CAD-ORIENTED HEMT MODELS FROM NOISE AND SCATTERING MEASUREMENTS

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ABSTRACT

The simultaneous determination of noise, gain and scattering parameters by means of a computer-driven noise figure test-set allows the rapid and accurate characterization of some samples of HEMTs of the same series.
An equivalent circuit model representing the behavior of the typical device then is extracted by means of a decomposition approach. Comparison between the model performance and the measured parameters of all devices are reported for the FHR 02FH (by Fujitsu).
The modeling procedure is oriented to CAD of (M)MIC low noise amplifiers.

Keywords: HEMT, noise modeling.

1. INTRODUCTION

The characterization and modeling of HEMTs is a subject of active research because the determination and representation of the device performance strongly influence the CAD of low-noise wideband amplifiers. The device characterization in terms of noise, gain and scattering parameters (N-, G- and S-parameters) is usually represented as noise and gain circles and scattering parameter curves on Smith and polar chart by the manufacturers in the data sheets.
Until now, an extensive amount of work has been done in modeling the device noise properties, though separately from the modeling in terms of S-parameters. The noise information to be added to the equivalent circuit extracted from S-parameters are usually derived by either a) the use of semiempirical noise representations to predict the noise performance through a single frequency measurement, or b) the experimental determination of the four noise parameters which are then reported in numerical or graphical form vs. frequency.
In accordance with the procedure usually followed by the manufacturers to characterize the products, the S-parameters ([S]) are measured by an (Automatic) Network Analizer (ANA) at all the operating frequencies, whereas the G-parameters ({G}) are determined by gain measurements or computed by [S]. Similarly, the four N-parameters ({N}) can not be measured by a single instrument and, in addition, they require a more complex experimental and data processing procedure. In consequence, the characterization of the device in terms of {N} is often bypassed by the manufacturers.
The modeling approach presented in this paper derives the device model by either N- and S- parameters, measured at all the frequencies of interest. The complete characterization of the device is carried-out with high accuracy, repeatability and low time-consumption by a novel fully automated measuring system which performs the measurement of {N}, {G} and [S] simultaneously, vs. frequency and at different bias conditions, through a procedure of noise figure measurements only .
Consequently, the noisy model so derived gives a better description of the global performance of low-noise HEMTs devices because the circuit topology and the element values are determined by accounting for also the measured N-parameters.

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2. COMPLETE CHARACTERIZATION OF THE DEVICE BY NOISE FIGURE MEASUREMENTS

The dependence of the noise performance of a microwave transistor on the reflection coefficient Γ_s of the input termination is represented by the four N-parameters F_o, N_n, $|\Gamma_{on}|$, $/\Gamma_{on}$ defined by

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

where $F(\Gamma_s)$ is the transistor noise figure, F_o is the minimum noise figure, Γ_{on} is the relevant optimum value of Γ_s and N_n is the parameter indicating how the noise figure departs from the minimum as Γ_s differs from Γ_{on}.(*)

For the G-parameters G_{ao} (maximum available power gain), N_g, $|\Gamma_{og}|$, and $/\_\Gamma_{og}$ a similar relationship holds, given by

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

which describes the dependence on Γ_s of the available power gain $G_a(\Gamma_s)$.

A conventional noise figure measuring set-up is assembled, in principle, with a source injecting noise in the device under test (DUT) through a tuner, and a receiver which takes the noise from the DUT output and sends it to a noise figure meter; the tuner works as a transformer of the noise source admittance (50 ohm, nominal) in order to measure F and G_a in correspondence to selected values of the source reflection coefficient Γ_s.

The measured noise figure $F_m(\Gamma_s)$ of the whole system, as indicated by the meter, is given by

$$F_m(\Gamma_s) = a_{\Gamma s}\left[F(\Gamma_s) + \frac{F_r(\Gamma_{out}) - 1}{G_a(\Gamma_s)}\right] \tag{3}$$

where $a_{\Gamma s}$ represents the loss of the tuner (and all the other stages preceding the DUT), and F_r is the noise figure of the receiver which depends on its input termination, i.e. on the DUT output reflection coefficient.

From (3), $F(\Gamma_s)$ is determined provided that $G_a(\Gamma_s)$, $a_{\Gamma s}$ and $F_r(\Gamma_{out})$ are measured for each configuration of the tuner. Alternatively $G_a(\Gamma_s)$ and $a_{\Gamma s}$ are computed from the S-parameters.

This procedure is repeated for some redundant values of Γ_s (i.e. more than four, for accuracy) and the N- and G-parameters are derived from (1) and (2) by a data processing based on an error minimization technique.

The conventional experimental methods based on this procedure are inaccurate and time consuming because different measuring systems (Network Analyzer, Noise Figure set-up, Gain set-up) are used in different times. At present, some automatic N-parameter test sets are commercially available which solve the problem of

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(*) *The terminal invariant parameter* N_n *, first introduced by Lange* (Ref.1) *is related to the more known noise resistance* R_n *by* $N_n = R_n\, g_{on}$, *where* g_{on} *is the real part of* Γ_{on} *expressed in terms of conductance ; a similar relationship holds for* N_g.

time-consumption in measuring {N}, but they are inaccurate because of the methodology they are based on. Furthermore, they employ as meters other different instruments connected by switches: the S-parameters are measured by an ANA and the available power gain is measured by a gain meter or computed by [S]. The losses of the stages connected at the DUT input are measured (or computed through the characterization in terms of [S]) in a previous calibration step; unfortunately this implies the need for using tuners with known discrete configurations only (as the strip-line pin-diode switched tuners), which represents a strong limitation for the experimenters in selecting the best values of Γ_s from the viewpoint of the accurate determination of {N} and {G}.

Because of these difficulties, the device data sheets mostly report few measured noise data : F_o, Γ_{on} (and the noise resistance R_n) and the associated available power gain G_{ass}, for one or two frequencies. Other manufacturers even furnish the complete characterization through N- and G-parameters as computed from the circuit model extracted by the measured S-parameters.

The methodology of the measuring system here presented in its computer-controlled version has been expressly studied to allow the simultaneous determination of N-, G- and S-parameters by means of a noise figure meter only. The losses $a_{\Gamma s}$ of all the passive stages which precede the DUT, the noise figure $F_r(\Gamma_{out})$ of the receiver and the available power gain $G_a(\Gamma_s)$ of the DUT are all simultaneously measured by noise figure measurements. Once a set of noise figures F_m and of the (tuner) losses $a_{\Gamma s}$ are measured for some values of Γ_s and for some values of the receiver noise figure F_r (more than two for accuracy), the corresponding sets of $F(\Gamma_s)$ and $G_a(\Gamma s)$ are derived by a proper data processing based on (3); the N- and G-parameters are then obtained by (1) and (2). From the G-parameters, all the S-parameters required for amplifier design are also derived by computation; in addition, since the DUT is driven at noise level, non-linearity effects in the HEMTs due to signals not low enough, as those delivered by a network analyzer, are avoided.

The automatic N-, G-,and S-parameter test set is shown in the simplified block diagram of Fig.1. Details on the basic theory can be found in (Refs. 2,3) and relevant references.

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 vs. frequency and bias requires a small amount of time for data acquisition and processing . It has been employed to characterize 32 samples of four different manufacturers (NEC NE32083A, FUJTSU FHRO2FH, MITSUBISHI MGF4401, SONY 2SK677).

On request of amplifier designers (by CSELT, Italy) , the HEMTs have been tested in the 8-12 GHz range (2 GHz step) at the bias conditions suggested by the manufacturers. The N- and S-parameters have shown well-defined patterns for each series. This uniformity of the behavior is represented in the column hystogram of Fig. 2, where the values of the F_o and $|S_{21}|$ parameters only, for the different groups of samples, are reported as example.

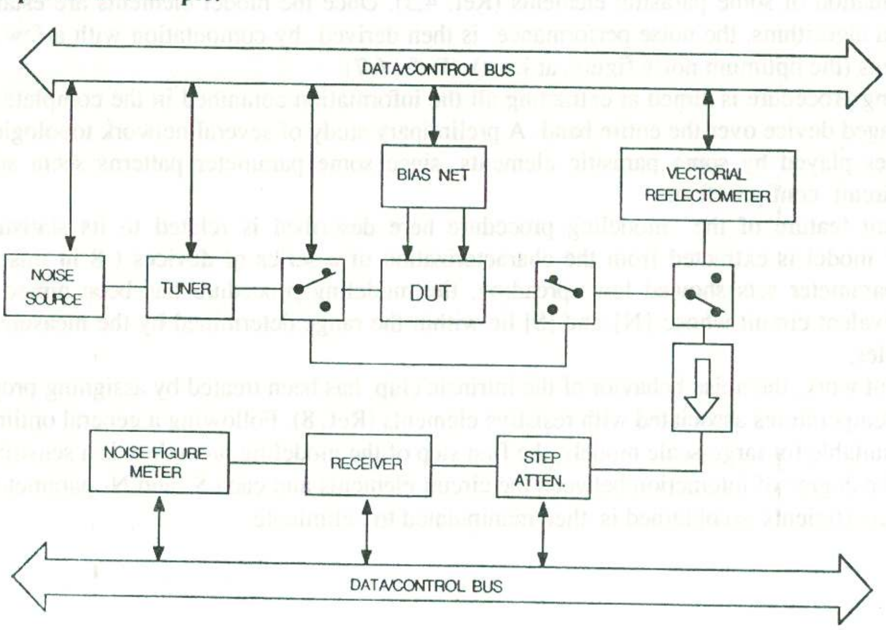

Figure 1: *Simplified block diagram of the computer-controlled N-, G, and S-parameters measuring system.*

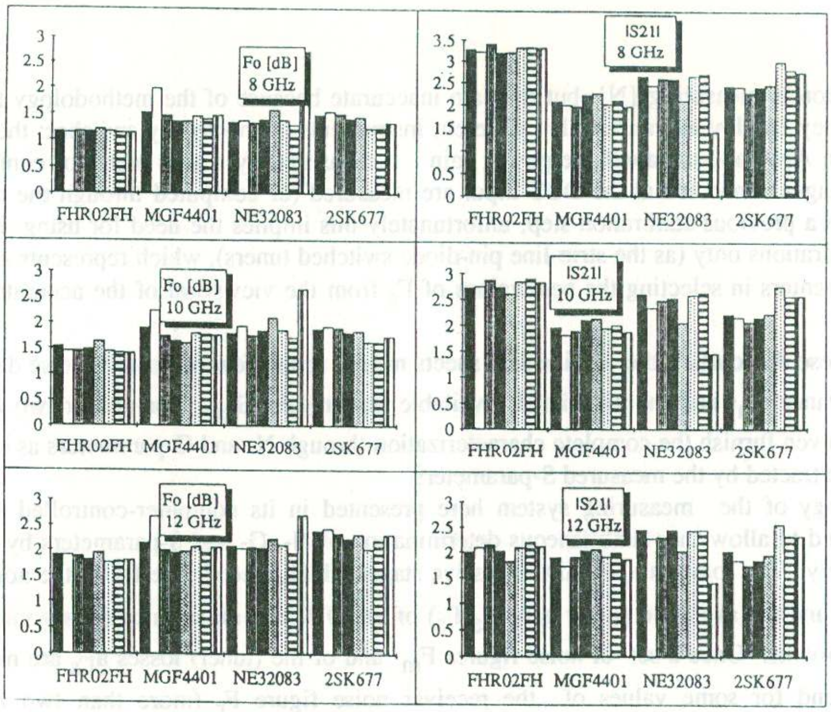

Figure 2: *Bar graph representation of the minimum noise figure F_o and of S_{21} of all the tested HEMTs at the bias conditions suggested by the manufacturers for the optimum low-noise performance.*

3. MODELING PROCEDURE

The purpose of an accurate RF characterization is to obtain a circuit representation which describes the device operation by an equivalent two-port network. For the case of packaged HEMTs, the circuit model has to account for both the chip and the package properties. The resulting equivalent network is therefore complicated and, even though the chip equivalent circuit has a fairly standard topology, it is not possible to extract the models for the package and the chip separately since a strong interaction exists between them.

The overall equivalent circuit is then expected to give a satisfactory description of the packaged device and it as to be determined as a whole.

The conventional techniques adopted to determine the equivalent circuit are based on the broad-band characterization of FETs in terms of S-parameters. In addition, DC measurements are required for a more precise evaluation of some parasitic elements (Ref. 4,5). Once the model elements are established by using optimization algorithms, the noise performance is then derived by computation with a few additional noise measurements (the optimum noise figure, at least) (Refs. 6,7).

Our modeling procedure is aimed at extracting all the information contained in the complete characterization of the packaged device over the entire band. A preliminary study of several network topologies has illustrated the key roles played by some parasitic elements, since some parameter patterns seem strictly related to particular circuit configurations.

An important feature of the modeling procedure here described is related to its statistical significance because the model is extracted from the characterization of a series of devices (8 in this case). Since the measured parameter sets showed low spreading, the modeling procedure has been aimed at obtaining a typical equivalent circuit whose {N} and [S] lie within the range determined by the measured data of all the tested samples.

In the present work, the noise behavior of the intrinsic chip has been treated by assigning proper values to the equivalent temperatures associated with resistive elements (Ref. 8). Following a general optimization technique suitable for large-scale models, the first step of the modeling procedure is a sensitivity analysis that points out the degree of interaction between the circuit elements and each S- and N- parameter. The matrix of numerical coefficients so obtained is then manipulated to eliminate

the small value entries indicating a weak element-to-parameter interconnection. This allows to mark the correlation patterns by which the overall optimization problem is decomposed into different subproblems. The procedure then carries on with repeated cycling of the optimization step sequence (Ref. 9) .
It is important to note that some information concerning the decomposition properties is correctly extracted from noise data; thus the 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 family (Ref. 10). For instance, the role of the input parasitic capacitance (see C_{cg} in Fig.3) is of primary importance in modeling the optimum noise reflection coefficient Γ_{on}, whereas the noise resistance R_n is greatly influenced by the intrinsic channel resistance (R_{ch}) which is known to be determined with uncertainty from S-parameter information only.

4. RESULTS

The spreading of the [S] and the {N} measured for each lot of devices defined the range adopted in the modeling procedure. The lower and higher values measured vs. frequency thus represent the limits which characterize the performance of the device series.
For the case of the FHR 02 FH device lot (biased at 2 V, 10 mA, as suggested by the manufacturer for the optimum noise performance) the patterns and the values of $|S_{11}|$, $|\Gamma_{on}|$, $|S_{12}|$ and $\angle S_{12}S_{21}$ were of fundamental importance in determining the choice of the model topology which is reported in Fig. 3.

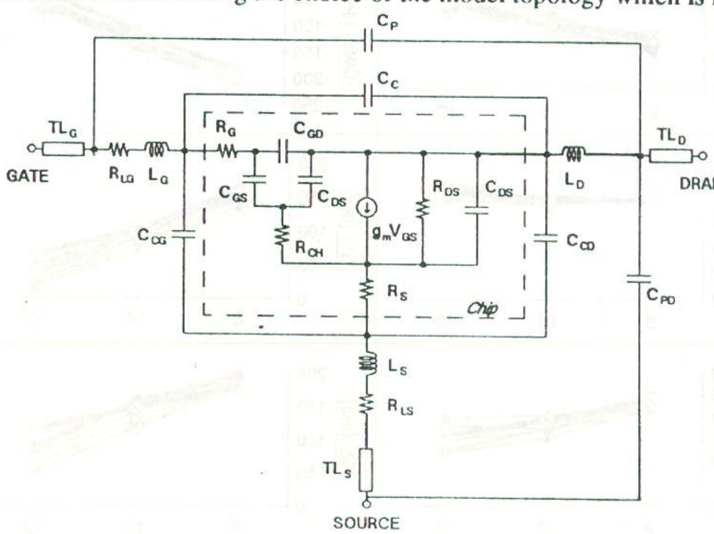

Figure 3: *Topology of the circuit model selected to represent the performance of all the FHR 02 FH tested samples.*

The S- and N- parameters of the typical device represented by the model are shown in Fig. 4 together with all the experimental data (*). The relevant element values are listed in Tab.1 .
The scattering parameters as measured by our system are in good agreement with those listed in the manufacturer's data sheet. The phase shifts evidenced in S_{11} and S_{22} are clearly related to displacements of about 4 mm and 3 mm in the input and output reference plane , respectively, due to different deembedding procedure.

Different considerations need to be done about the N-parameters: it is not understood whether the Fujitsu device data are a representation of measurements of many samples or a single-sample measurement data or, even, obtained by some model computation. Anyway, a careful comparison between the N-parameters given by the manufacturer in the FHR 02X (chip device) and in the FHR 02FH (packaged device) data sheets points out controversial values of the N_n invariant parameter. The value of N_n is mainly determined by the

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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.*

chip properties and it is only slightly influenced by the package which introduces low effects of parasitic feedback and losses. As calculated from the manufacturer {N} tables, the values of N_n triplicate from chip to package thus indicating the existence of heavy losses or parasitic feedback that are not likely to occur in real package structures. In addition, either F_o and $|\Gamma_{on}|$ values exhibit very small changes. However, the N-parameters measured by our system for all the 8 samples show large differences as compared with the ones reported in the data sheets.

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

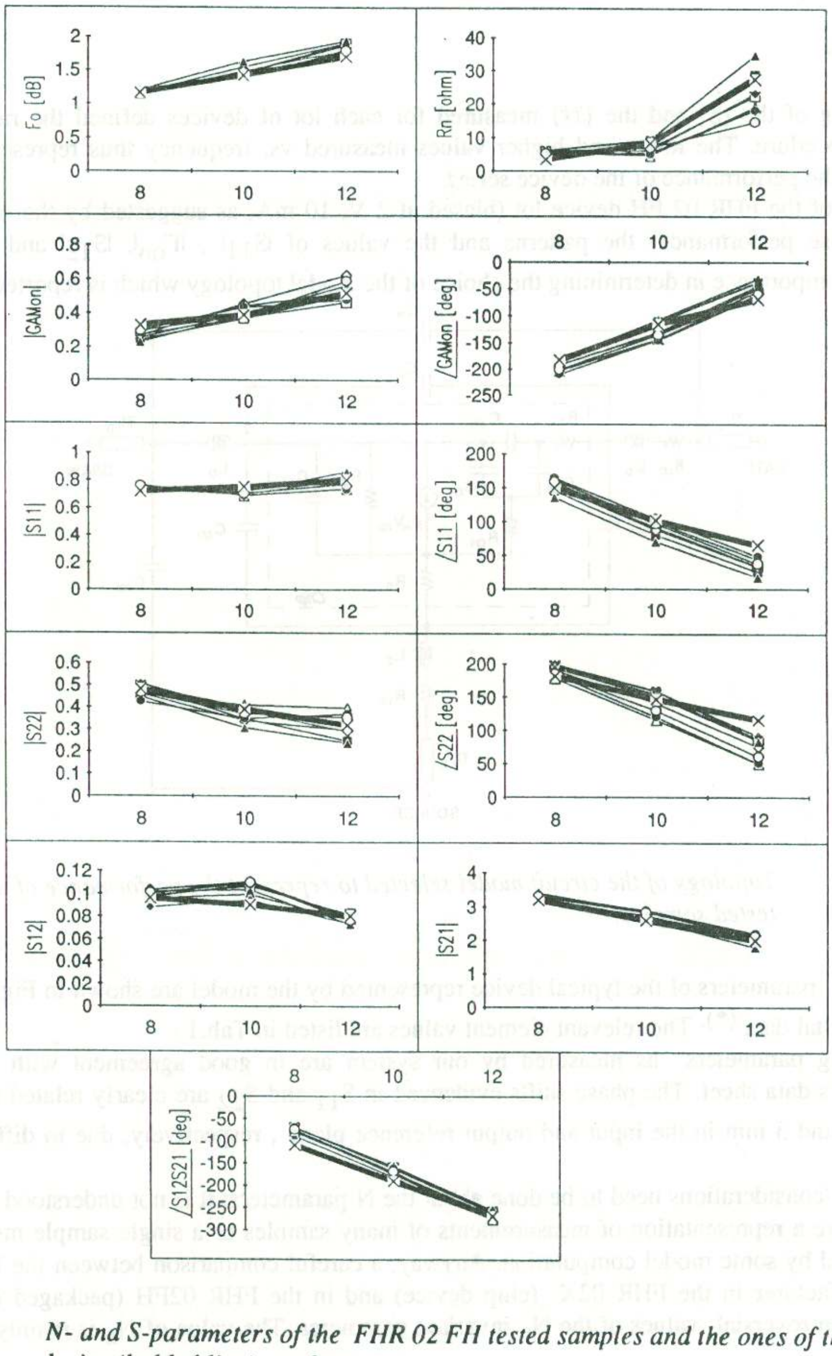

Figure 4: *N- and S-parameters of the FHR 02 FH tested samples and the ones of the modeled typical device (bolded line), vs. frequency.*

Tab 1
Values of the elements of the model of Fig. 3.

C_P	.005	pF	L_D	.5	nH
C_C	.01	pF	L_G	.75	nH
C_{GD}	.019	pF	L_S	.15	nH
C_{PD}	.05	pf	R_{LG}	1.5	ohm
C_{GS}	.25	pF	R_G	4	ohm
C_{DG}	.025	pF	R_S	1	ohm
C_{DS}	.04	pF	R_{DS}	450	ohm
C_{CG}	.18	pf	R_{CH}	1	ohm
g_m	55	ms	R_{LS}	1.5	ohm
t	.85	psec			

T_{LG}	E=18
T_{LD}	E=65
T_{LS}	E=-1

E = line electrical length in degree @ 8 GHz; Z=50 ohm
All resistors warmed @ 290 K ;R_{DS} @ 3573,18 K.

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