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An Analytical Approach to the HEMT Noise Wave Model Parameter Determination

Vladica Đorđević[1], **Zlatica Marinković**[2],
Olivera Pronić-Rančić[2], **Vera Marković**[2]

Abstract: This paper presents an analytical approach to determination of the noise wave model parameters for a high electron-mobility transistor working under different temperature and frequency conditions. The presented approach is composed of two steps and provides more efficient determination of these parameters than in the case of optimization procedures commonly applied for that purpose in circuit simulators. The first step is extraction of the noise parameters of transistor intrinsic circuit from the measured noise parameters of whole transistor using an analytical noise de-embedding procedure. The second step is calculation of the noise wave model parameters from the de-embedded intrinsic noise parameters using existing formulas. The accuracy of the presented approach is validated in a wide frequency and temperature range by comparison of the transistor noise parameters simulated for the determined noise wave model parameters with the measured noise parameters.

Keywords: Analytical Approach, HEMT, Noise Parameters, Noise Wave Model.

1 Introduction

In the last few decades, there have been a plenty of papers dealing with the modeling of the noise parameters (Γ_{opt} – optimum source reflection coefficient, $F_{\min}$–minimum noise figure and R_n – noise resistance) in the case of microwave transistors [1 – 10]. The authors of these papers usually deal with the transistor noise model development based on the additional voltage and/or current noise sources [3, 5, 6]. However, the noise wave model using the wave representation of noise has gained recognition as a suitable alternative to the most commonly used representations of noise generated in a network [2, 7 – 9, 11 – 21]. This is primarily because the noise wave model has ability to treat the network noise in terms of incident and reflected waves, which further leads to the fact that the complete noise analysis can be performed using the scattering parameters. This is very important since these parameters are obtained with a

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[1] Innovation Center of Advanced Technologies, Bulevar Nikole Tesle 61, lokal 5, 18000 Niš, Serbia; E-mail: vladica.djordjevic@icnt.rs
[2] University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia; E-mails: zlatica.marinkovic@elfak.ni.ac.rs; olivera.pronic@elfak.ni.ac.rs; vera.markovic@elfak.ni.ac.rs

high accuracy by using vector network analyzers, which contribute to the accuracy of the noise analysis [18]. Moreover, the noise wave model offers alternative noise measurement techniques [2, 7, 17].

The noise wave model is characterized by its parameters, called the noise wave temperatures. They are usually determined from the measured transistor noise parameters using optimization procedures in microwave circuit simulators. Nevertheless, as the noise wave temperatures are bias, temperature and frequency [14] dependent, optimization procedures become time-consuming in situations when repeated extractions are needed. Therefore, in such cases optimization procedures can be a quite inadequate extraction tool due to the need for efficient noise modeling with acceptable extraction time. On the other hand, the noise wave model provides direct relationships between the noise wave temperatures and the noise parameters of transistor intrinsic circuit [2]. Hence, it is possible to extract the noise wave temperatures analytically avoiding time-consuming optimization procedures.

In this paper, the analytical approach to determination of the noise wave temperatures in the case of GaAs high electron-mobility transistor (HEMT) is presented. The presented approach provides extraction of the noise parameters of transistor intrinsic circuit from the measured transistor noise parameters using the analytical noise de-embedding procedure [22 – 25], and further calculation of the noise wave temperatures based on the de-embedded intrinsic noise parameters using existing formulas [2].

The paper is organized as follows. After Introduction, a short description of the noise wave model is given in Section 2. The analytical extraction approach is presented in Section 3. Section 4 contains the most illustrative numerical results and the discussion. Concluding remarks are given in the last section.

2 The Noise Wave Model of Microwave Transistors

In the case of the noise wave model, the transistor small-signal intrinsic circuit, which is a linear noisy two-port network, can be considered as a noiseless two-port defined by transfer scattering parameters [T] with additional noise wave sources, a_n and b_n, referring to the input, Fig. 1 [2]. This representation of noisy two-port network can be described by using the following matrix equation:

$$\begin{bmatrix} a_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} b_2 \\ a_2 \end{bmatrix} + \begin{bmatrix} a_n \\ b_n \end{bmatrix}, \tag{1}$$

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

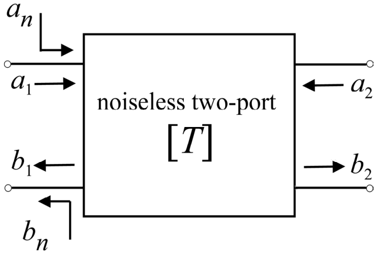


Fig. 1 – *Noisy two-port network.*

As already mentioned, the parameters of the noise wave model are the noise wave temperatures – two real temperatures, T_a and T_b, and one complex correlation temperature, T_c [2, 13]. They are expressed in terms of the noise parameters of transistor intrinsic circuit, $F_{\min,i}$, $R_{n,i}$ and $\Gamma_{opt,i}$, as follows [2]:

$$T_a = T_0(F_{\min,i} - 1) + \frac{4R_{n,i}T_0\left|\Gamma_{opt,i}\right|^2}{Z_0\left|1+\Gamma_{opt,i}\right|^2}, \tag{2}$$

$$T_b = \frac{4R_{n,i}T_0}{Z_0\left|1+\Gamma_{opt,i}\right|^2} - T_0(F_{\min,i} - 1), \tag{3}$$

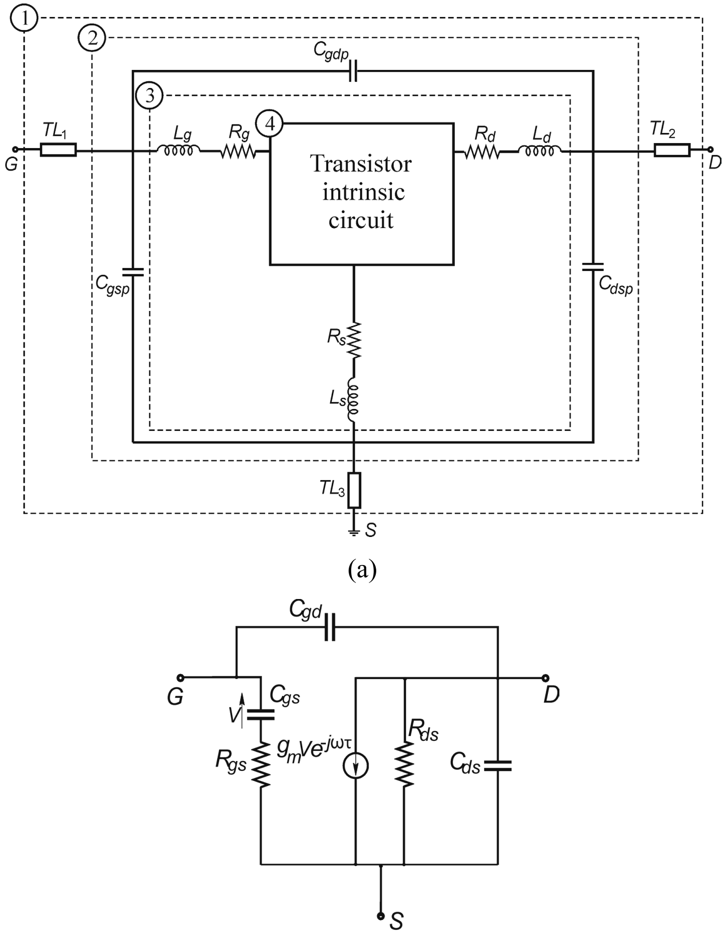
$$T_c = \frac{4R_{n,i}T_0\Gamma_{opt,i}}{Z_0\left|1+\Gamma_{opt,i}\right|^2}, \tag{4}$$

where Z_0 is the normalization impedance (50Ω) and T_0 is the standard reference temperature (290K).

3 The Analytical Approach to Determination of the Noise Wave Temperatures of HEMTs

The analytical approach to determination of the noise wave temperatures presented in this section is related to the equivalent circuit of HEMT in a packaged form, Fig. 2a [26]. It consists of intrinsic and extrinsic part. As the intrinsic circuit is common to the most of microwave field-effect transistor (FET) models, it is shown in Fig. 2b separately [26]. The extrinsic elements embedded in the circuit in Fig. 2a represent parasitic effects and depend on the type of package.

As mentioned above, the proposed analytical procedure is composed of two steps. The first step is extraction of the transistor intrinsic noise parameters from the transistor measured noise parameters using the analytical noise de-embedding procedure [22 – 25]. The second step is straightforward, and represents calculation of the noise wave temperatures using the de-embedded transistor intrinsic noise parameters [2]. Both steps will be explained below.



(a)

(b)

Fig. 2 – (a) *Equivalent circuit of HEMT in a packaged form and de-embedding planes*, (b) *Intrinsic equivalent circuit of considered transistor.*

3.1 The analytical noise de-embedding procedure

The main purpose of the presented analytical noise de-embedding procedure related to Fig. 2a is determination of the transistor intrinsic noise parameters from the transistor measured noise parameters. To achieve that, the equivalent circuit shown in Fig. 2a is divided into four planes. The noise de-embedding is done by eliminating the noise influence of the extrinsic elements connected in cascade, series and parallel using *ABCD*, *Z* and *Y* representations, respectively [22 – 25].

First, it is necessary to determine *ABCD* noise correlation matrix in the plane 1, based on the transistor measured noise parameters:

$$C_{A,1} = 2\mathrm{k}T_0 \begin{bmatrix} R_n & \dfrac{F_{\min-1}}{2} - R_n Y_{opt}^{\;*} \\ \dfrac{F_{\min-1}}{2} - R_n Y_{opt} & R_n \left| Y_{opt} \right|^2 \end{bmatrix}, \tag{5}$$

where k is Boltzmann's constant ($1.38 \times 10^{-23}\,\mathrm{J/K}$), Y_{opt} is optimum source admittance associated to Γ_{opt}, and * indicates complex conjugate.

Then, since transmission lines TL_1 and TL_2 are connected in cascade with the rest of the circuit, their noise influence is removed by calculating the *ABCD* noise correlation matrix of circuit without TL_1 and TL_2:

$$C'_{A,2} = ABCD_{\mathrm{TL}_1}^{\;-1}\left(C_{A,1} - C_{A,TL_1}\right)\left(ABCD_{TL_1}^{\;H}\right)^{-1} - ABCD'_2 C_{A,TL_2} ABCD'^{H}_2, \tag{6}$$

where $ABCD_{TL_1}$ is the *ABCD* matrix of transmission line TL_1, C_{A,TL_1} and C_{A,TL_2} are the *ABCD* noise correlation matrices of transmission lines TL_1 and TL_2, respectively, $ABCD_2'$ is the *ABCD* matrix of circuit without TL_1 and TL_2, and superscript *H* indicates Hermitian complex conjugate transpose.

By treating transmission line TL_3 as a short-circuited line, the *Z* noise correlation matrix in the plane 2 is calculated based on:

$$C_{Z,2} = C'_{Z,2} - C_{Z,TL_3}, \tag{7}$$

where $C'_{Z,2}$ is the *Z* noise correlation matrix corresponding to $C'_{A,2}$, and C_{Z,TL_3} is the *Z* noise correlation matrix of transmission line TL_3.

The *Y* noise correlation matrix in the plane 3 is calculated by removing the noise influence of three capacitors connected in parallel with the rest of the circuit (C_{gsp}, C_{gdp} and C_{dsp}):

$$C_{Y,3} = C_{Y,2} - C_{Y,C}, \tag{8}$$

where $C_{Y,2}$ is the *Y* noise correlation matrix corresponding to $C_{Z,2}$, and $C_{Y,C}$ is the *Y* noise correlation matrix of three capacitors embedded in the circuit between the planes 2 and 3.

The noise influence of the last three inductors (*L*) and resistors (*R*) connected in series with the rest of the circuit (L_g, L_d, L_s, R_g, R_d and R_s) is removed by calculating the *Z* noise correlation matrix in the plane 4:

$$C_{Z,4} = C_{Z,3} - C_{Z,LR}, \tag{9}$$

where $C_{Z,3}$ is the Z noise correlation matrix corresponding to $C_{Y,3}$, and $C_{Z,LR}$ is the Z noise correlation matrix of inductors and resistors embedded in the circuit between the planes 3 and 4.

In general, the noise correlation matrices of the series, $C_{Z,e}$, and shunt, $C_{Y,e}$, circuit elements, used in (7) – (9) can be determined by the following way:

$$C_{Z,e} = 2\mathrm{k}T_0 \operatorname{Re}(Z_e), \tag{10}$$

$$C_{Y,e} = 2\mathrm{k}T_0 \operatorname{Re}(Y_e), \tag{11}$$

where Z_e and Y_e are the Z and Y matrices of the series and shunt elements embedded in transistor extrinsic circuit, respectively. The *ABCD* noise correlation matrices of passive elements connected in cascade with the rest of the circuit, which are used in (6), are derived from the noise correlation matrices given in (10) and (11).

In the analytical noise de-embedding procedure, the noise correlation matrices must be converted from *Y* to *Z* or *ABCD*, and vice versa. In particular, the noise correlation matrix conversions are based on the following equation:

$$C''_{\beta} = T \times C'_{\alpha} \times T^{*}, \tag{12}$$

where C' and C'' are the noise correlation matrices before and after conversion, respectively, and *T* is the transformation matrix that depends on the parameters α and β, **Table 1** [22]. It should be noted that the small-signal de-embedding procedure must precede the noise de-embedding procedure because the extrinsic small-signal circuit element matrices are needed for the noise correlation matrix conversions.

Table 1

Noise correlation matrix conversion parameters.

	$\alpha = A$	$\alpha = Y$	$\alpha = Z$
$\beta = A$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & A_{12} \\ 1 & A_{22} \end{bmatrix}$	$\begin{bmatrix} 1 & -A_{11} \\ 0 & -A_{21} \end{bmatrix}$
$\beta = Y$	$\begin{bmatrix} -Y_{11} & 1 \\ -Y_{21} & 0 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$	$\begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix}$
$\beta = Z$	$\begin{bmatrix} 1 & -Z_{11} \\ 0 & -Z_{21} \end{bmatrix}$	$\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}$	$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

Finally, the obtained Z noise correlation matrix in the plane 4 should be converted to the $ABCD$ form in order to calculate the intrinsic noise parameters using [22 – 24]:

$$F_{\min,i} = 1 + \frac{1}{kT_0}\left(\mathrm{Re}(C_{A,4_{12}}) + \sqrt{C_{A,4_{11}} C_{A,4_{22}} - (\mathrm{Im}(C_{A,4_{12}}))^2}\right), \tag{13}$$

$$R_{n,i} = \frac{C_{A,4_{11}}}{2kT_0}, \tag{14}$$

$$Y_{opt,i} = \frac{\sqrt{C_{A,4_{11}} C_{A,4_{22}} - (\mathrm{Im}(C_{A,4_{12}}))^2} + j\,\mathrm{Im}(C_{A,4_{12}})}{C_{A,4_{11}}}, \tag{15}$$

$$\Gamma_{opt,i} = \frac{Y_0 - Y_{opt,i}}{Y_0 + Y_{opt,i}}, \tag{16}$$

where Y_0 is the normalization admittance ($Y_0 = 1/Z_0$).

In addition, the overall noise de-embedding procedure is shown in Fig. 3.

3.2 Calculation of the noise wave temperatures

This is a relatively simple step and represents calculation of the noise wave temperatures based on the intrinsic noise parameters determined in the previous step in (13) – (16). For that purpose, the noise wave model expressions given in Section 2 in (2) – (4), are used [2].

4 Numerical Results and Discussion

In order to validate the presented approach to determination of the noise wave temperatures, it was applied to a packaged HEMT by NEC (NE20283A), working under different temperature and frequency conditions. To obtain the S and noise parameters of the considered transistor, a measurement procedure described in [26] was used. In particular, an automated measuring system with the ability to measure the noise factor up to 40 GHz and software that calculates the noise parameters based on the measured data were used. The measurements were performed in the frequency range 6 – 18 GHz and the temperature range 233 – 333 K, 20 K step. The measurements at different temperatures were done by placing the device test fixture in a thermo-controlled chamber. Based on the measured S parameters, the values of the transistor small-signal equivalent circuit elements (*ECPs*) were determined [26].

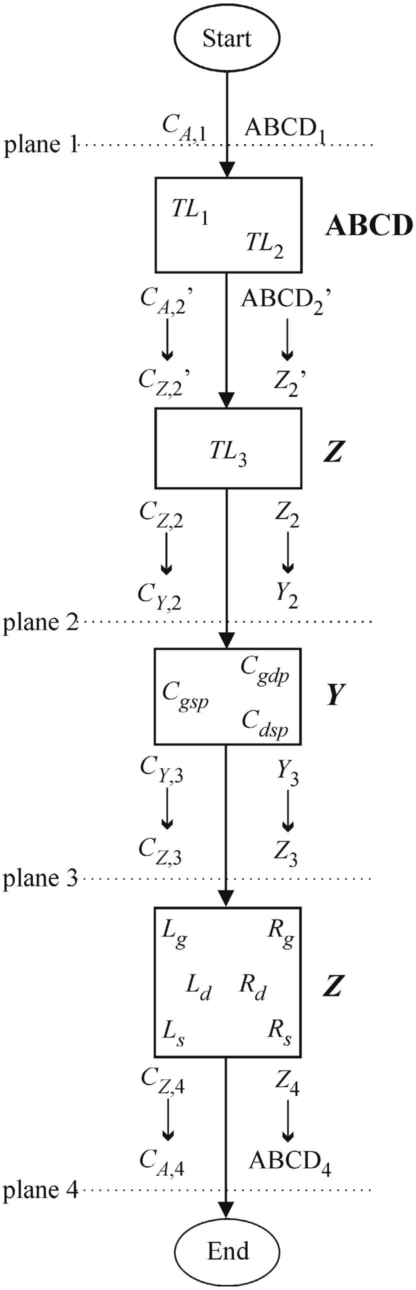


Fig. 3 – *The noise de-embedding procedure flowchart. The elements to be de-embedded are reported inside the boxes and the obtained matrices and their conversions are shown between the boxes. The formulation used (ABCD, Z or Y) is reported at the right side of the boxes.*

The two-step de-embedding procedure has been implemented within MATLAB [27] software environment and used to determine the noise wave temperatures of the considered transistor. The noise wave temperatures were determined for all six temperatures at which the measurements were done. For each temperature, the noise wave temperatures were calculated from 6 to 18 GHz, with step of 0.2 GHz. Further, the determined noise wave temperatures were assigned to the noise wave model implemented within the ADS (Advanced Design System) [28] circuit simulator and the noise parameters of whole transistor were simulated. After that, the simulated noise parameters were compared with the measurements.

To express the accuracy of the noise modeling using proposed analytical approach, average test error (*ATE*), worst case error (*WCE*) and Pearson product-moment correlation coefficient (*r*), which are defined below, were used.

ATE is defined by using the mean value of the absolute value of the relative error $\left|\bar{\delta}\right|$:

$$ATE = \left|\bar{\delta}\right| = \frac{1}{m}\sum_{j=1}^{m}\left|\delta_j\right|, \tag{17}$$

where m is the number of samples of datasets containing the parameters' simulated and target (measured) values, and δ_j is the relative error of the j-th sample. Namely, δ_j can be determined by the following way:

$$\delta_j = \frac{y_j - d_j}{d_{\max} - d_{\min}}, \tag{18}$$

where y_j and d_j are the j-th samples of datasets containing the parameters' simulated and target values, respectively, while $d_{\max}$ and $d_{\min}$ are the maximum and minimum parameters' target values, respectively.

WCE is defined as:

$$WCE = \max_{j=1}^{m}\left|\delta_j\right|. \tag{19}$$

The correlation coefficient r, which is the measure of agreement between the simulated and corresponding target values, is defined as:

$$r = \frac{\sum_{j=1}^{m}\left(y_j - \bar{y}\right)\left(d_j - \bar{d}\right)}{\left[\sum_{j=1}^{m}\left(y_j - \bar{y}\right)^2\right]\left[\sum_{j=1}^{m}\left(d_j - \bar{d}\right)^2\right]}, \tag{20}$$

where

$$\bar{y} = \frac{1}{m}\sum_{j=1}^{m} y_j \,, \tag{21}$$

$$\bar{d} = \frac{1}{m}\sum_{j=1}^{m} d_j \,. \tag{22}$$

ATE, *WCE* and *r* were calculated using the simulated and measured noise parameters in the whole frequency and temperature range, and their values are given in **Table 2**.

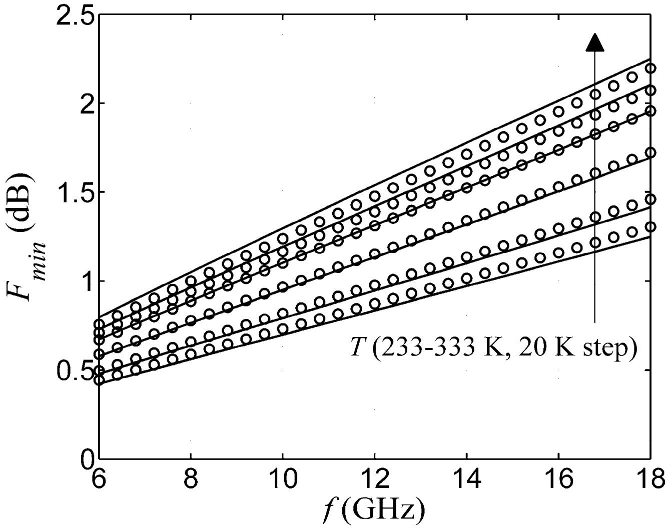
Moreover, as an illustration, Fig. 4 presents frequency dependence of the simulated and the measured values of $F_{\min}$ and R_n. The results are presented in the frequency range from 6 to 18 GHz, for the temperatures from 233 to 333 K, step 20 K.

In order to clearly present the results for $|\Gamma_{opt}|$ and $\angle\,\Gamma_{opt}$, their measured and simulated values are given as functions of temperature, Fig. 5. The results are presented in the temperature range from 233 to 333 K, for the frequencies from 6 to 18 GHz, 2 GHz step.

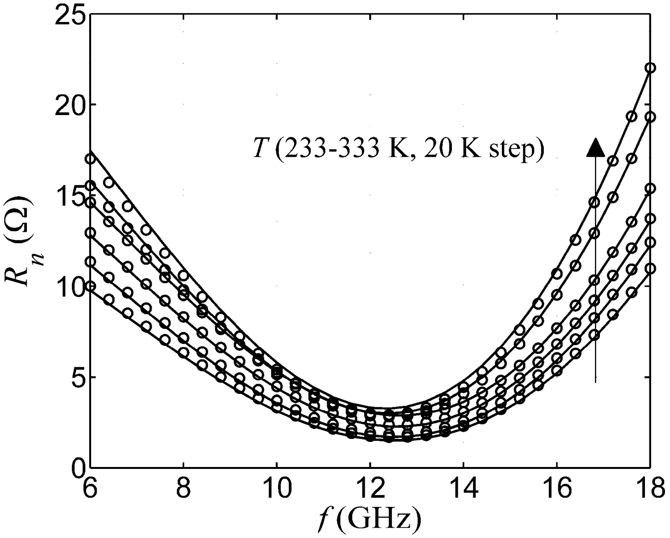
Table 2
Test errors for the modeled noise parameters.

		$F_{\min}$	R_n	$\lvert\Gamma_{opt}\rvert$	$\angle\Gamma_{opt}$
233 K	*ATE* (%)	4.44	1.97	5.08	0.43
	WCE (%)	6.49	2.50	6.45	0.54
	r	0.9999992	0.9999609	0.9999963	0.9999960
253 K	*ATE* (%)	3.17	1.43	3.65	0.28
	WCE (%)	4.55	1.76	4.73	0.36
	r	0.9999994	0.9999910	0.9999959	0.9999980
273 K	*ATE* (%)	1.69	0.95	1.75	0.18
	WCE (%)	2.62	1.29	2.25	0.25
	r	0.9999990	0.9999977	0.9999958	0.9999991
293 K	*ATE* (%)	0.16	0.21	0.47	0.06
	WCE (%)	0.25	0.67	0.98	0.09
	r	0.9999973	0.9999781	0.9999911	0.9999998
313 K	*ATE* (%)	2.06	0.96	3.39	0.28
	WCE (%)	2.36	1.44	4.76	0.35
	r	0.9999931	0.9999111	0.9999864	0.9999975
333 K	*ATE* (%)	3.97	1.70	7.58	0.38
	WCE (%)	4.49	2.39	10.49	0.55
	r	0.9999291	0.9997924	0.9999268	0.9999856

The obtained results presented in **Table 2** and Figs. 4 and 5 show that the simulated values of the noise parameters are very close to the measured ones in whole frequency and temperature range, which confirms the accuracy of the proposed analytical approach to determination of the noise wave temperatures.

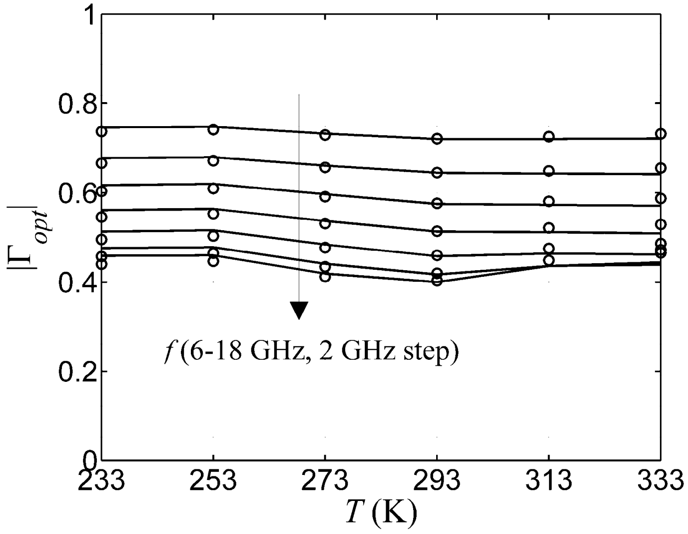


(a)



(b)

Fig. 4 – *Frequency dependence of the measured (symbols) and simulated (lines) values of:* (a) F_{min} *and* (b) R_n *at different temperatures.*



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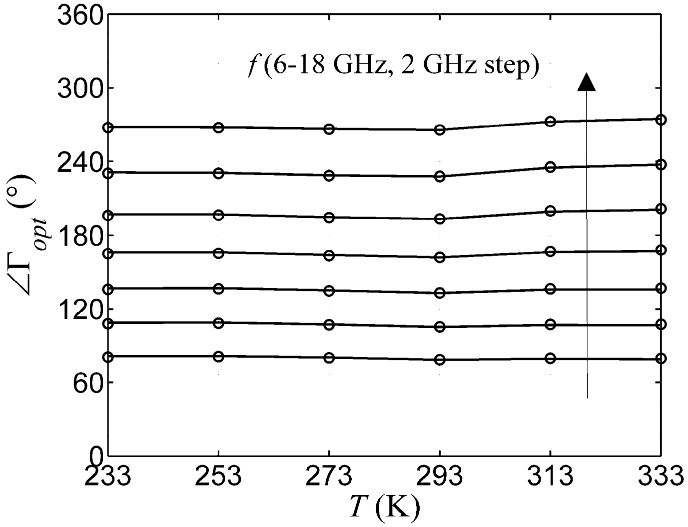

(b)

Fig. 5 – *Temperature dependence of the measured (symbols) and simulated (lines) values of:* (a) $|\Gamma_{opt}|$ *and* (b) $\angle\Gamma_{opt}$ *at different frequencies.*

5 Conclusion

Since the noise wave temperatures are bias, temperature and frequency dependent, optimization procedures in microwave circuit simulators, usually used for their extraction, require a lot of time. Therefore, the analytical procedure providing the more efficient determination of the transistor noise wave temperatures is presented in this paper. Namely, the presented analytical approach was developed for a GaAs HEMT in a packaged form and provides extraction of the transistor intrinsic noise parameters from the measured transistor noise parameters, leading to the simple determination of the noise wave temperatures based on the de-embedded intrinsic noise parameters using the existing formulas.

In order to validate the presented analytical approach, it was applied to a specific GaAs HEMT device in a packaged form. The determined noise wave temperatures were assigned to the noise wave model implemented within the ADS circuit simulator and the noise parameters of whole transistor were simulated. A good agreement between the simulated and measured noise parameters proves validity of the presented analytical approach to determination of the noise wave temperatures.

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