes ensemble average and $|Y_{ij}|$ denotes the magnitude of the admittance parameter Y_{ij}. For operating frequencies lower than the intrinsic cut-off frequency $F_c = G_m/2\pi C_{gs}$, the magnitude of Y_{21} is nearly equal to the transconductance G_m. As a consequence, the equivalent noise resistance R_n is frequency-independent. However, this statement needs some explanations. In fact, expression (1) is only valid for the intrinsic device with its parasitic resistances R_s and R_g (two-port 2-2' in Fig. 1(a). For a device mounted in a test fixture, parasitic inductances and capacitances have to be introduced. Since $R_n\cdot G_{\mathrm{opt}}$ (where G_{opt} is the real part of the optimum admittance Y_{opt}) is invariant under lossless transformation [11], any parasitic series element (for instance the gate inductance and/or a line length) modifies G_{opt} and R_n consequently. So, if any frequency-dependent reactive series element is introduced at the device input, the equivalent noise resistance R_n becomes frequency-dependent [12] but this behaviour is not related to the noise processes of the intrinsic device. Therefore, if wafer probing is used for the FET noise measurement, the reference plane is very close to the device and in this case, R_n can be considered as a frequency-independent parameter. Experimental determination of the four noise parameters of FET's and HEMT's are in quite good agreement with this simple result [13].

Concerning the correlation admittance Y_{cor}, expression (6) shows two important properties:

(i) The imaginary part B_{cor} is much larger than the real part G_{cor}. This property, already mentioned in [4], is simply due to the fact that the imaginary part B_{11} of Y_{11} is larger than the real part G_{11} while $\langle i_g i_d^*\rangle$ is mainly imaginary and Y_{21} is mainly real. In addition expression (6) shows that B_{cor} increases linearly versus frequency. (ii) G_{cor} can be approximated by G_{11} because the second term in the right hand side of expression (6) is mainly imaginary. As a consequence, G_{cor} increases versus frequency as ω^2.

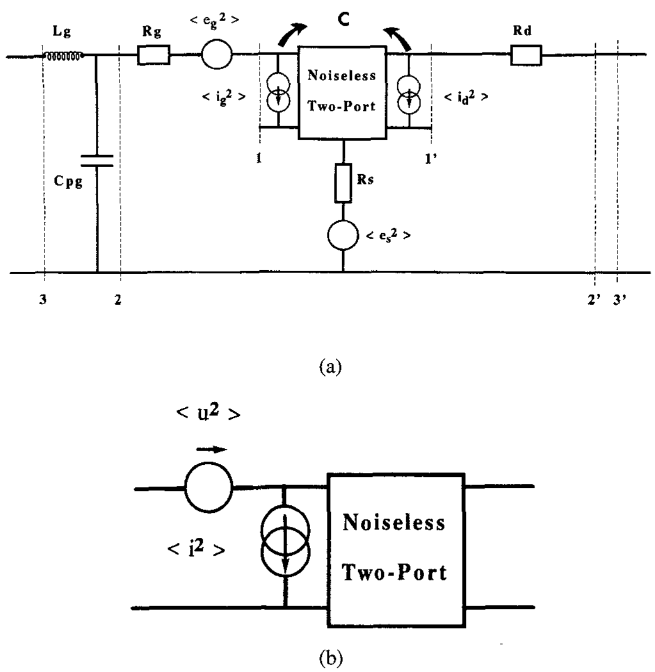


Fig. 1. (a) Noisy small signal equivalent circuit of MESFET's and HEMTs. (b) Equivalent circuit using the chain representation.

In order to show the validity of these general properties of the MESFET's and HEMT's noise behavior, Fig. 2. shows the results of the complete noise model included in the software HELENA [14]. In this physical noise model, the device is considered as a nonuniform noisy active line [15]. The noise sources are calculated using the well-known impedance field method [16] and the noise performance is calculated rigorously using the noise correlation matrix method [10]. This model which constitutes our reference model will be referred in the following as the "exact" model. The variations of G_{11} and G_{cor} are plotted in Fig. 2(a) in a large frequency range for a typical low noise device (0.2 μm gate pseudomorphic HEMT, $I_{ds} = 50$ mA/mm, $V_{ds} = 1.5$ V). This figure shows clearly the validity of the preceding approximations. In addition the real part of the optimum generator admittance G_{opt} given by:

$$G_{\mathrm{opt}} = \sqrt{G_{\mathrm{cor}}^2 + \frac{G_n}{R_n}} \tag{7}$$

where G_n is the equivalent noise conductance [1] is also shown together with G_{cor} in Fig. 2(b). This figure shows that G_{opt} is much larger than G_{cor} which indicates that the ratio G_n/R_n is much larger than G_{cor}^2.

To summarize, the following features of the FET noise parameters should be pointed out:

(i) R_n is frequency independent. (ii) $G_{\mathrm{cor}} \ll B_{\mathrm{cor}}; G_{\mathrm{cor}} \ll G_{\mathrm{opt}}$. (iii) $G_{\mathrm{cor}}^2 \ll \frac{G_n}{R_n}$. (iv) B_{cor} varies as $\omega; G_{\mathrm{cor}}$ varies as ω^2.

These results are valid for any field effect transistor because they are only consequences of the capacitive coupling between gate and channel and they constitute the basis of the new method for determining the device noise parameters, the description of which will follow.

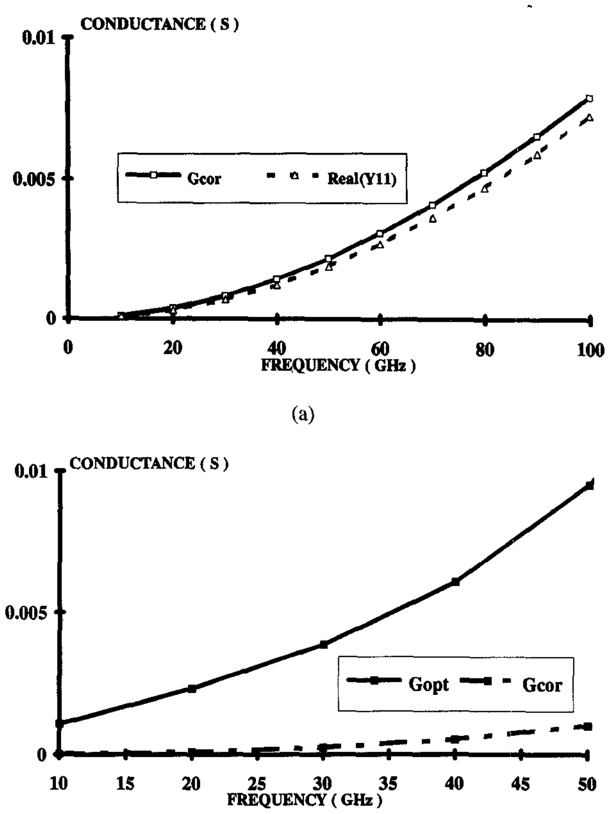


Fig. 2. (a) Theoretical variations of G_{cor} and G_{11} versus frequency for a 0.2 μm gate pseudomorphic HEMT under low noise biasing conditions. (b) Theoretical variation of G_{cor} and G_{opt} versus frequency for the same device.

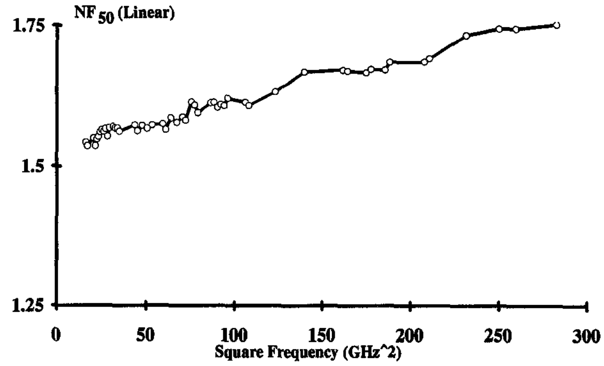


Fig. 3. Evolution of the noise figure for a 50 Ω impedance source generator versus the square of the frequency. The device is a 0.2 μm gate pseudomorphic HEMT ($V_{ds} = 1.5$ V, $I_{ds} = 3$ mA).

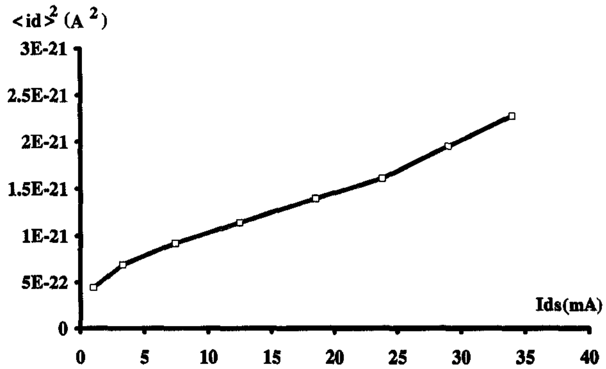


Fig. 4. Experimental dependence of the noise current source $\langle i_d^2 \rangle$ versus dc drain current I_{ds}.

III. Basis of the New Method

For any generator admittance $Y_g = G_g + j \cdot B_g$, the noise figure is given by the well known expression [1], [11]:

$$F = F_{\min} + \frac{R_n}{G_g} \cdot |Y_g - Y_{\text{opt}}|^2$$
$$\text{with}\, F_{\min} = 1 + 2 \cdot R_n \cdot (G_{\text{opt}} + G_{\text{cor}}). \quad (8)$$

In the case of a 50 Ω generator impedance ($Y_g = G_o = 20$ mS), the noise figure F_{50}, easily deduced from (8) becomes:

$$F_{50} = 1 + R_n \cdot G_o + \frac{R_n}{G_o} \cdot (2 \cdot G_o \cdot G_{\text{cor}} + |Y_{\text{opt}}|^2). \quad (9)$$

This expression is very important for two reasons:

(i) Since R_n is mostly frequency independent while G_{cor} and $Y_{\text{opt}}|^2$ vary as ω^2, the plot of F_{50} versus ω^2 is linear and the F_{50} value at $\omega = 0$ is $(1 + R_n \cdot G_o)$. Thus R_n can be easily deduced from the F_{50} extrapolation at $\omega = 0$. (ii) Since G_{cor} can be approximated by G_{11}, the slope of F_{50} versus ω^2, provides the magnitude of the optimum admittance $|Y_{\text{opt}}$.

So, the measurement of the noise figure with 50 Ω source impedance provides two important parameters R_n and $|Y_{\text{opt}}|$ or, in terms of noise voltage and current sources, $\langle u^2 \rangle$ and $\langle i^2 \rangle$ [11]. This measurement is very simple, no tuner is needed and the measurement accuracy is high as it will be shown in Fig. 3. From the noise physics point of view, the accurate determination of R_n is very important because R_n is directly related to the drain noise current source $\langle i_d^2 \rangle$ (formula (4)). So, the measurement of R_n can also be considered as a direct measurement of $\langle i_d^2 \rangle$ which allows a direct comparison of the noise behavior of different devices. In the case of a 0.2 μm gate length pseudomorphic HEMT, Fig. 4 shows the variation of the drain noise current source $\langle i_d^2 \rangle$ as a function of the dc drain current I_{ds} for a fixed drain-to-source voltage. In good agreement with theoretical predictions [2], this figure shows a linear increase of $\langle i_d^2 \rangle$ versus I_{ds}. In addition to the determination of $\langle i_d^2 \rangle$, the knowledge of R_n and $|Y_{\text{opt}}|$ can highly simplify the noise parameters measurement according to the two following strategies.

A. Improvement of the Conventional Method

If a conventional on-wafer noise measurement bench is available, the determination of R_n and $|Y_{\text{opt}}|$ from the F_{50} measurement can be used to reduce the number of unknowns and therefore to reduce the number of source admittances that have to be presented to the DUT. A higher measurement accuracy is then expected as compared with the conventional method. It should be noted that this accuracy improvement is obtained with a reduced additional effort because the measurement of F_{50} is very simple and fast.

Even with the proposed improvement, the conventional noise measurement technique, based on several noise power measurements and a least square fit, remains rather complicated and not easy to develop. So, it seems interesting to develop a completly novel technique for the noise parameter determination of MESFET's and HEMT's.

B. New Noise Parameter Measurement

The new method is based on the fact that G_{cor} can be approximated by G_{11} and is small as compared with G_{opt} as shown in the previous section. As a consequence, only three noise parameters R_n, G_{opt} and B_{opt} are needed to described the FET noise performance. Since the F_{50} measurement provides two noise parameters (R_n and $|Y_{\text{opt}}|$), only one additional information (measurement result or theoretical relation) is needed to provide $F_{\min}, R_n$ and Y_{opt}. To obtain a second relation, a test device with a long gate access can be used [17]. In this case, different generator admittances are obtained by simply moving the probe along the gate line [17]. This method will be described in a next paper and only conventional devices—without long gate access—will be considered here. In this case the second information can be obtained from theoretical considerations. For this purpose the theoretical model proposed by Gupta [4] and Pospieszalski [18] is very well suited. In these analysis, it is assumed that only two uncorrelated noise sources are sufficient to describe the intrinsic FET behavior. Assuming the validity of this approach, the correlation coefficient between the gate and drain noise current is given by:

$$C = \frac{\langle i_g i_d^* \rangle}{\sqrt{\langle i_g^2 \rangle \langle i_d^2 \rangle}} \sim j \cdot \frac{|Y_{21}|}{|Y_{11}|} \cdot \sqrt{\frac{\langle i_g^2 \rangle}{\langle i_d^2 \rangle}} \tag{10}$$

The main advantage of introducing formula (9) in the noise analysis is that the F_{50} measurement only is sufficient to determine the four noise parameters of FET's according to the following method:

(i) Determination of the small signal equivalent elements from $[S]$ parameters. (ii) F_{50} is measured versus frequency which provides R_n and $|Y_{\text{opt}}|$ (or, in terms of noise sources, $\langle u^2 \rangle$ and $\langle i^2 \rangle$). (iii) $\langle i_d^2 \rangle$ is deduced from $\langle u^2 \rangle$ by using (1). (iv) Introducing the approximation (10) in (2) provides $\langle i_g^2 \rangle$. (v) Introducing (10) in (3) provides $\langle u^* i \rangle$ and Y_{cor}.

However, no clear theoretical support has been given for the validity of (10) and this approximation will be discussed in a first step. For this purpose, Fig. 5. shows the comparison between the imaginary part of the correlation coefficient C given by the software HELENA and the approximate formula (10). This figure shows the validity of formula (10) in the case of a 0.2 μm gate length pseudomorphic HEMT. Similar agreement has been obtained by varying the gate length and the active layer structure. This result can be related to the fact that the conventional small signal equivalent circuit of MESFET's and HEMT's is valid in a very large range of gate length and layer topology.

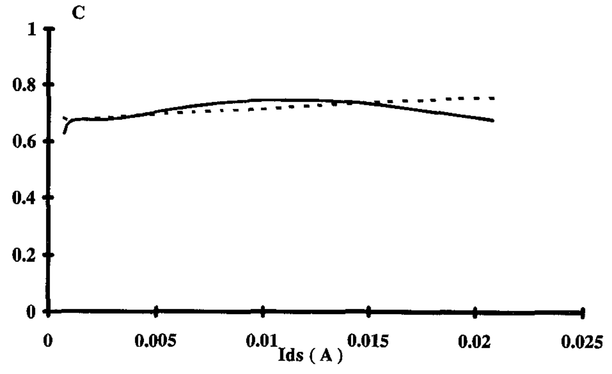


Fig. 5. Imaginary part of the correlation coefficient $C = \langle i_g i_d^* \rangle / \sqrt{\langle i_g^2 \rangle \langle i_d^2 \rangle}$ versus frequency. The device is a 0.2 μm gate pseudomorphic HEMT ($V_{ds} = 1.5$ V). Solid line: "exact" model (HELENA); broken line: approximate expression (10).

IV. The On- Wafer Noise Measurement Bench

The synopsis of the on-wafer set-up for noise characterization is presented in Fig. 6. This bench contains an Automatic Network Analyzer, a noise receiver and an on-wafer microwave measurement station.

This measurement station consists of two parts. Each part contains a mechanical microwave switch, a bias tee and a coplanar probe. These passive components are connected together with a 0.118 inch semi-rigid cable. In order to decrease the length of these connections and then to increase the microwave performance of the bench, all microwave elements are directly located on the riser of the probe positioner.

The switches (SPDT) are used for measuring both the $[S]$ parameters and the noise performance. Although the frequency range of this bench is yet limited to 18 GHz, all the microwave components (connectors, semi-rigid cable, bias tee ...) making up this noise measurement station, can be used up to 40 GHz and the measurement frequency range will be extended in the future.

The noise receiver contains a noise figure meter, a broad band double side band mixer and a synthetizer is used as local oscillator. In order to reduce the noise figure of this receiver, a Low Noise Amplifier (L.N.A.) is used. Finally, different high quality isolators (narrow band) are placed in front of the noise receiver.

Such a noise measurement bench can be implemented without major alterations on a conventional on-wafer microwave measurement station.

A. Microwave Performance of the Bench

By using an on-wafer measurement station, the measurement accuracy mainly depends on the microwave performance of the noise receiver and the microwave components making-up the bench.

By using a broad band L.N.A. ($NF = 3$ dB with 25 dB gain), the receiver noise figure is close to 4 dB in the 4–18 GHz frequency range. The noise figure of the input two-port,

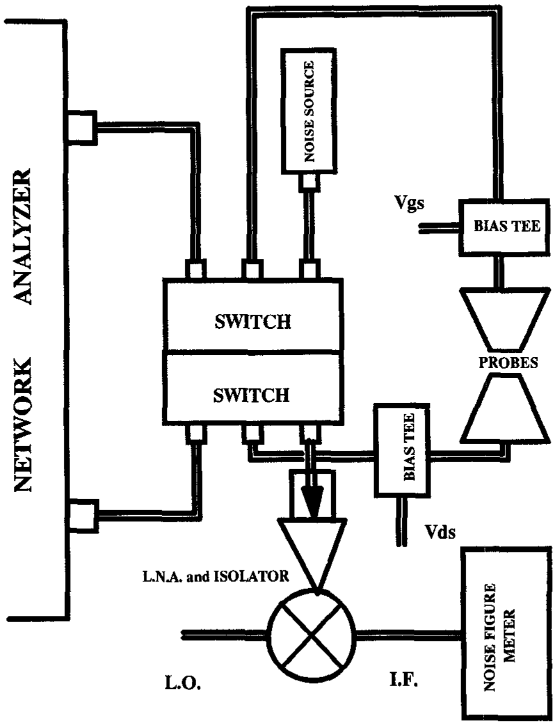


Fig. 6. Synopsis of the noise measurement bench.

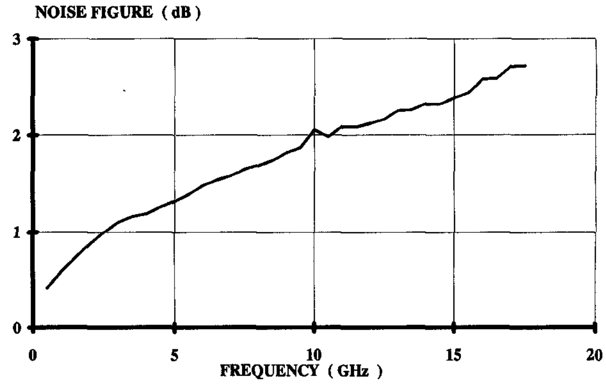


Fig. 7. Noise figure of the input two-port (located between the noise source and the input probe) versus frequency.

located between the noise source and the input probe (see Fig. 6.), is plotted versus frequency in Fig. 7. It should be pointed out that this noise figure is lower than 3 dB up to 18 GHz which is half of the noise figure corresponding to an input head tuner used in a conventional noise parameters test system. Therefore, the dynamics and then the accuracy of the [S] parameters measurement are not strongly altered.

B. Calibration of the Bench

Before performing noise measurements, the entire system has to be accurately calibrated. The calibration procedure involves three steps:

In a first step, the calibration between the two probe reference planes is performed by using a L.R.M. [19] calibration technique.

In a second step, the calibration of the input/output two-ports is carried out. The reference planes of these passive in/out two-ports are located between the noise source and the input probe, and between the output probe and the noise receiver respectively. A one-port calibration method with precision short, open and matched load (APC 3.5 mm) is used.

In a third step, the calibration of the noise receiver is performed. The noise source is directly connected in front of the noise receiver. The calibrated frequency points for the noise measurement, are a subset of those used in the two calibration steps previously described.

Although the above calibration procedure seems to be complicated, the use of a simple software to control each apparatus of the noise measurement bench, makes it straightforward. Except for the calibration of the noise receiver (step 3), experience has shown that the calibrations of the bench remain valid for several noise characterizations.

C. Device Noise Measurement

The aim of this original noise characterization, is to measure accurately the 50 Ω noise figure (F_{50}) of the D.U.T. versus frequency.

In order to increase the measurement accuracy, some undesirable frequency points are avoided. Consequently, to determine experimentally these frequency points, the two following drastics features are enforced:

(i) The magnitude of the reflection coefficient presented at the input of the D.U.T. has to be better than −20 dB. (ii) The fluctuations of the noise figure versus frequency, in the case of a short through-line, have to be less than 0.1 dB.

After this preliminary check, effected once for all, the F_{50} of a D.U.T. is deembedded from both the noise figure measured by the receiver and the available losses of the in/out two-port blocks described above. This characterization is effected for several bias conditions by using a programmable dc power supply.

In order to show the validity of the proposed method, the four noise parameters determined from the measurement of F_{50} have been compared with the results obtained with a commercial on-wafer noise measurement bench. The structure investigated is a $0.2 \times 50\,\mu m^2$ gate geometry pseudomorphic HEMT realized by Thomson CSF on a Picogiga layer. In the following results, the biasing conditions ($I_{ds} = 5$ mA, $V_{ds} = 1.5$ V) correspond to the minimum noise figure of the device. The minimum noise figure $F_{\min}$, the optimum reflection coefficient $\Gamma_{\rm opt}$, and the equivalent noise resistance R_n are shown in Fig. 8. from 6 to 26 GHz. A good agreement between the two methods is obtained over the whole frequency range. The differences are lower than 0.1 dB for the minimum noise figure value, 0.05 for the magnitude and 2 degrees for the phase of the optimum reflection coefficient and 3 Ω for the equivalent resistance value. In addition, the analysis of the results given by the conventional noise measurement bench shows that all the approximations described in the first section of the paper—and constituting the basis of this work—are very well verified even in the case of the short gate length and short

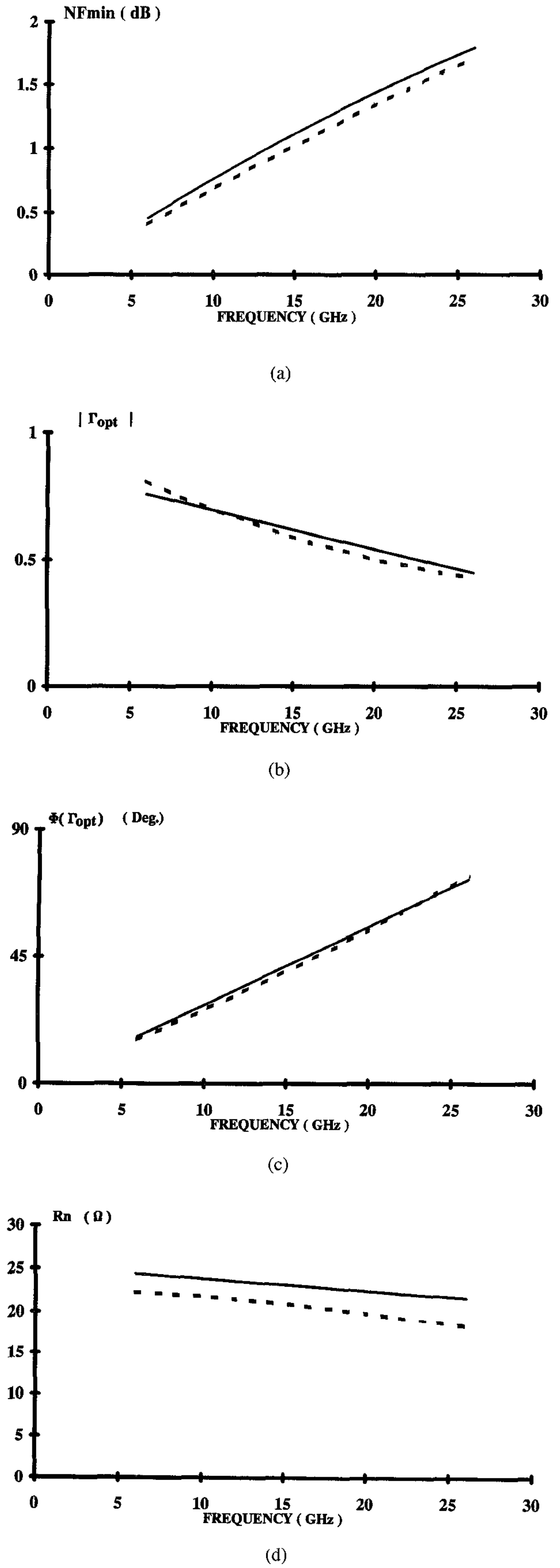


Fig. 8. Comparison of the measured four noise parameters versus frequency. Solid line: conventional technique by using a commercial set-up. Broken line: new technique. In the case of the new method, the 18–26 GHz data are extrapolated data.

gate width device investigated. These results show clearly the validity of the proposed method for the determination of the FET noise performance.

V. Conclusion

A new method for the determination of the noise parameters of MESFET's and HEMT's has been proposed. This method is based on the fact that the four noise parameters of FET's are not independent. As a consequence the equivalent noise resistance and the magnitude of the optimum admittance can be deduced from the measurement of the noise figure with a 50 Ω generator impedance, F_{50}. Using an additional relation between the intrinsic noise sources, it has been shown that this measurement is sufficient for determining the four noise parameters. A good agreement is obtained with the conventional on-wafer noise measurement bench. Since this method is very simple and easy to develop, it can be used either for systematic control in industrial laboratories or as a fast noise parameter determination of FET's for the design of IC's.

Acknowledgment

The authors would like to thank Dr. C. Versnayen from Thomson T.C.M. for his helpful contribution concerning the experimental noise results obtained using a commercial On-Wafer bench.

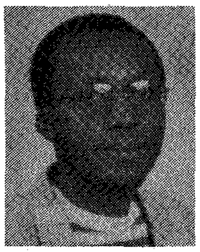
References

[1] H. Rhote and W. Dahlke, "Theory of Noisy Fourpoles," *Proc. IRE,* vol. 44, no. 6, pp. 811–818, June 1956.
[2] A. Cappy "Noise modeling and measurement techniques," *IEEE Trans. Microwave Theory Tech.*, vol. 36, no. 1, Jan. 1988.
[3] R. Q. Lane, "The determination of device noise parameters," *Proc. IEEE,* vol. 57, pp. 1461–1462, Aug. 1969.
[4] M. S. Gupta, O. Pitzalis, S. E. Rosembaum, and P. Greiling, "Microwave noise characterization of GaAs MESFET's by on-wafer measurement of the output noise current," *IEEE Trans. Microwave Theory Tech.*, vol. 35, no. 12, pp. 1208–1217, Dec. 1987.
[5] A. Van Der Ziel, "Thermal noise in field effect transistor," *Proc. IRE,* vol. 50, pp. 1808–1812, 1962.
[6] ——, "Gate noise in field effect transistors at moderately high frequencies," *Proc. IRE,* vol. 51, pp. 461–467, 1963.
[7] R. A. Pucel, H. A. Haus, and H. Statz, "Signal and noise properties of gallium arsenide field effect transistors," *Advances in Electronics and Electron Physics,* vol. 38, pp. 195–265, 1974.
[8] B. Carnez, A. Cappy, R. Fauquembergue, and E. Constant and G. Salmer, "Noise modelling in sub-micrometer-gate FET's," *IEEE Trans. Electron Devices,* vol. ED28, no. 7, pp. 784–789, 1981.
[9] Y. Ando and T. Itoh, "DC, small-signal, and noise modeling for two-dimensional electron gas field effect transistors based on accurate charge-control characteristics," *IEEE Trans Electron Devices,* vol. 37, no. 1, pp. 67–78, Jan. 1990.
[10] H. Hillbrand and P. H. Russer, "An efficient method for computer aided noise analysis of linear amplifier networks," *IEEE Trans. Circuits Syst.*, vol. CAS-23, no. 4, pp. 235–238, Apr. 1976.
[11] J. Lange, "Noise characterization of linear twoports in terms of invariant parameters," *IEEE J Solid-State Circuits,* vol. SC-2, no. 2, June 1967.
[12] M. Gupta and P. T. Greiling, "Microwave noise characterization of GaAs MESFET's: Determination of extrinsic noise parameters," *IEEE Trans. Microwave Theory Tech.*, vol. 36, no. 4, pp. 745–751, Apr. 1988.
[13] R. I. Taylor, D. M. Brookbanks, and A. J. Holden, "Determining intrinsic noise parameters of 0.25 μm gate pseudomorphic HEMT," *Electron. Lett.*, vol. 27, no. 21, pp. 1923–1924, Oct. 1991.
[14] H. Happy, O. Pribetich, G. Dambrine, J. Alamkan, Y. Cordier, and A. Cappy, "HELENA: A new software for the design of MMICS," in *IEEE-MTT-S, Int Microwave Symp. Dig.*, Boston, June 1991, pp. 627–630.

[15] A. Cappy and W. Heinrich, "High-freqeuncy FET noise performance: A new approach," *IEEE Trans. Electron Devices,* vol. 36, no. 1, pp. 403–409, Feb. 1990.
[16] W. Shockley, W. Copeland, and R. P. James, "The impedance field method of noise calculation in active semiconductor device," in *Quantum Theory of Atoms, Molecules and the Solid State.* New York: Academic, 1966, pp. 537–563.
[17] G. Dambrine and A. Cappy, "A new method for on-wafer high frequency noise measurement of FET's," in *IEEE-MTT-S, Int. Microwave Symp. Dig.,* Boston, June 1991, pp. 169–172.
[18] M. W. Pospieszalski, "Modeling of noise parameters of MESFET's and MODFET's and their frequency and temperature dependence," *IEEE Trans. Microwave Theory Tech.,* vol. 37, no. 9, pp. 1340–1350, Sept. 1989.
[19] H. J. Eul and B. Schiek, "A generalized theory and new calibration procedures for network analyzer self-calibration," *IEEE Trans. Microwave Theory Tech.,* vol. 39, no. 4, pp. 724–731, Apr. 1991.

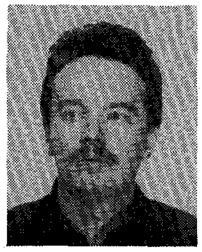
Gilles Dambrine was born in Avion, France, on May 15, 1959. He received the Dipl. Eng. degree from the E.U.D.I.L. and the Ph.D. degree from the University of LILLE respectively in 1986 and 1989.

Since 1989, he has been working in the Institut d'Electronique et de Microelectronique du Nord (I.E.M.N.) as a C.N.R.S. (national centre for research) researcher. His main research interests are concerned with modeling and microwave characterization of the low noise field effect devices.

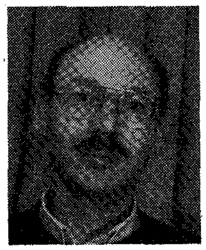


Henri Happy was born in Yaoundé, Cameroon, in 1964. He received the "Maîtrise E. E. A" from the University of Lille I, France.

He joined the Centre Hyperfréquences et Semiconducteurs of the University of Lille I, Villeneuve d'Ascq, where he obtained the Ph.D. in 1992. His principal research interests are the modeling of HEMT using self-consistent, and quasi-2-D approach. He is one of the principal designers of the software HELENA - for Hemt ELEctrical properties and Noise Analysis.



Francois Danneville was born in Ham, France, on March 16, 1964. He received the Ph.D. degree from the University of Lille in 1991. He is currently with the Institut d'Electronique et de Microélectronique du Nord as lecturer at the University of Lille. His main research interests are concerned with noise modeling and characterization techniques in Field Effect Transistors.



Alain Cappy was born in Chalons sur Marne, France on January 15, 1954. In 1977 he joined the "Centre Hyperfrequences et Semiconducteurs", University of Lille, France. In 1986 he received the "Docteur es Sciences" degree from the University of Lille for his work on the modeling and the characterization of MESFET's and HEMT's.

He is now Professor of Electronics at the University of Lille. His main research interests are concerned with the modeling, the realization and the characterization of low noise devices for applications in the centimeter and millimeter wave ranges. He is a founder of the International GaAs Simulation Group.