HEMT for Low Noise Microwaves: CAD Oriented Modeling

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***Abstract*—By means of an automatic measuring system which allows the rapid and accurate characterization of microwave transistors in terms of noise and scattering parameters simultaneously, 32 HEMT's of four manufacturers have been tested. From the experimental data so obtained the equivalent circuit of the "typical" device which represents each transistor set has been extracted using a decomposition technique. This procedure allows the optimum fitting of the global performance by exploiting the correlation between the model elements and the measured parameters over the operating frequency range. Since the method takes into account also the noise behavior of several devices of each series, we get a substantial improvement of the model performance to be employed in (M)MIC CAD of low noise amplifiers.**

I. Introduction

RECENT developments in GaAs technology have yielded a device, the High Electron Mobility Transistor (HEMT), which exhibits excellent performance at microwave and millimeter-wave frequencies.

To design wideband low-noise amplifiers the CAD-oriented model of the *typical* device is needed which represents at best the performances of the transistor series to be employed for the realization. The implementation of this model requires the complete characterization of some samples of the series in terms of the four noise parameters $\{F\}$, the four gain parameters $\{G\}$ and the scattering parameters $[S]$ versus frequency over the whole range of interest and at different bias values.

So far, the conventional methods employed to perform the complete characterization of low noise transistors are inaccurate and very time-consuming since they require different instrument set-ups for S-parameter and noise parameter measurement, and also manual disassembling and re-assembling of the instruments.

Consequently, from the manufacturer's point of view, it is often more convenient to represent the noise behavior of the transistor in terms of noise parameters by means of mathematical or semiempirical models. This approach is usually based on the equivalent circuit extracted from fitting of the S-parameters only, which can be measured rapidly and accurately by means of an Automatic Network Analyzer.

On the basis of a methodology that allows the determination of all the noise, gain and scattering parameter sets through noise figure measurements only [1]–[5], a fully automated system for the complete characterization of microwave transistors through a unique experimental procedure has been realized. The computer-controlled instrumentation is driven step-by-step by complex (unpublished) software which selects the best measuring conditions for accuracy and verifies it, drives all the instruments, collects the experimental data and performs the data processing to give all the above parameter sets [6].

This allows to accomplish very rapid and accurate characterization of many devices even without the presence of (unskilled) operator.

The automatic set-up has been recently used to test 32 HEMT's of four different manufacturers in the 8–12 GHz frequency range. By means of the extensive amount of data so obtained ($\{N\}$, $\{G\}$ and $[S]$ parameters), the modeling of each devices series has been carried out. The lumped element network thus derived reproduces at best the behavior of the "typical" device in the frequency range of interest.

The results of the modeling procedure show excellent agreement with the experimental results, thereby providing information on the transistor performance useful for implementing CAD of (M)MIC low-noise amplifiers.

II. Device Characterization

The noise performance of the device under test (DUT) is determined by the knowledge of the four noise parameters F_o, N_n, $|\Gamma_{\text{on}}|$, $\angle\Gamma_{\text{on}}$ which are defined by the relationship:

$$F(\Gamma_s) = F_o + 4N_n \frac{|\Gamma_s - \Gamma_{\text{on}}|^2}{(1 - |\Gamma_s|^2)(1 - |\Gamma_{\text{on}}|^2)} \qquad (1)$$

where Γ_s is the reflection coefficient of the input termination of the DUT, F_o is the minimum noise figure, Γ_{on} is the relevant optimum value of the input reflection coefficient Γ_s and N_n is the parameter indicating how the noise figure departs from the minimum as Γ_s differs from Γ_{on}. A similar relationship holds for the gain parameter set G_{ao}

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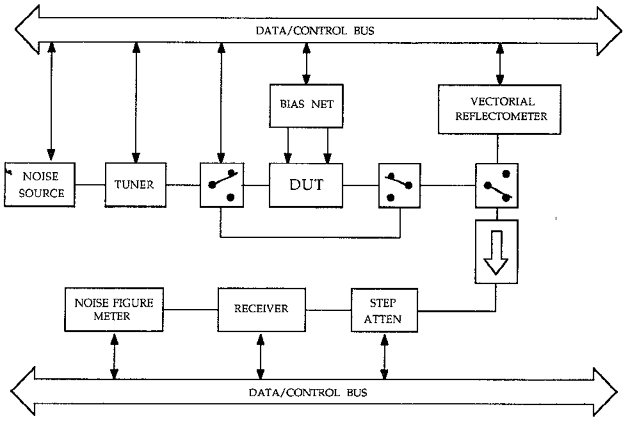


Fig. 1. Simplified block diagram of the measuring set-up for the complete characterization of the device.

(maximum available power gain), N_g, $|\Gamma_{og}|$, $\angle\Gamma_{og}$

$$\frac{1}{G_a(\Gamma_s)} = \frac{1}{G_{ao}} + 4N_g \frac{|\Gamma_s - \Gamma_{og}|^2}{(1 - |\Gamma_s|^2)(1 - |\Gamma_{og}|^2)} \quad (2)$$

which describes the DUT behavior in terms of the available power gain $G_a(\Gamma_s)$.

After $F(\Gamma_s)$ and $G_a(\Gamma_s)$ are obtained by proper measurement procedures for different values of Γ_s (more than four for best accuracy), (1) and (2) can be solved and the noise and gain parameter sets determined by computation based on error minimization techniques (e.g., least-squares method). From the gain parameters the scattering parameters are derived [1]-[3]. The simplified block diagram of the measuring system is reported in Fig. 1.

Once a set of measurements of F_m (the noise figure of the whole system) is performed for a given value of Γ_s and for some values of F_r (more than two for accuracy) the values of $F(\Gamma_s)$ and $G_a(\Gamma s)$ are derived from the well known Friis's formula

$$F_m(\Gamma_s) = \alpha_{\Gamma s}\left[F(\Gamma_s) + \frac{F_r(S'_{22}) - 1}{G_a(\Gamma_s)}\right] \quad (3)$$

provided that $\alpha_{\Gamma s}$, which represents the tuner losses, is measured on-line [4], [5].

The different values of the receiver noise figure are obtained by acting on a programmable step attenuator connected to the receiver input [1], [2]. The microwave switches operate the proper connections of the instruments to realize the different configurations related to the above described measuring steps. Since the computation of the noise and gain parameters at different frequencies and for some typical values of the drain current (e.g., 15-, 30- and 50% I_{DSS}) requires the acquisition and processing of an extensive amount of data, the measurement procedure clearly needs to be automated in order to avoid an extremely large time consumption. This is accomplished by a proper computer-controlled instrumentation set and a complex software necessary to drive all the test measuring, data acquisition and data processing steps. With respect to previous versions of the set-up, the automation has been recently completed by adoption of a computer-controlled step-motor double slide-screw tuner which acts as a mismatching network of the noise source output in order to realize the different values of Γ_s.

III. Model Features and Procedure

On the basis of the obtained results, we have found satisfactory to model all sets of the tested devices by the lumped element network shown in Fig. 2.

In this circuital representation two distinct sections can be pointed out: the inner part which models the chip behavior and the outer part which adds the parasitic effects due to the package. As it can be derived from several papers concerning this topic e.g. [7], [8], the chip equivalent circuit has a well-assessed topology and the elements take on values included in the known typical ranges reported in Table I. The external network, instead, may be synthesized in different ways for both connections and values of the elements, mostly representing parasitic coupling effects and lossless signal propagation along metallic paths.

Since the aim of the equivalent circuit is to reproduce the device performance over the frequency band of interest, the noise and scattering parameters calculated should provide the best fit of the experimental data that are available at a discrete number of frequencies.

The conventional techniques adopted to extract the equivalent circuit are based on the broad-band characterization of FETs in terms of S-parameters measured with the device under pinch-off and at typical bias operating conditions. Once the model elements are established by using optimization algorithms, the noise performance is then derived by computation allowing a prediction of the noise parameter values [9], [11]. Since our measuring set-up performs the characterization of the devices in terms of noise and scattering parameters simultaneously the equivalent circuit model is derived from either data sets.

An essential feature of the modeling procedure here described is related to its statistical significance: all models are extracted from the characterization of series of devices (8 in this case), thereby giving a "typical" circuit whose $\{N\}$ and $[S]$ parameters values are included in the experimental data ranges.

The modeling procedure has been carried out using software which has noise analysis tools utilizing different theoretical models for the chip noise. In the present work a noise representation has been chosen which incorporates all the noise sources existing in the HEMT in terms of equivalent temperatures associated with resistive elements.

Following a general technique which is known as a valuable tool for the optimization of large-scale models [12], the procedure starts from a sensitivity analysis that points out the degree of interaction between the circuit elements and the relevant S- and N-parameter sets. This leads to a matrix of coefficients indicating the correlation patterns that allow to decompose the overall optimization problem

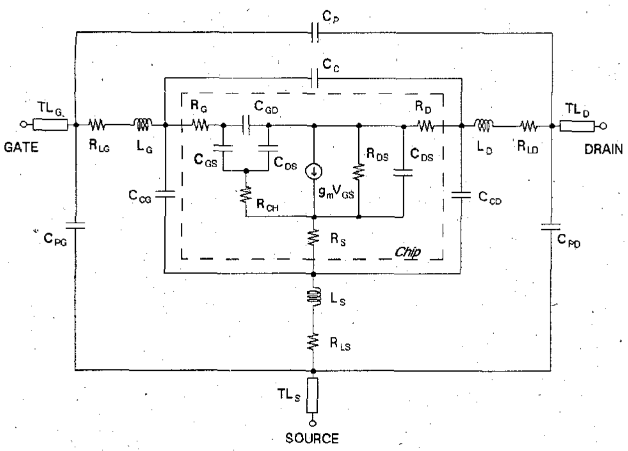


Fig. 2. Lumped element network adopted for the device modeling.

TABLE I
TYPICAL RANGES OF THE VALUES OF THE CHIP ELEMENT FOR HEMT'S

R_G	1-5 Ω	C_{GS}	.15-.3 pF
R_D	3-5 Ω	C_{DG}	.01-.5 pF
R_{CH}	2-10 Ω	C_{GD}	.01-.03 pF
R_{DS}	100-400 Ω	L_S	.05-.2 nH
R_S	3-4 Ω	L_G, L_D	.1-.5 nH
	τ 0 5 psec		

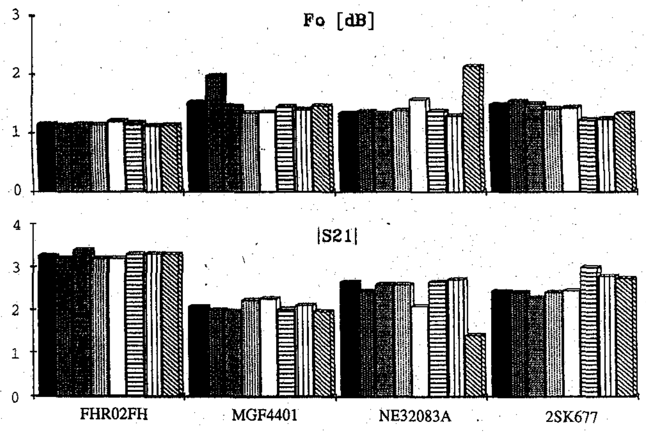
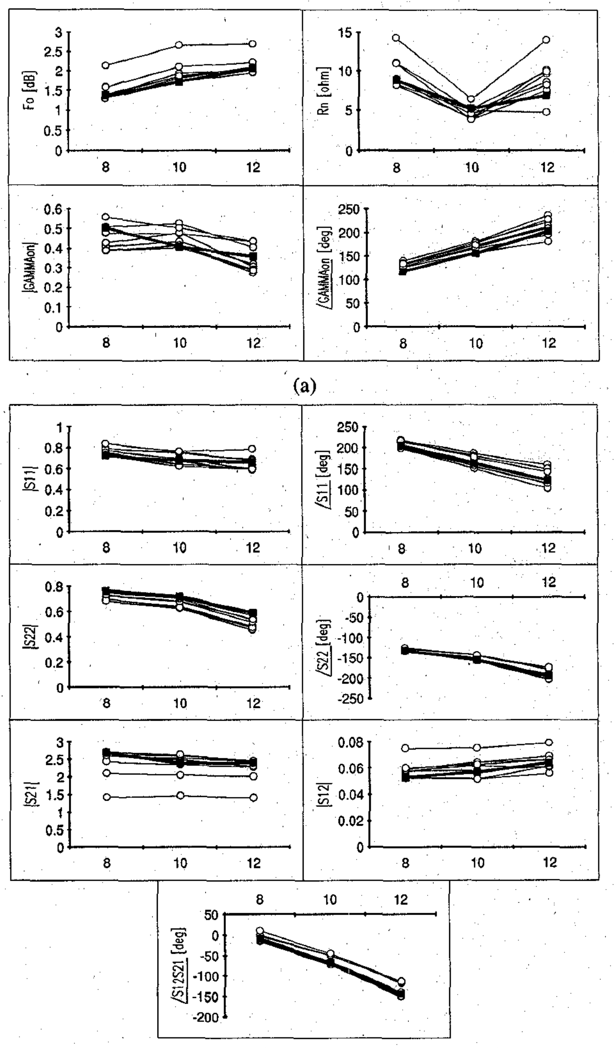


Fig. 3. Bar graph representation showing the experimental results in terms of F_o and S_{21} only, as example, for each lot of the tested devices. They show the low spreading of the device characteristics ($f = 8$ GHz).



(a)

(b)

Fig. 4. Noise (a) and scattering (b) parameters, measured and computed through the model (bolded line).

into different subproblems. Upon identification of the decomposition scheme, the procedure consists of repeated cycling of the optimization step sequence.

As initial values the chip elements as given by the manufacturer's data sheet have been set. The starting values of the parasitics have been estimated from a preliminary investigation of S- and N-parameter sensitivity ranges.

It is to be noted that some information concerning the decomposition properties is best extracted from noise data; thus our modeling procedure based on $[S]$ and $\{N\}$ simultaneously measured is likely to give a consistent set of element values which reproduces the typical performance of a device.

IV. RESULTS

As previously stated, the described automatic measuring system is an effective tool for characterizing the noise behavior of several transistors of the same series since the complete testing of each device versus frequency and bias requires a small amount of time for data acquisition and processing (about 20 min for each frequency). It has been recently employed to characterize 32 samples of different manufacturers (NEC NE32083A, Fujitsu FHRO2FH, Mitsubishi MGF4401, Sony 2SK677) before and after a thermal storage of 300 hrs @ 200°C. The measurement of the noise and gain performance of the devices has been aimed to assess the existence of degradation mechanisms (or damages) caused by the thermal storage.

On request of low-noise amplifier designers (of CSELT, Italy), the HEMT's have been tested in the 8–12 GHz range (2 GHz step) at the bias conditions suggested by the manufacturers for the best low-noise behavior.

The performance of the devices in terms of N- and S-parameters has shown well-defined patterns for each se-

TABLE II
VALUES OF THE MODEL ELEMENT FOR THE HEMT's MEASURED

C_P	.08 pF	R_{LG}	1 Ω
C_C	.001 pF	R_{LD}	1 Ω
C_{GD}	.01 pF	R_{LS}	1 Ω
C_{GS}	.27 pF	R_G	4 Ω
C_{DG}	.01 pF	R_S	3 Ω
C_{DS}	.0072 pF	R_{DS}	350 Ω
C_{CG}	.11 pf	R_D	4 Ω
C_{CD}	.12 pF	R_{CH}	5 Ω
C_{PG}	.1 pf	L_D	.7 nH
C_{PD}	.09 pf	L_G	.55 nH
g_m	45 mS	L_S	.08 nH
	τ 2.5 psec		

T_{LG} $E = 15$

T_{LD} $E = 28$ $(Z = 50\ \Omega, F = 8\text{ GHz})$

T_{LS} $E = -2$

E = electrical length in degree

ries. This uniformity of the behavior is clearly represented in the column hystogram of Fig. 3, where the values of the F_o and $|S_{21}|$ parameters only, at a given frequency for the different groups of samples are reported as example. The results of the characterization obtained after the thermal storage (6 months later) has shown negligible degradation of the device characteristics; this also stressed the excellent performance of the system in terms of repeatability and reliability.

The low spreading of the parameters measured for each lot of devices defines the tolerance range adopted in our modeling procedure as shown in Fig. 4. The lower and higher values measured at each frequency thus represents the limits which characterize the performance of the device series (*).

The N- and S-parameters of the typical device represented by the model for the NE 32083 A series are reported in Fig. 4 (bolded line). The values of the circuit elements which make the calculated parameters lie within the experimental data ranges are listed in Table II.

The S-parameters as measured by our system show a very good agreement with those listed in the manufacturer's data sheet. The only difference is a phase shift in both S_{11} and S_{22} at the measuring frequencies of 8, 10 and 12 GHz. Simple computation points out that it is related to a displacement of 2 mm of the input/output reference planes due to slightly different de-embedding.

V. CONCLUSION

The decomposition approach for the optimization of large scale models has been employed to reproduce the performance of several low-noise microwave HEMT's distributed by four different manufacturers. The procedure starts from a complete characterization of all the devices in terms of scattering and noise parameters which are then grouped into the data series for the modeling. The calculated parameters show an excellent agreement with the experimental data within the relevant ranges. Since some information on transistor equivalent circuit is best extracted from measured N-parameters, this procedure gives models of improved consistency as compared with the ones based on S-parameters only, thus leading to a better outline of the product.

The HEMT models so obtained are highly suitable for applications in computer-aided design of low-noise (M)MIC amplifiers.

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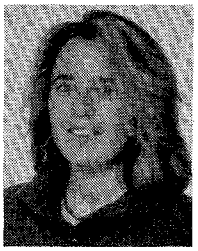

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(*)It is to be noted that the plots report the phase of the product of S_{12} and S_{21} which is the output of the measurement procedure. The separation of this quantities is not necessary for low-noise amplifier CAD [1], [2].

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Mr. Sannino has written about 70 papers, for the most part on theory and experiments of noise measurements.