Analysis of correlations between noise and scattering parameters for a consistent FET modeling approach

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Abstract

By means of an original procedure for characterizing and modeling low-noise transistors, the equivalent circuit model of a pseudomorphic HEMT series has been extracted. This model has been employed to analyze the nature of a link between the optimum source reflection coefficient Γ_{opt} and the S_{11}^* parameter exhibited by all experimental data concerning the characterization of MESFETs and HEMTs. The noisy model analysis and the relevant remarks on the obtained results are here reported.

Introduction

As an original way of approaching the extraction of noisy equivalent circuits for CAD applications of packaged HEMTs at microwave frequencies, we have successfully employed a partitioning technique for the simultaneous optimization of the noise (N-) and the scattering (S-) parameters [1,2]. These two parameter sets are determined through the complete characterization of a given device series based on source pull measurements of the noise figure only by appropriate selection criteria of the Γ_s noise source reflection coefficient . The measuring set-up allows for the simultaneous extraction of N- and S-parameters of the transistor under test (TUT) vs. bias conditions, temperature and frequency in the 2-18 GHz range (implementation of a more compact version operating up to 40 Ghz is in progress) [3,4]. In determining the TUT circuit model, the above cited partitioning approach enhances the selective influence of each circuit element on the object functions that have to fit all the measured N- and S-parameter value spreads. Besides, by using the noise parameters as additional constraints we have observed an improvement of accuracy and consistency in the modeling procedure.

Such an extracted model (whose performance is here referred to as *typical* in a CAD-oriented sense with respect to a measured series of 8-10 devices) is inherently broad-band and has shown to be the only satisfactory solution to each measurement set of packaged FETs we have carried out.

On the basis of a noisy equivalent circuit recently determined from the characterization of a 10-sample series of pseudomorphic HEMTs (CFB001-03 by Celeritek) over the 8-16 GHz frequency range, we have observed and verified the occurrence of a link between the optimum source reflection coefficient Γ_{opt}, for which the TUT noise figure reaches its minimum value F_{min}, and the S_{11} parameter. In the present paper, theoretical investigation and relevant experimental data on this topic are presented.

Noisy model analysis

The *typical* noisy model extracted for the CFB001-03 packaged HEMT is shown in Fig.1 with the relevant element values. This model allows for the best fit of the measured noise and scattering parameters and exhibits optimum performances in CAD applications of low-noise amplifiers. The noise performance is computed by associating equivalent noise temperatures to the resistive elements of the circuit. It has been demonstrated that the temperature T_{ch} to be assigned to the channel resistance R_{ch} is close to the ambient temperature, whereas the output conductance temperature T_d takes on values of thousands Kelvins [5].

A careful analysis of the small-signal parameters vs. frequency plots brings evidence of a correlation between Γ_{opt} and the complex conjugate S_{11}^* of S_{11}. This has occurred also for several device series we have characterized and modeled. As an example, the parameters S_{11} and Γ_{opt} are shown in Fig.2 for the Celeritek p-HEMT series and for the GaAs HEMT series MGF4401 (by Mitsubishi).

With reference to the reported equivalent circuit, we have analyzed the effect of deembedding the various passive elements sequentially encountered from the device terminals towards the internal structure. By doing so, the link between $|S_{11}^*|$ and $|\Gamma_{opt}|$ patterns, as well as between $/S_{11}^*$ and $/\Gamma_{opt}$, becomes tighter and reaches its maximum strength for the model configuration commonly referred to as the *intrinsic* chip (i.e. chip without the access gate, source and drain resistances and the drain-to-gate feedback capacitance). In this situation, we determined the expressions for S_{11}^* and Γ_{opt} with the aim of making some considerations. Thus, we obtained:

$$|S_{11}^*| = \frac{1 + \omega^2 C_{gs}^2 (R_{ch} - R_o)^2}{1 + \omega^2 C_{gs}^2 (R_{ch} + R_o)^2} \quad ;$$

$$|\Gamma_{opt}| = \frac{1 + \omega^2 C_{gs}^2 (\alpha(\omega) R_{ch} - R_o)^2}{1 + \omega^2 C_{gs}^2 (\alpha(\omega) R_{ch} + R_o)^2}$$

$$/S_{11}^* = \mathrm{arctg} \frac{2\,\omega C_{gs} R_o}{1 + \omega^2 C_{gs}^2 (R_{ch}^2 - R_o^2)} \quad ;$$

$$/\Gamma_{opt} = \mathrm{arctg} \frac{2\,\omega C_{gs} R_o}{1 + \omega^2 C_{gs}^2 (R_{ch}^2 - R_o^2) + \partial}$$

where: $\alpha(\omega) = [1 + (f_t/f)^2 (R_{ds} T_{ch} / R_{ch} T_d)]^{1/2}$

$$\partial = g_m^2 R_{ch} R_{ds} T_{ch} / T_d$$

From these equations it is clearly seen that the difference between S_{11}^* and Γ_{opt} can be canceled for the limit cases of $T_{ch}=0$ or $T_d=\infty$ which cause $\alpha(\omega) = 1$ and $\partial = 0$. Actually, for T_{ch} approaching cryogenic temperaure values, as well as for highly increased values of T_d, Γ_{opt} closely resembles S_{11}^*.

It is worth noting that $\alpha(\omega)$ in the X band for common intrinsic HEMT models takes on values of 10÷30 which are primarily due to the ratio R_{ds}/R_{ch} typically in the range of 10^2. Therefore, the difference between S_{11}^* and Γ_{opt} is also directly related to those parts of the device (omhic and saturated channel sections) from which the noise is originated. As the value of T_{ch}/T_d counterbalances R_{ds}/R_{ch}, then Γ_{opt} approaches S_{11}^*.

With the aim of validating these results for the general case of packaged HEMT modeling, we have then evaluated the analytical expressions of the variations caused to S_{11}^* and Γ_{opt} of the *intrinsic* chip by adding a wide variety of parasitic elements as it is done when building a model. These very complex equations containing the S-parameters of both the passive element and the *intrinsic* twoport, as well as their transfer scattering correlation matrices, have been simplified for each case by accounting for the typical element value ranges and the usual operating frequencies ($f << f_t$).

For the cases of an input series resistance R it is required that $R/R_o <= 0.1$ (where R_o is the normalizing resistance of 50 Ω); for an input capacitance C it should be verified that $\omega C R_o <= 0.5$, which also holds for an input inductance L ($\omega L/R_o <= 0.5$). As far as feedback elements are concerned, a capacitance C connected between the gate and the drain terminals must not exhibit a value higher than 0.05 pF, whereas a source inductance should not exceed 0.05 nH.

It can be easily seen that, actually, all the element values commonly determined for packaged HEMT models fit the above reported ranges.

Upon fulfillment of these approximation conditions, the relation between S_{11}^* and Γ_{opt} is maintained as we have noticed in the characterization of several MESFET and HEMT series.

Concluding remarks

As a results of extensive characterization and model extraction of packaged HEMT series, we have observed a characteristic link between S_{11}* and Γ_{opt} in magnitude and phase. We have therefore carried out a theoretical investigation based on the typical equivalent circuit of a commercial pseudomorphic HEMT family and we have derived guidelines for the general topologies of package models that allows to maintain the above cited relation.

It has to be noted that, 25 years ago, two papers were published reporting experimental data and theoretical support for assessing that, for FETs and BJTs, the opyimum noise asorce admittance Y_{opt} could be approximated by Y_{11}* and, since the relevant measurement frequencies were in the range of a few GHz, this could be extended to S_{11}* itself (being S_{12} negligible) [6,7].

We here point out that this approximation is no longer valid for the FET devices now available and, obviously, neither could be said that $Y_{11}* = S_{11}*$. In addition, the preliminary results of characterization and modeling of a bipolar transistor series (with polysilicon emitter and very short base width) currently carried out in our laboratory have shown that both approximations (i.e. Γ_{opt} linked to S_{11}* , or Y_{opt} similar to Y_{11}*) do not hold. Theoretical investigation on the relevant noisy model for this last case is in progress.

It is therefore to be concluded that the topic of the present paper only applies to MESFETs and HEMTs operating in the microwave range.

References

[1] A. Caddemi, G. Martines, M. Sannino, " Automatic characterization and modeling of microwave low-noise HEMTs", *IEEE Trans. on Instr. and Meas.*, (Special Issue on Selected Papers: IMTC92), vol. IM- 41, pp. 946-950, Dec. 1992.

[2] A. Caddemi, M. Sannino, " Modeling of low-noise microwave HEMTs for CAD-oriented applications", *Int. Journal of Microwave Millimeter - Wave Computer- Aided Engi-neering*, (Special Issue on Modeling of MESFETs and HEMTs for microwave CAD), pp. 29-36, Jan. 1993.

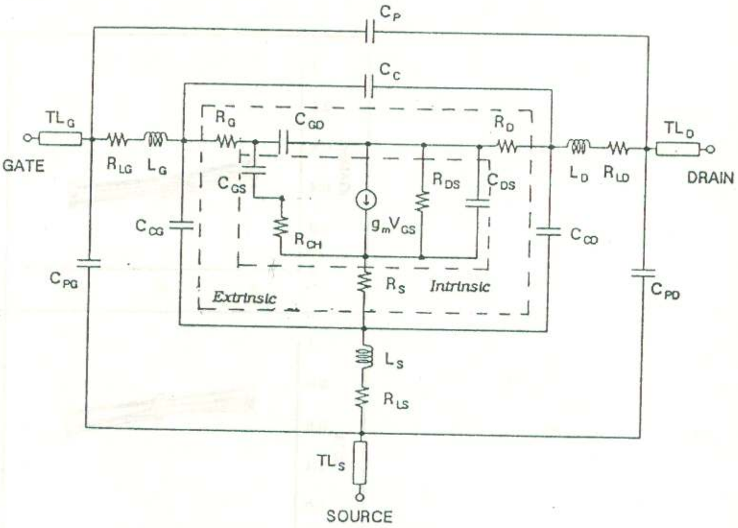
[3] G. Martines and M. Sannino, "An automated test set for the complete characterization of low noise transistors", *Microwave Eng. Europe*, pp. 57-64, Nov/Dec. 1990.

[4] G. Martines and M. Sannino, "The determi-nation of the noise, gain and scattering parameters of microwave transistors (HEMTs) using only an automatic noise figure test-set", to be published on IEEE Trans. Microwave Theory Tech., July 1994.

[5] M. Pospieszalski, "Modeling of noise parameters of MESFETs and MODFETs and their frequency and temperature dependence", *IEEE Trans. Microwave Theory Tech.*, vol.MTT- 37, pp.1340-1350, Sept.1989.

[6] A. Leupp, M. Strutt, "High-frequency FET noise parameters and approximation of the optimum source admittance, *IEEETrans. Electron Dev.*, vol.ED-16, pp.428-431, May 1969.

[7] W. Bachtold, M. Strutt, "Optimum source admittance for minimum noise figure of microwave transistors", *Electronics Lett.*, Vol.4, N. 17, Aug.23, 1968.



$C_{PG} = 0.06$ pF	$R_{DS} = 180\ \Omega$
$R_{LG}=0.3\ \Omega$	$T_d = 1610$ °K
$L_G = 0.47$ nH	$C_{DS} = 0.07$ pF
$C_{CG} = 0.03$ pF	$R_D = 1.5\ \Omega$
$R_G = 2.3\ \Omega$	$L_D = 0.49$ nH
$C_{GS} = 0.23$ pF	$R_{LD} = 1\Omega$
$R_{CH} = 1.4\ \Omega$	$R_S = 1.1\Omega$
$C_{GD} = 0.023$ pF	$L_S = 0.033$ nH
$g_m = 66$ mS	$R_{LS} = 1.2\ \Omega$
$\tau = 2.1$ ps	$C_{PD} = 0.08$ pF
TL_G L=840µm	Z=50 Ω
TL_D L=280µm	Z=50 Ω
TL_S L=500µm	Z=50 Ω

Fig.1 - Noisy model extracted for the CFB001-03 p-HEMT series. The relevant element values are reported in the enclosed table.

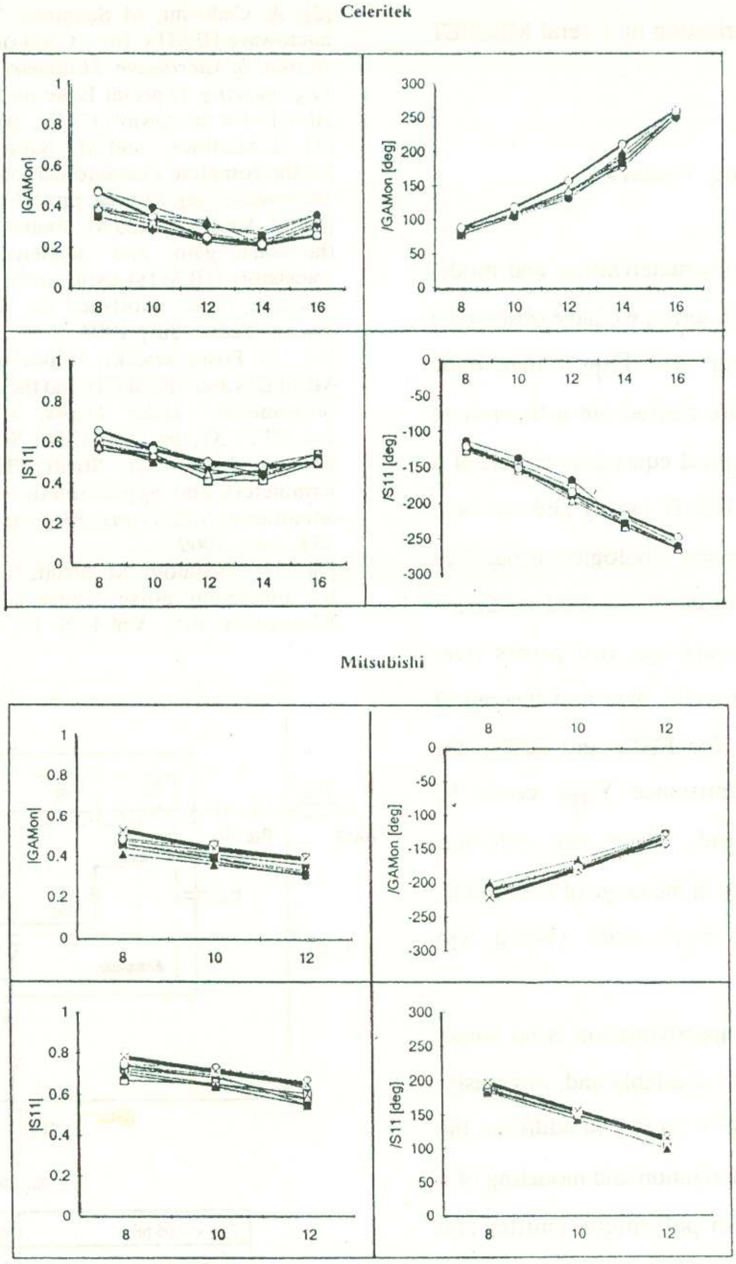


Fig. 2 - Measured and computed S_{11} and Γ_{opt} parameters for the Celeritek CFB001-03 p-HEMT series and for the Mitsubishi MGF 4401 GaAs HEMT series.