Noise Wave Model of RF MOSFETs - Development and Software Implementation

Olivera R. Pronić, Vera V. Marković

Abstract — **Noise wave model of RF MOSFETs based on *T* representation of transistor intrinsic circuit is derived in this paper. The presented modeling procedure is based on circuit theory concepts and on similar kind of analysis we proposed earlier for MESFETs / HEMTs noise modeling. The noise wave temperatures are introduced as empirical parameters of the model. The complete noise modeling procedure is implemented in microwave circuit simulator Libra. Noise parameter values modeled by proposed procedure are verified by the comparison with the measured ones for a typical RF MOSFET.**

Keywords – **MOSFET, noise parameters, noise wave temperatures**

I. INTRODUCTION

For decades, the high-frequency properties of silicon integrated circuits have been considered inferior comparing to the GaAs counterpart. The situation is now changing. Namely, by scaling down the CMOS technology, the RF gain and noise performance of deep and ultradeep sub-micrometer MOSFET are improved so that it can be used for wireless communications, [1]. The advantages of MOSFET-based technology are: low cost, low power consumption, small dimensions and weight, high reliability, high-level integration possibility and ability to combine digital, analog and RF circuits on the same chip [2]. Because of that, today ultradeep-submicrometer CMOS technology is considered as the most promised technology for 3G mobile terminals and other wireless products such as GPS, Home RF, Bluetooth, etc.

For these new wireless applications, designers need reliable RF small signal models, which are easy to extract and use. In some cases MOSFET noise models are also requiered. Physical models, like the well-known models of the BSIM family, for instance BSIM3v3, [3], are not quite adequate for RF and microwave MOSFETs. In addition, their application is time consuming, requiring much technological data. Because of that, many efforts were made during the last few years, in order to develop the appropriate empirical device models that can be implemented into the microwave CAD tools, [4].This task still remains a challenge because mechanisms of noise generating and other effects inside the short-channel MOSFETs are complex and even not yet completely explained. Therefore, there is still an interest for new results in the field of RF MOSFET modeling.

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On the other hand, during the last two decades, much more work has been done for developing small-signal and noise models of the traditionally used microwave FET transistors, like MESFETs and HEMTs. Small-signal equivalent circuits of MESFETs and MOSFETs are very similar. Consequently, having a great experience in noise modeling of MESFETs, in previous papers we applied the similar kind of analysis to RF MOSFET noise parameter modeling, [5], [6].

In this paper we present a new noise wave model for microwave MOSFETs based on *T* representation of transistor intrinsic circuit. Namely, for high frequency circuit applications a wave interpretation of noise is advantageous since it allows the use of scattering parameters for noise computations, [7], [8]. The complete microwave MOSFETs' noise modeling procedure proposed in this paper is based on circuit theory concepts and therefore is very convenient for implementation in microwave CAD programs.

II. NOISE WAVE MODEL OF RF MOSFET

We considered a typical MOSFET small-signal equivalent circuit, as shown in Fig. 1. The intrinsic part of the circuit is denoted by the dashed line.

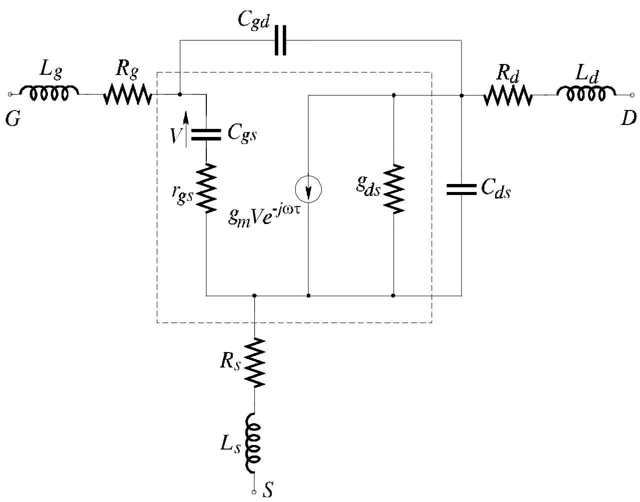

Fig. 1. MOSFET small-signal equivalent circuit

Noise in linear two-port networks can be characterized in many different ways, [9]. Any noisy linear two-port can be replaced by the noiseless two-port network and two additional correlated noise sources. Noise is typically characterized using equivalent voltage and current sources, or a combination of both. Therefore, impedance and admittance matrix representations, 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 emanates from its port.

It is known that 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 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, $F_{min} = 1 + T_{min}/T_0$, 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.

The noise parameters of transistor intrinsic circuit can be determined in terms of noise waves in the following way:

We consider T representation of a transistor intrinsic circuit. In this 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.

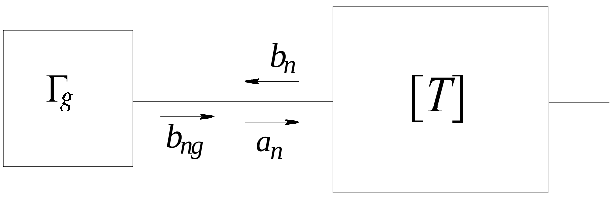

Fig. 2. *T* representation of a linear noisy two-port

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, [8]. In this 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 noise wave temperatures could be derived considering the representation of a noisy two-port as shown in Fig. 2. A source of reflection coefficient $\Gamma_g = \left|\Gamma_g\right| e^{j\varphi_g}$ and 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 source and two-port noise, after some elementary mathematical transformations, [8], [10], 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:

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

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

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

III. NUMERICAL EXAMPLE

The numerical results presented in this paper are related to the modeling of RF MOSFETs fabricated by 0.35 μm technology, [11]. The MOSFET small-signal and noise simulations are performed by using microwave circuit simulator Libra, [12]. The modeling of S parameters is done in the frequency range of (1 - 20) GHz. The noise parameters are modeled in the frequency range of (2 - 10) GHz, for which the experimental data for noise parameters were available.

At the beginning, the equivalent circuit element values are extracted from the scattering parameter data. For this purpose, the optimization routine of the circuit simulator Libra was used. In order to obtain as accurate small-signal model as possible, an extended set of optimization goals (S parameters, input and output reflection coefficients, stability factor and maximum available gain) was used, [13]. In that way the following element values were extracted: R_g=5.68Ω, L_g=2.83pH, R_d=4.11Ω, L_d=6.86pH, R_s=0.05Ω, L_s=0.1pH, g_m=8.73mS, τ=3.12ps, C_{gd}=14.72fF, R_{gs}=0.6Ω, C_{gs}=157.1fF, R_{ds}=1368.9Ω and C_{ds}=140.2fF.

The comparison of simulated S parameters (MOD) and referent data (REF) taken from [11], is shown in Fig. 3. It can be seen that all simulated parameters are in good agreement with the referent data.

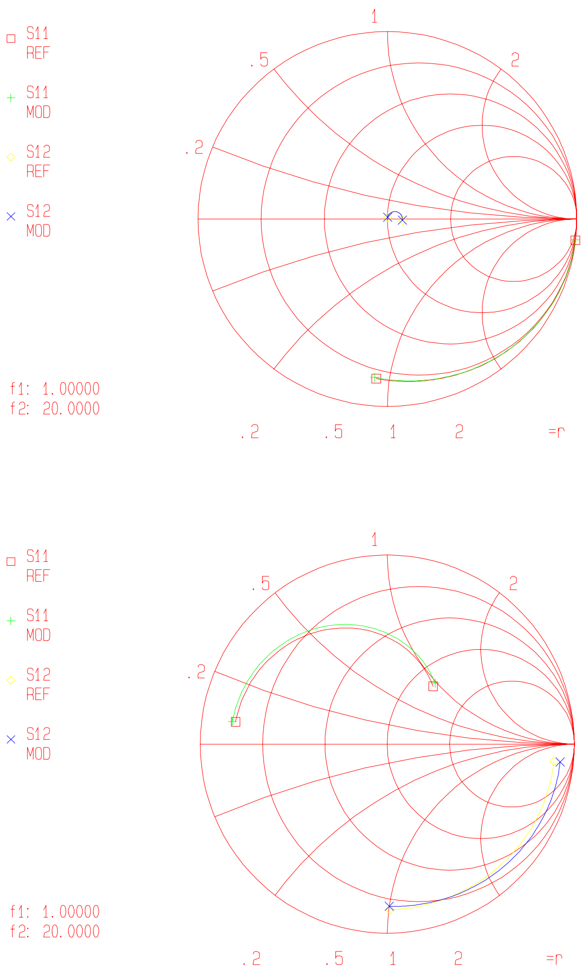

Fig. 3. S parameters

In order to determine all model parameters, after the extraction of the small-signal equivalent circuit elements, it is also necessary to determine the noise wave temperatures. The noise wave temperatures are also obtained by using the optimization capabilities of microwave circuit simulator Libra, in the following way: First, the expressions for the intrinsic circuit noise parameters (Eqs. (7) - (9)) are programmed using the “equation” capability of the applied circuit simulator and assigned to the intrinsic circuit by the corresponding statement. After that, all parasitic elements are connected and the topology of the entire transistor is described. Finally, the noise wave temperatures are optimized with the aim that the complete model fits the measured noise parameters. In that way, the following values of noise wave temperatures are extracted: T_a=1714 K, T_b=1649 K, $|T_c|$=1677 K, τ_c=14.7 ps. It can be observed, that the noise wave temperatures obtained for RF MOSFET are much higher than those typically obtained for microwave MESFETs / HEMTs, [10].

Using the obtained model and circuit simulator Libra, the noise parameters for the complete transistor over the frequency range 2 - 10 GHz were computed. The results are presented in following figures.

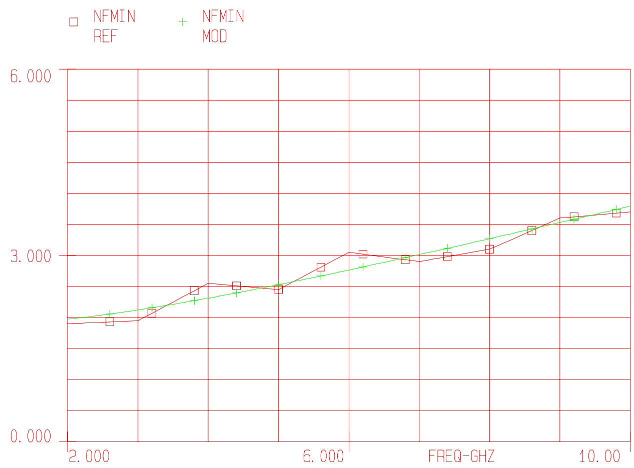

Fig. 4. Minimum noise figure

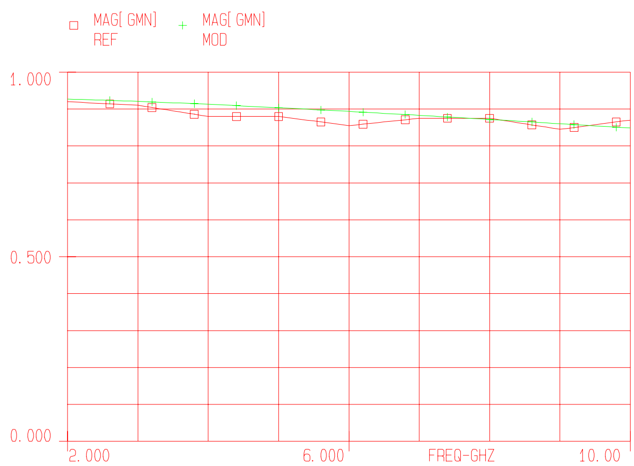

Fig. 5. Magnitude of optimum reflection coefficient

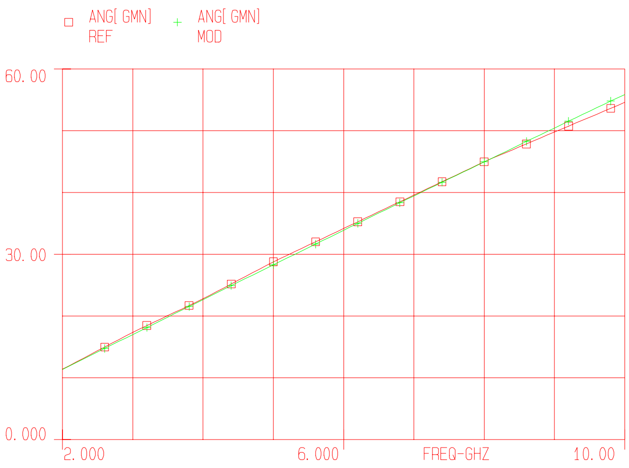

Fig. 6. Angle of optimum reflection coefficient

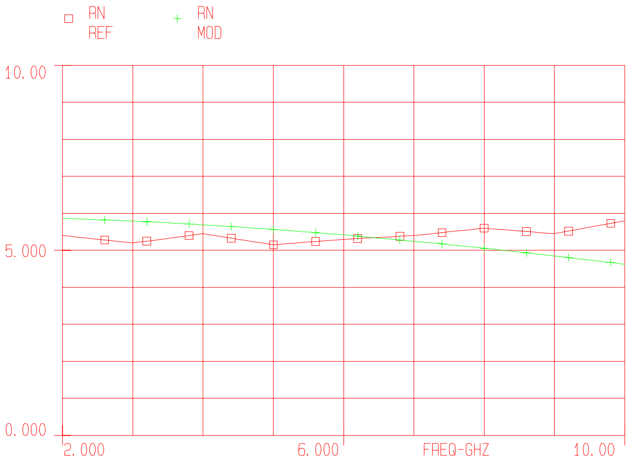

Fig. 7. Normalized noise resistance

For all four noise parameters, the curves obtained by using the model proposed in this paper are denoted by MOD. Minimum noise figure is shown in Fig. 4, magnitude and angle of optimum reflection coefficient are shown in Figs. 5 and 6, respectively, and normalized noise resistance is presented in Fig. 7. In the same figures the simulated noise parameter characteristics are compared with those based on referent data [11] (denoted by REF). Quite a good agreement can be observed for all noise parameters.

IV. Conclusion

A noise wave model of MOSFETs for RF and microwave low-noise wireless applications is proposed in this paper. The presented procedure is very convenient for CAD applications, enabling a simple, fast and reliable prediction of noise parameters over a wide frequency range.

The modeling procedure is based on an empirical approach, in a similar way we proposed earlier for the other technology microwave transistors. A noise wave representation based on transfer scattering parameters (*T*) is used. The expressions for the noise parameters of transistor intrinsic circuit are derived in terms of three equivalent noise wave temperatures. These temperatures are extracted on the basis of experimental data by using a simple procedure incorporated within a standard microwave circuit simulator. Having the values for three noise wave temperatures in addition to the other equivalent circuit elements, the model is completed and can be used for simulation.

In the presented example, *S* and noise parameter characteristics obtained by the proposed method were compared with the referent ones and quite a good agreement was achieved.

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