Analysis of GaAs-FET Noise Properties at VHF-/UHF-Frequencies

G. Braun

MBB Space Systems Division, Ottobrunn, West Germany

ABSTRACT

Many theories and measurements of GaAs-FET noise behavior have been presented in the past. Almost all of them restricted themselves to amplifier applications above 2 GHz. Although GaAs-FETs are increasingly used in VHF-/UHF-amplifiers and are well suited for low noise oscillators in that frequency range [4],[5], their noise properties at VHF-/UHF-frequencies as well as important parameters for low noise GaAs-FET oscillator operation were not considered.

In this work a noise equivalent circuit for two different kinds of GaAs-FETs is presented which is based on DC- and S-parameter measurements. It is verified by noise measurements between 50 and 200 MHz.

NOISE EQUIVALENT CIRCUIT

Any GaAs-Field Effect Transistor can be described by the noise equivalent circuit of Fig.1. It is similar to the equivalent circuits given by [1],[2] but contains an additional noise voltage source v_i relating to the Schottky gate losses described by R_i.

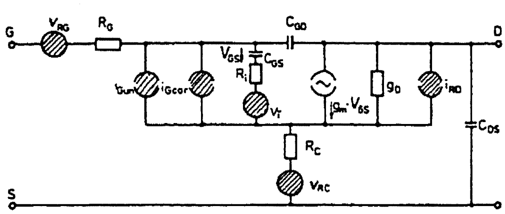

Fig.1: GaAs-FET Noise Equivalent Circuit

The noise voltage sources v_{Rg}, v_{Ri}, and v_{Rc} describe the thermal noise of the gate resistance R_g, of the losses R_i of the gate capacitance C_{GS}, and of the source resistance R_C in the bandwidth B, respectively.

$$\overline{v_{Rg}^2} = 4 \cdot kT_0 \cdot B \cdot R_g \qquad (1)$$

$$\overline{v_{Ri}^2} = 4 \cdot kT_0 \cdot B \cdot R_i \qquad (2)$$

$$\overline{v_{Rc}^2} = 4 \cdot kT_0 \cdot B \cdot R_C \qquad (3)$$

The noise current source i_{RD} comprises the thermal noise of the channel admittance g_D and the current noise in the channel which is partially correlated with the gate current noise.

$$\overline{i_{RD}^2} = 4 \cdot kT_0 \cdot B \cdot (g_m \cdot m + g_D) \qquad (4)$$

The constant factor m is determined by comparing calculated and measured noise parameters. It is found to be typically $0.4 \le m \le 0.8$.

The gate noise current source i_G

$$\overline{i_G^2} = \overline{i_{Gun}^2} + \overline{i_{Gcor}^2} = 2 \cdot e \cdot I_G \cdot B \qquad (5)$$

represents the current noise of the gate leakage current I_G. i_G consists of one part i_{Gcor} which is fully correlated with i_{RD} and another part i_{Gun} which is not correlated with i_{RD}.

The correlation between i_G and i_{RD} is described by the complex correlation

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coefficient $\underline{\gamma}_G$

$$\underline{\gamma}_G = \frac{\overline{\underline{i}_{G\,cor} \cdot \underline{i}_{RD}^*}}{\sqrt{\overline{i_G^2} \cdot \overline{i_{RD}^2}}} \qquad (6)$$

With $\underline{\gamma}_G$ the noise current i_G is determined by

$$\underline{i}_{G\,cor} = \underline{\gamma} \cdot \sqrt{\frac{\overline{i_G^2}}{\overline{i_{RD}^2}}} \cdot \underline{i}_{RD} \qquad (7)$$

$$\overline{i_{G\,un}^2} = \overline{i_G^2} - \overline{i_{G\,cor}^2} = \overline{i_G^2} \cdot (1 - |\underline{\gamma}_G|^2) \qquad (8)$$

By comparing calculated and measured noise parameters the complex correlation coefficients $\underline{\gamma}_G$ are determined as

$\underline{\gamma}_G = 0.1 + j \cdot 0.4$		NE 244
$\underline{\gamma}_G =$	$j \cdot 0.4$	GAT 1/010

DERIVATION OF TRANSISTOR NOISE PARAMETERS

A noisy two-port can be represented by a noiseless two-port with partially correlated noise current and noise voltage sources at the input [6],[7]. Any one of the internal GaAs-FET noise sources can be transformed into a pair of fully correlated equivalent noise sources (index "+") at the transistor input (Fig.2). For the noise equivalent circuit of Fig.1 six pairs of noise sources $\underline{v}_{r\nu}^+$, $\underline{i}_{r\nu}^+$ with $\nu = 1 \ldots 6$ are obtained.

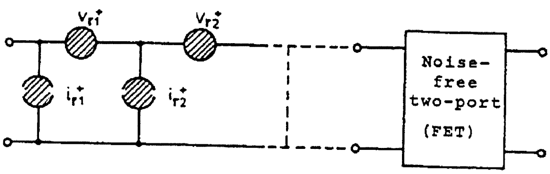

Fig.2: Transformation of Noise Sources

For the calculation of the transistor noise parameters the noise sources $\underline{v}_{r\nu}^+$ and $\underline{i}_{r\nu}^+$ ($\nu = 1 \ldots 6$) have to be summed up to get one partially correlated pair of equivalent noise sources $\underline{v}_r$, $\underline{i}_r$ at the transistor input. At first the fully correlated sources $\underline{v}_{r\mu}^+$ and $\underline{v}_{r\xi}^+$, and $\underline{i}_{r\mu}^+$ and $\underline{i}_{r\xi}^+$ which are derived from the internal noise sources $\underline{i}_{Gcor}$ ($\nu = \mu$) and $\underline{i}_{RD}$ ($\nu = \xi$), respectively, have to be added. With the remaining five pairs of noise sources the resulting equivalent noise sources $\underline{i}_r$ and $\underline{v}_r$ at the input are obtained as

$$\overline{i_r^2} = \sum_{\nu=1}^{n} \overline{i_{r\nu}^2} \qquad \overline{v_r^2} = \sum_{\nu=1}^{n} \overline{v_{r\nu}^2} \qquad (9)\ (10)$$

For a fully correlated pair of noise sources $\underline{v}_{r\nu}^+$, $\underline{i}_{r\nu}^+$ with $\nu = k$ the complex correlation coefficient $\underline{\gamma}_k = \gamma_{kR} + j \cdot \gamma_{kI}$ is defined as

$$\underline{\gamma}_k = \frac{\overline{\underline{i}_{rk} \cdot \underline{v}_{rk}^*}}{\sqrt{\overline{i_{rk}^2} \cdot \overline{v_{rk}^2}}} \qquad (11)$$

The indices R and I classify the real and imaginary parts of $\underline{\gamma}_k$. The complex correlation coefficient between $\underline{v}_r$ and $\underline{i}_r$ is then (n = 5)

$$\underline{\gamma} = \gamma_R + j \cdot \gamma_I = \frac{\sum_{\nu=1}^{n} \gamma_{\nu R} \sqrt{\overline{v_{r\nu}^2} \cdot \overline{i_{r\nu}^2}}}{\sqrt{\sum_{\nu=1}^{n} \overline{v_{r\nu}^2} \cdot \sum_{\nu=1}^{n} \overline{i_{r\nu}^2}}} + j \cdot \frac{\sum_{\nu=1}^{n} \gamma_{\nu I} \sqrt{\overline{v_{r\nu}^2} \cdot \overline{i_{r\nu}^2}}}{\sqrt{\sum_{\nu=1}^{n} \overline{v_{r\nu}^2} \cdot \sum_{\nu=1}^{n} \overline{i_{r\nu}^2}}} \qquad (12)$$

The optimum source admittance for noise matching of the transistor is $\underline{Y}_{opt} = G_{opt} + j \cdot B_{opt}$ with [3]

$$G_{opt} = \sqrt{\frac{\overline{i_r^2}}{\overline{v_r^2}}} \cdot \sqrt{1 - \gamma_I^2} \qquad (13)$$

$$B_{opt} = - \gamma_I \cdot \sqrt{\frac{\overline{i_r^2}}{\overline{v_r^2}}} \qquad (14)$$

$\underline{Z}_{opt} = R_{opt} + j \cdot B_{opt}$ is the optimum source impedance. It is obtained with

$$R_{opt} = \frac{G_{opt}}{|\underline{Y}_{opt}|^2} \qquad X_{opt} = - \frac{B_{opt}}{|\underline{Y}_{opt}|^2} \qquad (15)\ (16)$$

$F_{Tmin} = F_{min} - 1$ is the minimum additional noise figure of the transistor.

$$F_{Tmin} = \frac{\sqrt{\overline{v_r^2} \cdot \overline{i_r^2}}}{2 \cdot kT_o \cdot B} \cdot \left[\gamma_R + \sqrt{1 - \gamma_I^2} \right] \qquad (17)$$

RESULTS OF THEORY AND MEASUREMENTS

Fig.3 shows the measured optimum source impedances for the GaAs-FETs GAT 1/010 and NE 244. The calculated values lie well within the uncertainty limits of the measurements.

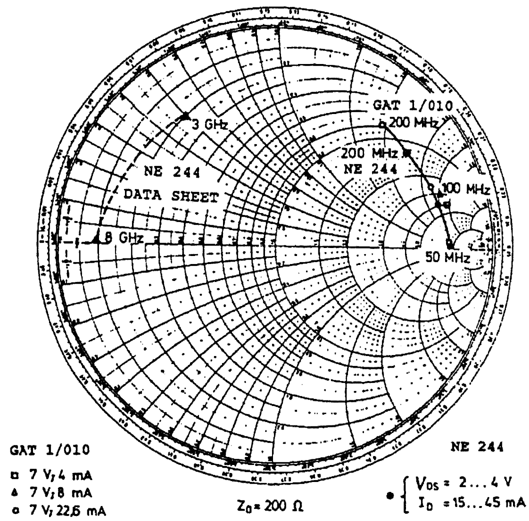

Fig.3: Optimum Source Impedances

The influence of biasing on the minimum noise figures is indicated by Figs. 4, 5. The values are measured at f = 100 MHz.

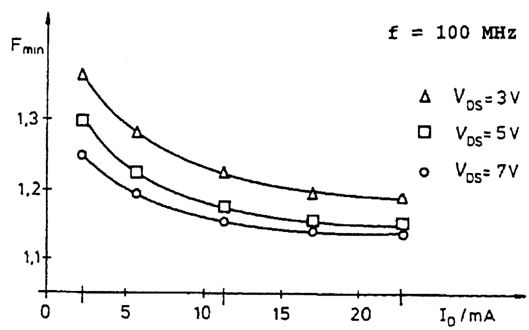

Fig.4: Minimum Noise Figure of GAT 1/010

It can be seen that - mainly due to the shorter gate length of the NE 244 - there is a considerable difference concerning optimum biasing of the FETs. Since the determination of the optimum biasing by noise measurements is a rather time consuming task it is suggested to take advantage of a qualitative correlation which has been found for all measured FETs between the noise figures of the noise matched FETs and the gate leakage currents I_G. Fig. 6 shows the gate leakage currents for both kinds of FETs for all bias variations.

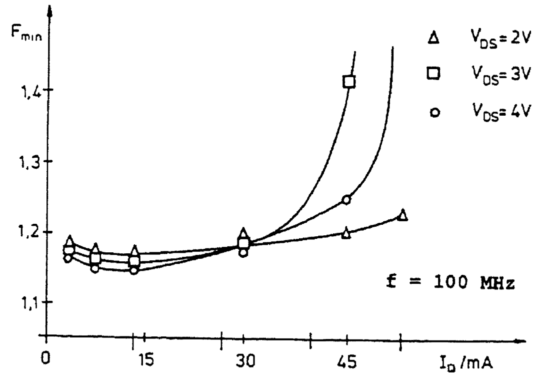

Fig.5: Minimum Noise Figure of NE 244

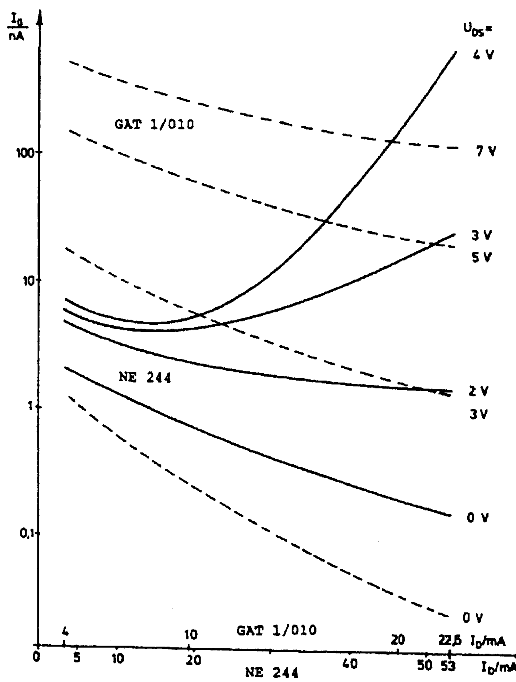

Fig.6: Gate Leakage Currents of GAT 1/010 (----) and NE 244 (——)

Figs. 7 and 8 show the calculated and measured noise figures of the noise matched FETs between 50 MHz and 200 MHz. Whereas the qualitative agreement is good for the GAT 1/010 there is a difference between theory and measurement for the NE 244. This difference can be explained with the 1/f-noise of the NE 244 which is superimposed on the calculated noise figure and dominates the overall noise in the frequency range up to 200 MHz. For oscillator applications the upconversion of the 1/f-noise near the carrier may decrease the carrier-to-noise ratio near the carrier considerably.

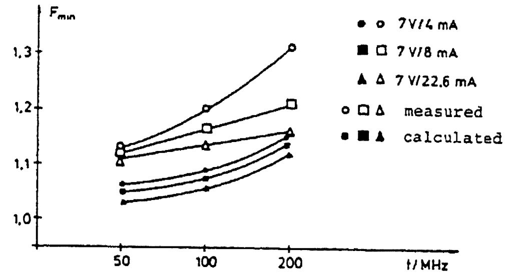

Fig.7: Minimum Noise Figure of GAT 1/010

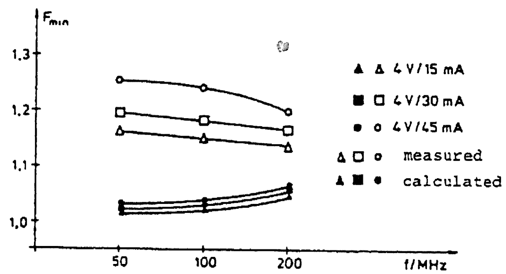

Fig.8: Mimimum Noise Figure of NE 244

Finally Fig. 9 shows the complex correlation coefficient $\underline{\gamma}$ between the equivalent noise sources $\underline{v}_r$ and $\underline{i}_r$ at the transistor input. The calculated values of $\underline{\gamma}$ are almost the same for both FETs. The measured values confirm the theoretical values, however, they are not drawn because they are subject to large errors even for very small measurement errors of F_{Tmin} and $\underline{Y}_{opt}$.

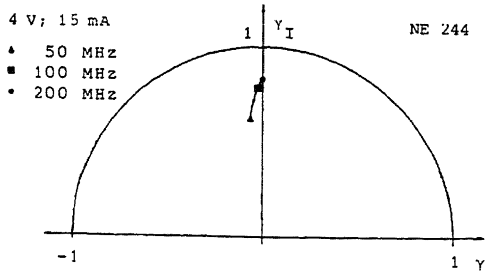

Fig.9: Complex Correlation Coefficient $\underline{\gamma}$

According to (17) a complex correlation coefficient with $\gamma_R = 0$ and $|\gamma_I| \rightarrow 1$ minimizes the additional noise figure of the transistor. Whereas this is desirable in amplifier applications it has no positive influence on the noise contribution of the active element in an oscillator circuit which is proportional to [5]

$$\frac{F_{Tmin}}{\left(\gamma_R + \sqrt{1-\gamma_I^2}\right)} .$$

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