HEMT for Low-Noise Microwaves: CAD-Oriented Performance Evaluation

Giuseppe Capponi, Bruno Di Maio, and Patrizia Livreri

***Abstract*—This paper shows how a graphic processing of low-noise HEMT's small signal parameters, allows evaluating and comparing the actual performance obtainable in front-end applications. HEMT's tradeoff charts which solve tradeoffs among the basic low-noise amplifier performance are reported. Figures of merit for microwave low-noise HEMT which represent a fast way of evaluating HEMT in actual working conditions and of selecting the proper transistor, are defined. As an example, the tradeoff charts and the figures of merit of two HEMT's (Fujitsu FHR02FH, Sony 2SK677) and a pseudomorphic-HEMT (Celeritek CFB001-03) are reported and compared with the data sheets.**

I. Introduction

Low-noise HEMT's data sheets usually report, together with the device's scattering parameters, minimum noise figure ($F_{\min}$), minimum source reflection coefficient ($\Gamma_{\min}$) from a noise viewpoint, and associated gain (G_{ass}) at selected frequencies.

Low-noise amplifiers (LNA) with combined $F_{\min}$ and G_{ass} can be achieved at a given frequency by using lossless impedance transformers at both active device ports. However, this provision will often result in a high VSWR at the amplifier input and low gain. Hence, LNA design requires a compromise in selecting a Γ_s capable of providing a low input VSWR, without largely increasing the noise figure (F), and, at the same time, a proper choice of the load reflection coefficient (Γ_L) to assure also a high transducer power gain. In particular, with reference to low-noise HEMT amplifiers any deviation of Γ_S from $\Gamma_{\min}$ causes a rapid increase in transistor noise figure and overall system noise figure since the noise mismatch ($\Delta F = F - F_{\min}$) is proportional to the equivalent noise resistance (R_n). Therefore, knowing the transistor's performance in a nonoptimum noise condition, is very useful from a design standpoint.

In order to determine all the optimum LNA-performance tradeoff values (i.e., operating power gain, noise figure, and input VSWR), starting with HEMT noise, gain and scattering parameters, two microwave tools, named "performance chart" and "performance window," useful for estimation of HEMT devices in CAD-oriented applications and of importance for accurate simulation of the LNA response, have been developed [1].

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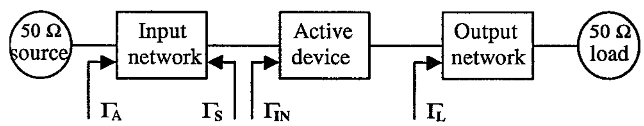

Fig. 1. Block diagram of the first stage of an LNA.

Figures of merit (M' and S_{ng}) for microwave low-noise HEMT, extracted from the performance chart and representing a fast way of evaluating HEMT in actual working conditions and of selecting the proper transistor, are defined [2].

Using the characterization of 26 HEMT's from the FHR02FH, 2SK677, and CFB001-03 families spanning 8–12 GHz at a low-noise bias point, the respective performance charts were plotted at 12 GHz and the figures of merit were calculated and compared with the data sheets.

II. Tradeoff Charts

First, we briefly recall some theoretical considerations the two tools are based on. Let us refer to a one-stage amplifier driven by a matched source and delivering power to a matched load, as shown in Fig. 1. Under the hypothesis of a lossless input impedance transformer, quite reasonable for low-noise amplifiers, a well-known relationship occurs [3]

$$|\Gamma_A| = \frac{|\Gamma_{IN} - \Gamma_S^*|}{|1 - \Gamma_{IN}\Gamma_S|} \tag{1}$$

where

$$\Gamma_{IN} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1 - S_{22}\Gamma_L}. \tag{2}$$

Equation (1) is recognized as a family of circles in the Γ_{IN} plane on the Smith chart with $|\Gamma_A|$ and Γ_S as parameters. The conformal transformation represented by (2) maps such family into one more set of circles depending on the device scattering parameters, in the Γ_L plane. A range of $|\Gamma_A|$ values does exist for which, in the Γ_L plane, the corresponding circles give rise to a nonzero intersection with the $\Gamma_L = 1$ circle. For the minimum noise figure, let us identify a circle belonging to such range with the pair ($F_{\min}, |\Gamma_A|$). In the same plane, the operating power gain circle set does exist and is completely defined through the knowledge of the scattering parameters.

The noise factor for the two-port in Fig. 1 may be written as [4]

$$F(\Gamma_S) = F_{\min} + 4r_n \frac{|\Gamma_S - \Gamma_{\min}|^2}{(1 - |\Gamma_S|^2)|1 + \Gamma_{\min}|^2} \tag{3}$$

representing a circle in the Γ_S-plane.

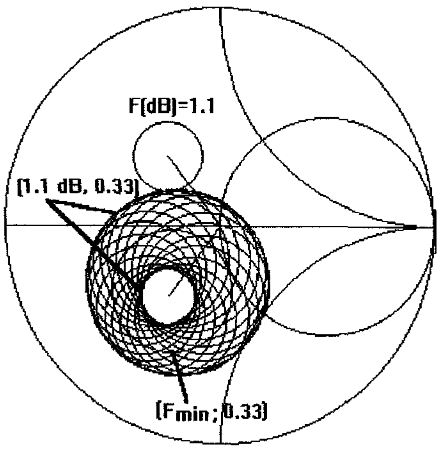

Fig. 2. Example of circles and envelopes for a Celeritek p-HEMT CFB001-03 plotted onto the source plane impedance chart.

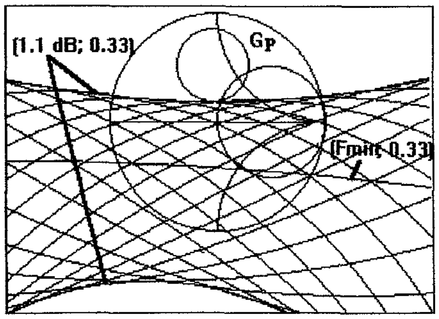

Fig. 3. Example of envelopes and operating power gain circle for a Celeritek p-HEMT CFB001-03 plotted onto the load plane impedance chart.

For each Γ_A selected value, from (1) a set of circles in the Γ_{IN} plane, one for each Γ_S value located along the noise circle mentioned above, is obtained, and from (2) a corresponding set of circles on the Γ_L plane is mapped. Simple calculations show that both sets are enveloped in their relevant planes by two circles (one inside and the other outside), labeled $(F, |\Gamma_A|)$ (Figs. 2 and 3), whose centers and radii were calculated [5].

The portion of Smith chart which belongs to the area lying within the envelope circles is the locus of the Γ_{IN} and Γ_L vectors, respectively, compatible with the specific F and $|\Gamma_A|$ values. In case of potential instability, the portion to be considered must be the one inside the stable region.

If F is sufficiently close to $F_{\min}$, the Γ_L producing an operating power gain equal to the maximum available gain (MAG) of the transistor lies outside the area defined above. In this case there are, in principle, two operating power gain circles tangent to the envelope circles, respectively. The lesser radius one produces the maximum operating power gain (G_P) compatible with the pair $(F, |\Gamma_A|)$ (Fig. 3). The Γ_L vector defined by the tangent A point realizes the necessary condition to get simultaneously the following performance:

—noise figure: F;

—amplifier input reflection coefficient: $|\Gamma_A|$;

—maximum operating power gain: G_P.

A comprehensive representation of the performance available from the transistor at a given frequency, called "performance chart," can be readily obtained by plotting G_P versus

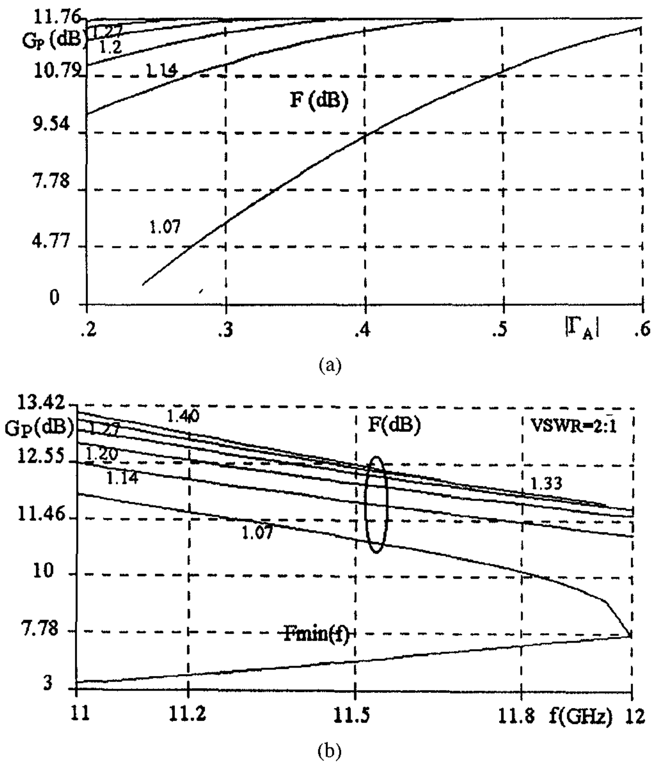

Fig. 4. (a) Performance chart of Celeritek p-HEMT CFB001-03. (b) Performance window of Celeritek p-HEMT CFB001-03.

$|\Gamma_A|$ with F as a parameter. The chart represents the whole set of optimum tradeoff conditions since, for each $(|\Gamma_A|, F)$ combination, it provides the maximum obtainable operating power gain at a given frequency. An example is shown in Fig. 4(a).

The performance chart is important to the design of the LNA's first stage, because it provides information about the operating performance before optimization and permits a separate synthesis of the LNA first-stage input and output matching. The latter is accomplished by imposing as goal functions the Γ_{IN} and Γ_L values related to the chosen F and G_P values [1].

If the transistor has been characterized for noise measure (NM) instead of F, it is possible to draw the performance chart with NM as a parameter, since NM circles are plotted onto the Γ_S-plane as the noise figure ones. Therefore, this chart can give useful information on the multistage configuration's operation.

The performance window plots G_P versus frequency with F as a parameter at a given $|\Gamma_A|$ or VSWR (Fig. 4(b)). The window may be used for selection of a transistor's operating performance and for comparison of different transistor families with similar performances in a given frequency range.

The curves reported in Figs. 2–4 were obtained with reference to the pseudomorphic Celeritek HEMT CFB001-03, whose parameters are reported in Table I.

In the performance chart and performance window the transducer power gain (G_T) can be used in place of G_P, since for an amplifier driven by a matched source the following relationship occurs:

$$G_T = G_P(1 - |\Gamma_A|^2). \tag{4}$$

TABLE I
HEMTS' NOISE, GAIN, AND SCATTERING PARAMETERS

f = 12 GHz	Fujitsu FHR02FH V_{ds} = 2 V, I_d = 10 mA	Sony 2SK677 V_{ds} = 2 V, I_d = 15 mA	Celeritek CFB001-003 V_{ds} = 3 V, I_d = 15 mA
F_{min} (dB)	1.80	2.43	1.07
Γ_{min}	0.62 ∠-55°	0.30 ∠-59.5°	0.42 ∠127.1°
R_n	18 33	18.96	3.00
G_{ao} (dB)	11.78	8.51	11.90
Γ_{og}	0 81 ∠-33°	0.67 ∠51 7°	0.69 ∠-165°
N_g	0.022	0.036	0.011
S_{11}	0.80 ∠33.3°	0.58 ∠52°	0.449 ∠179°
S_{12}	0.08 ∠13.7°	0.10 ∠15.5°	0.099 ∠10°
S_{21}	2 02 ∠80°	1.84 ∠140°	2.84 ∠31°
S_{22}	0.29 ∠75.1°	0.36 ∠103°	0.415 ∠-80°

Note that the combined $F_{\min} - G_{\text{ass}}$ corresponds to the point "0" located on the $F_{\min}$ curve.

III. FIGURES OF MERIT

The performance chart makes use of knowledge of the transistor parameters required for optimization of HEMT-based LNA's. A figure of merit representing the transistor in actual working conditions may be extracted from it. In order to analitically define this figure of merit, we formally modify the Noise Measure by replacing the available power gain with the maximum operating power gain yielded by the performance chart [6]

$$M' = \frac{F-1}{1-1/G_P} = \frac{F-1}{1-(1-|\Gamma_A|^2)/G_T}. \tag{5}$$

M' is recognized as a figure of merit according to the following reasons:

1) M' decreases with decreasing F and with increasing G_P, so it is used for effective comparison among different HEMT's for selected $|\Gamma_A|$ and G_T;

2) M' represents a way to select a device operating point among those lying on a vertical line drawn on the performance chart for a selected $|\Gamma_A|$.

Moving up from the $(F_{\min}, |\Gamma_A|)$ point produces a minimum in M' for which the following relationship occurs:

$$\frac{dF}{dG_P}\Big|_{|\Gamma_A|=\text{cost}} = \frac{F-1}{G_P(G_P-1)}. \tag{6}$$

Designing an LNA with minimum M' as a goal, will cause sensitivity of the noise figure related to G_P; usually a low value, owing to the G_P^2 factor in (6).

On the performance chart, just a small increase in F above $F_{\min}$ at selected input VSWR results in a remarkable increase in G_P. Such useful information is not directly obtainable in any way from the transistors' data sheets or even from a transistor characterization in terms of all the parameters without the aid of the chart. In order to quantify such a property, the noise-gain sensitivity figure of merit is defined as

$$S_{ng} = \frac{\Delta G_P}{F - F_{\min}} \tag{7}$$

which is associated with each input VSWR value.

TABLE II
FUJITSU HEMT FHR02FH TRADEOFF PERFORMANCE AT $f = 12$ GHz

F (dB)	1.96	2 02	2.09	2.12
VSWR	G_P (dB)			
1.50 : 1	-----	7.20	8.53	9 25
1.63 : 1	1.45	8.21	9.21	9.78
1.78 : 1	4.95	8.96	9.76	10.22
1.94 : 1	6.76	9.59	10.22	10.60
2.12 : 1	7.97	10.09	10.60	10.92
2.33 : 1	8.85	10.51	10.94	11.20
2.57 : 1	9.55	10.87	11.22	11.44

TABLE III
SONY HEMT 2SK677 TRADEOFF PERFORMANCE AT $f = 12$ GHz

F (dB)	2.43	2.48	2.53	2.58
VSWR	G_P (dB)			
1 50 : 1	-----	6.69	7.57	8.02
1.63 : 1	3.51	7.37	8.00	8.33
1.78 : 1	5.32	7.87	8 32	8.54
1 94 : 1	6.46	8.23	8.54	8.67
2.12 · 1	7.25	8.49	8.68	8.72
2.33 : 1	7.82	8.65	8.72	8 72

TABLE IV
CELERITEK HEMT CFB001-03 TRADEOFF PERFORMANCE AT $f = 12$ GHz

F (dB)	1.07	1.13	1.19	1.34
VSWR	G_P (dB)			
1.50 : 1	-----	9.78	10.84	11.31
1.63 : 1	-----	10.31	11.13	11.49
1.78 : 1	5 05	10.72	11.36	11.63
1.94 : 1	7.19	11.05	11.54	11.72
2.12 : 1	8.51	11.31	11.66	11.76
2.33 : 1	9.44	11.51	11.74	11.76

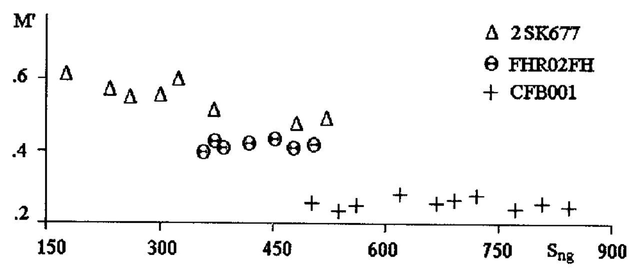

Fig. 5. Synopsis of different HEMT families performance.

S_{ng} may be calculated at an assigned noise mismatch $(F - F_{\min})$ or at the F value corresponding to minimum M'.

IV. APPLICATIONS

Starting from the characterization of 26 HEMT's from the FHR02FH, 2SK677, and CFB001-03 families in terms of noise, gain, and scattering parameters at a low-noise bias point [7], the respective performance charts at 12 GHz were drawn. The characterization of three samples are reported in Tables II–IV. Both S_{ng} (at an assigned noise mismatch) and minimum M' values, at $\text{VSWR}_i = 2{:}1$, for each sample were calculated. A synopsis of all the data is shown in Fig. 5, from which it appears that high performance in terms of low minimum M' at standard $|\Gamma_A|$ values correspond to high S_{ng} values.

As far as CAD application is concerned, it can be easily shown that HEMT's from different manufacturers, even if

TABLE V
CAD-ORIENTED HEMT'S COMPARISON

HEMT's	data sheets		computed values at VSWRi=2			
				at min-M'		
	F_{min} (dB)	G_{ass} (dB)	min-M'	S_{ng}	G_P (dB)	G_T (dB)
FHR02FH	0.75	10.8	0.66	296	9.29	8.78
CFB001-003	0.9	10.6	0.31	813	10.31	9.8

looking alike according to the data sheets, may not yield the same performance [1]. Table V shows such a comparison between the FHR02FH and the CFB001-03. At a standard input VSWR value, the CFB001-03 shows a markedly higher G_P than the FHR02FH, for an almost negligible increase of noise mismatch.

The computer program for mapping HEMT optimum tradeoff performance is available from the authors upon request.

V. CONCLUSION

Tradeoff charts for microwave low-noise HEMT's, well suited to represent in a compact form the performance of different devices, have been illustrated and employed. Figures of merit referring to actual LNA operation, extracted from the tradeoff charts, have been suggested and applied to carry out a deeper investigation on formally equivalent devices, before any design attempt was made.

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