An Accurate Procedure for Noise Wave Modelling of Microwave FETs versus Temperature

Olivera Pronić- Rančić, Zlatica Marinković, Vera Marković

Abstract – **A simple procedure for accurate prediction of noise parameters of microwave FETs versus temperature is proposed in this paper. The proposed modeling procedure presents a modification of noise wave transistor model with the aim to improve the model accuracy. For this purpose, frequency-dependent error correction functions are determined and incorporated into the noise parameter expressions. The error correction functions calculated for one temperature are used for efficient transistor noise parameter modelling for various device ambient temperatures, as it is shown by an example of packaged HEMT noise modelling.**

Keywords – **MESFET, HEMT, noise wave parameters, temperature**

I. INTRODUCTION

In the last few decades an extensive work has been carried out in the field of signal and noise modeling of microwave FET transistors (MESFETs, HEMTs). Their physical models are very complex and require many input technological parameters [1] - [2]. Therefore, in microwave CAD the empirical models, mostly based on equivalent circuits are often used [3] – [5].

The two-parameter noise model [5] is considered to be very suitable for implementation into the standard commercial microwave circuit simulators. It is based on *H* representation of transistor intrinsic circuit with two uncorrelated noise sources, the voltage noise source at the gate side and the current noise source at the drain side. However, it has been found that in some cases the inaccuracy in transistor noise modeling caused by the assumption that noise sources are uncorrelated is not negligible. Therefore, the model including the correlation between noise sources has been developed and implemented into a standard microwave circuit simulator, [6].

In the microwave frequency region a treatment of noise in terms of waves is more appropriate since it allows the use of scattering parameters for noise computations [7]. It has been shown [8] that the wave approach is useful for both noise modeling and measurement of microwave FETs. Using a similar approach, the new extraction formulas describing the noise wave sources in the noise equivalent circuit of MESFETs / HEMTs, where the correlation between noise sources is included, are proposed in [9]. The noise parameter characteristics obtained by using that procedure are in better agreement with the measurements than the existing model [8].

The noise wave modeling procedures of MESFETs, HEMTs and dual-gate MESFETs based on *T* representation of transistor intrinsic circuit are proposed in [10] and [11]. The proposed procedures are based on circuit theory concepts and therefore are very convenient for implementation in microwave CAD programs.

The improvement in modelling of MESFET / HEMT noise performance versus temperature has been investigated in this paper. The authors present a new more accurate noise wave model of microwave FETs based on *T* representation of transistor intrinsic circuit that is valid for various device ambient temperatures. In order to obtain more accurate prediction of noise parameters versus temperature, the error correction functions are included in transistor noise model. Once determined error correction functions are used for device noise parameters modelling for various device ambient temperatures. The verification of presented procedures is done by comparison with measured data.

II DESCRIPTION OF NOISE WAVE MODELLING PROCEDURE

As microwave FET devices in packaged form are considered in this work, their noise wave model is described in the text below. Due to the presence of parasitic effects, the equivalent circuit of a packaged transistor is more complex than that of a chip transistor. The equivalent circuit used in this work is shown in Fig.1. The intrinsic circuit, marked with a dashed line, is embedded in a network representing device parasitics.

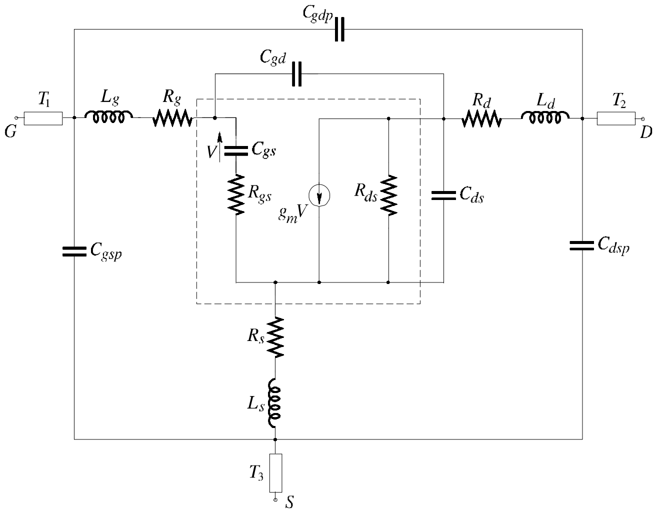

Fig.1. Equivalent circuit of packed MESFET / HEMT

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As it is known, noise in linear two-port networks can be characterized in many different ways, [12]. Any noisy linear two-port can be replaced by a noiseless two-port network and two additional correlated noise sources. Noise is typically characterized using equivalent voltage and/or current sources. Therefore, the impedance and admittance matrix representations, the chain matrix representation and a few others are often used in CAD of noisy networks. On the other hand, in the noise wave representation, a noisy two-port network is described by using a noiseless linear equivalent circuit and the waves that emanate from its ports.

A linear noisy two-port component can be characterized by a noise temperature T_n (or, alternatively, by a noise figure, F, defined as $F = 1 + T_n / T_0$, where T_0 is standard reference temperature of 290K), in following way:

$$T_n = T_{n\,min} + 4T_0 \frac{R_n}{Z_0} \frac{\left|\Gamma_g - \Gamma_{opt}\right|^2}{\left|1+\Gamma_{opt}\right|^2 \left(1 - \left|\Gamma_g\right|^2\right)}, \qquad (1)$$

where Z_0 is the normalization impedance (Z_0=50 Ω).

Eq.1 gives the depedence of device noise temperature on four noise parameters: minimum noise temperature $T_{n\,min}$ (alternatively, minimum noise figure, $F_{min} = 1 + T_{n\,min}/T_0$, can be used), magnitude and angle of optimum reflection coefficient, $\Gamma_{opt} = \left|\Gamma_{opt}\right| e^{j\varphi_{opt}}$, and noise resistance, R_n. The set of four noise parameters describe inherent behavior of the component and are independent of a connected circuit.

Since a transistor intrinsic circuit is a linear noisy two-port network, its noise parameters can be determined in terms of noise waves in the way described bellow.

We consider *T* representation of a transistor intrinsic circuit. In that case, noisy two-port is represented by a noiseless two-port defined by transfer scattering parameters, [*T*], and two noise wave sources a_n and b_n referred to the input, as shown in Fig. 2.

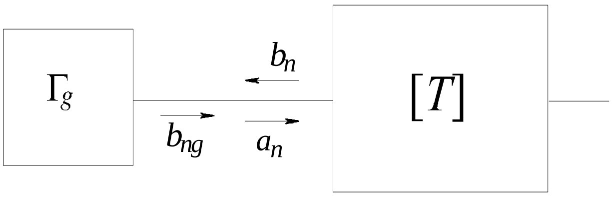


Fig. 2. *T* representation of a linear noisy two-port

The linear matrix equation describing this noisy two-port is:

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix} + \begin{bmatrix} a_n \\ b_n \end{bmatrix}, \qquad (2)$$

where a_i and b_i, i =1, 2, are incident and output waves at the i-th port.

Generally, the noise wave sources a_n and b_n are correlated and characterized by a correlation matrix $\boldsymbol{C_T}$ given by

$$\boldsymbol{C_T} = \begin{bmatrix} \langle |a_n|^2 \rangle & \langle -a_n b_n^* \rangle \\ \langle -b_n a_n^* \rangle & \langle |b_n|^2 \rangle \end{bmatrix}, \qquad (3)$$

where the brackets $\langle\,\rangle$ indicate time average of the quantity inside and * indicates complex conjugation.

It is very convenient to use the noise wave temperatures as empirical noise model parameters [13]. In that way, the correlation matrix $\boldsymbol{C_T}$ can be expressed by

$$\boldsymbol{C_T} = k\Delta f \begin{bmatrix} T_a & |T_c| e^{j\varphi_c} \\ |T_c| e^{-j\varphi_c} & T_b \end{bmatrix}, \qquad (4)$$

where k is the Boltzmann's constant and Δf is the noise bandwidth (it is assumed that Δf=1Hz). In this way the noise performance of a two-port network is completely characterized by two real temperatures T_a and T_b and a complex correlation temperature $T_c = |T_c| e^{j\omega\tau_c}$.

The expressions for the noise wave temperatures could be derived considering the representation of the noisy two-port as shown in Fig. 2. A source of reflection coefficient $\Gamma_g = \left|\Gamma_g\right| e^{j\varphi_g}$ and the noise wave b_{ng} is connected to the input of noiseless two-port. The total noise wave that is incident on the input of noiseless two-port is

$$a_{ng} = a_n + \Gamma_g b_n + b_{ng}. \qquad (5)$$

Assuming no correlation between the source and two-port noise, after some elementary mathematical transformations, the noise temperature is obtained as:

$$T_n = \frac{T_a + \left|\Gamma_g\right|^2 T_b - 2|T_c| \left|\Gamma_g\right| cos\left(\varphi_g - \varphi_c\right)}{1 - \left|\Gamma_g\right|^2}. \qquad (6)$$

Comparison of the Eqs. 6 and 1 yields to the following expressions for the noise parameters of transistor intrinsic circuit:

$$\Gamma_{opt} = \left(\frac{T_a + T_b}{2|T_c|} - \sqrt{\left(\frac{T_a + T_b}{2|T_c|}\right)^2 - 1} \right) e^{j\omega\tau_c}, \qquad (7)$$

$$R_n = Z_0 \frac{|T_c|}{4T_0 \left|\Gamma_{opt}\right|} \left[1 + 2\left|\Gamma_{opt}\right| cos\,\phi_{opt} + \left|\Gamma_{opt}\right|^2 \right], \qquad (8)$$

$$F_{min} = 1 + \frac{T_a - T_b}{2T_0} + \frac{1}{2T_0} \sqrt{\left(T_a + T_b\right)^2 - 4|T_c|^2}. \qquad (9)$$

The noise parameters of the complete circuit are computed after adding of parasitics.

However, the transistor noise parameters calculated in this way do not perfectly match measured noise parameters. In order to minimize deviations that exist between measured and modeled noise parameters, a correction procedure based on incorporation of frequency-dependent error correction functions into the noise equations is applied. The proposed noise modeling procedure is similar to that authors have previously developed for Pospieszalski's noise model, [14].

At the beginning, for each of four noise parameters the ratio of the measured and simulated transistor noise parameter values is calculated over the entire frequency range. Then, curve-fitting procedure is applied on these sets of data, in order to obtain suitable frequency dependences. In this way, corresponding mathematical functions are chosen for all four noise parameters. These functions represent error correction functions ($y_i(f)$, i=1, …, 4) for improving the accuracy of the proposed noise wave model. Namely, each intrinsic circuit noise parameter obtained by the wave approach is multiplied by the corresponding error correction function and, as a result, new equations for transistor intrinsic circuit noise parameters become:

$$F_{min_{new}} = F_{min} \cdot y_1(f) \tag{10}$$

$$r_{n_{new}} = r_n \cdot y_2(f) \tag{11}$$

$$Mag\left(\Gamma_{opt}\right)_{new} = Mag\left(\Gamma_{opt}\right) \cdot y_3(f), \tag{12}$$

$$Ang\left(\Gamma_{opt}\right)_{new} = Ang\left(\Gamma_{opt}\right) \cdot y_4(f). \tag{13}$$

By using the new set of equations, improved modeling of MESFET / HEMT noise parameters is achieved.

III NUMERICAL RESULTS

The proposed noise wave modelling procedure was applied to a packaged HEMT, type NE20283A, by NEC, and some of the obtained results are presented in this paper. All simulations are performed using microwave circuit simulator ADS (Advanced Design System) [15]. Measured S and noise parameters were available in the frequency range (6 – 18) GHz over the temperature range (233 – 333) K (step 20 K). They have been obtained earlier at the University of Palermo, Italy, by a convenient measurement procedure, [16].

First, the transistor noise wave model parameters are extracted from the experimental data. As illustration, modelled S parameters at T=333K are presented in Fig. 3 as solid lines, while the corresponding measured values are shown as symbols. It can be observed that the modeled values match very well the measured ones in the whole frequency range.

The noise parameter characteristics at 333K obtained by the noise wave approach (dashed line), together with measured data (circles) are presented in Figs. 4 - 7.

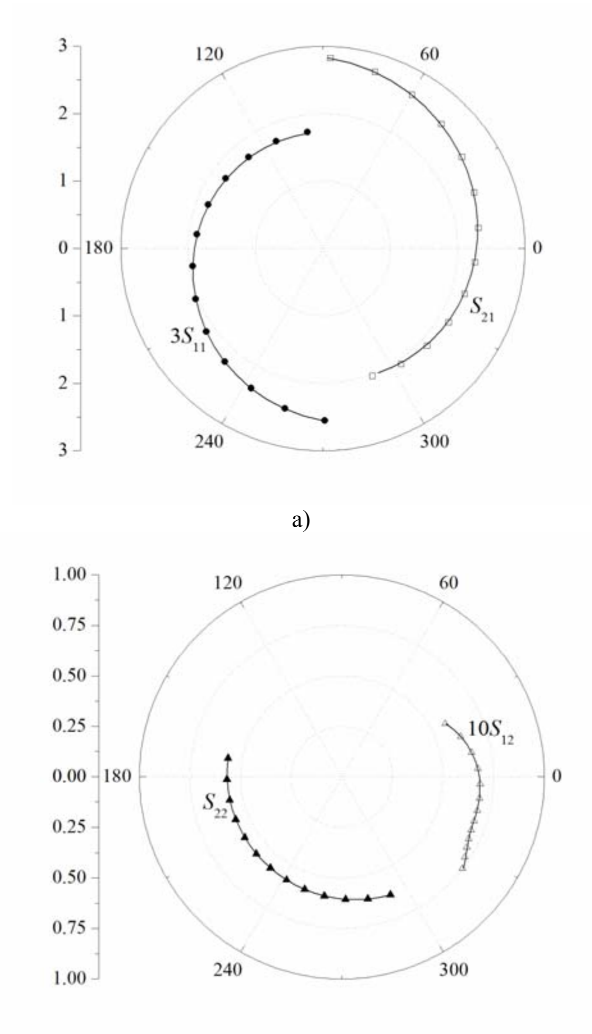
In order to eliminate deviations that exist between measured and modeled values of noise parameters, the error correction functions are determined and included in the transistor noise wave model, as described in previous section. In this case, the error correction functions are determined for minimum noise figure, magnitude of optimum reflection coefficient and noise resistance and have the form:

$$y_i(f) = a_i + b_i f + c_i f^2 + d_i f^3 , \quad i = 1,2,3 \tag{14}$$

where a_i, b_i and c_i are the constants and f is frequency in GHz. Modelling results for angle of optimum reflection coefficient versus frequency are in excellent agreement with measured ones and there was no need to include any correction for that parameter in the noise model. The parameters of polynomial functions (Eq.14) are given in Table I. Modified frequency dependences of noise parameters are also shown in Figs. 4 - 7 (solid lines). It is obvious that perfect match between measured and modeled parameters is now achieved.

TABLE 1: PARAMETERS OF THE POLYNOMIAL FUNCTIONS $y_1(f)$, $y_2(f)$ AND $y_3(f)$

	a	*b*	*c*	*d*
$y_1(f)$	2,1094	-0,10403	0,00391	0
$y_2(f)$	2,44577	-0,61819	0,06601	-0,002
$y_3(f)$	1,01112	-0,02907	0,00181	0



a)

b)

Fig. 3. S parameters at T=333: a) S_{11} and S_{21} b) S_{22} and S_{12}

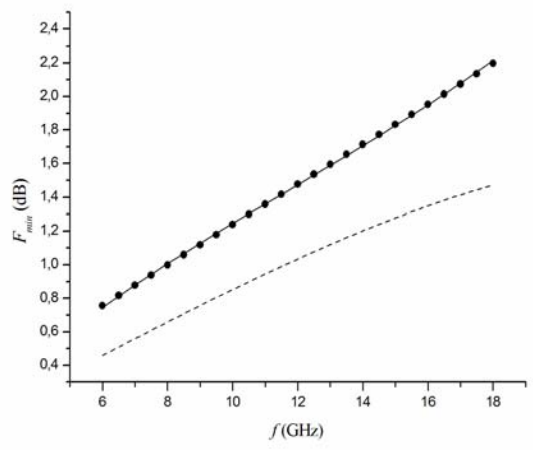


Fig. 4. Minimum noise figure at T=333 K

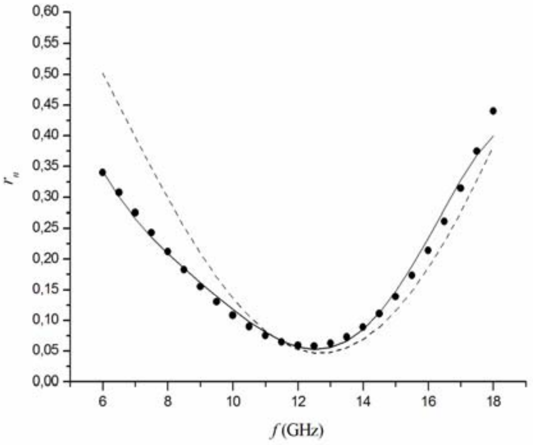


Fig. 5. Normalised noise resistance at T=333 K

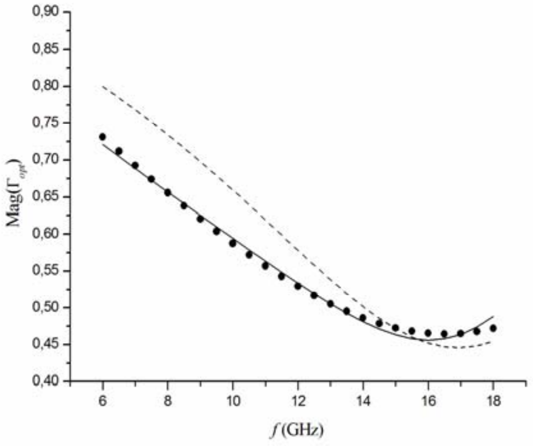


Fig. 6. Magnitude of optimum reflection coefficient at T=333 K

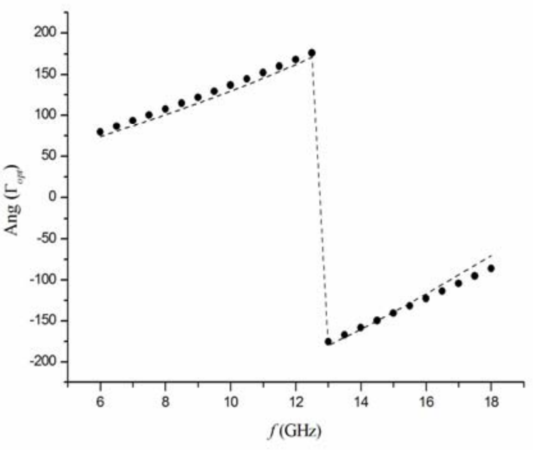


Fig. 7. Angle of optimum reflection coefficient at T=333 K

The investigation has been carried out to in order to verify the reliability of prediction of noise parameters versus temperature by applying the proposed procedure. Since scattering and noise parameters are temperature dependant, it is necessary to repeat extraction procedure of equivalent circuit elements and equivalent noise wave temperatures for various ambient temperatures. It was found that once determined error correction functions can be used for efficient noise parameter prediction of the same transistor for all considered temperatures, as it is shown further. In that way, overall procedure has been simplified.

As illustration, the modeling results for noise parameters at temperature 293 K, obtained by the wave approach (dashed line) and by suggested technique applying error correction functions determined for the temperature 333K (solid lines), together with experimental values (circles) are given in Figs. 8 - 10. It is obvious that the presented method provide results that agree much better with the measured characteristics than the wave model.

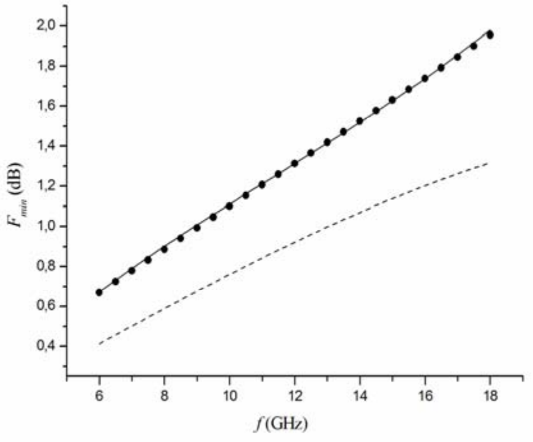


Fig. 8. Minimum noise figure at T=293 K

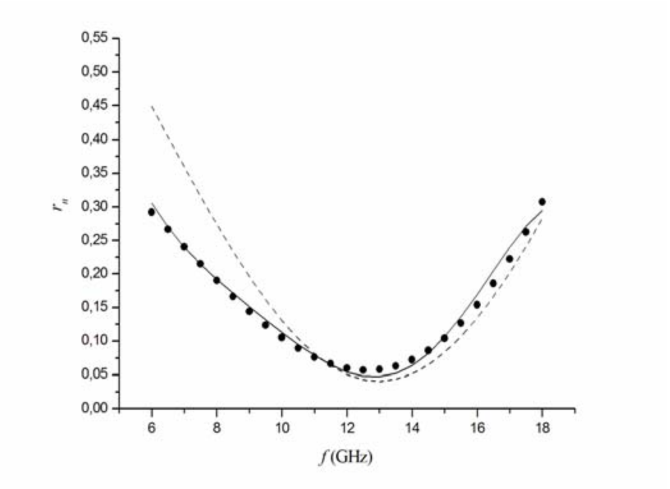


Fig. 9. Normalized noise resistance at *T*=293 K

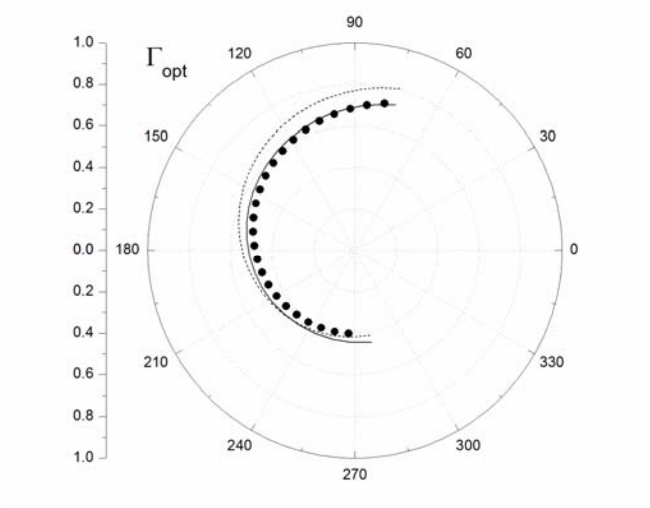


Fig. 10. Optimum reflection coefficient at *T*=293 K

IV CONCLUSION

An efficient noise wave modeling procedure of microwave FETs versus temperature is presented in this paper. The presented noise model is a modification of noise wave model. The modification is done by including the error correction functions to the noise parameters' expressions. In that way, deviations that exist between measured and modeled data are significantly reduced, and therefore better noise prediction is achieved. It is shown that once determined error correction functions enable efficient noise modeling of the same transistor for various ambient temperatures. The presented method provide results that agree well with the measured characteristics, as is shown by the example of transistor noise modeling for HEMT in packaged form.

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