Wave Approach to the Noise Modeling of a GaAs HEMT under Optical Illumination

Vladica Đorđević, Emanuele Cardillo[1], Zlatica Marinković[2], Olivera Pronić-Rančić[2], Alina Caddemi[1], Vera Marković[2]

Abstract – **GaAs-based HEMTs can be successfully employed in modern integrated communication systems as optically controlled devices. Therefore, for performing an accurate and effective noise analysis of their performance under optical illumination, an accurate noise model is needed. The wave approach has been employed for the modeling of a GaAs HEMT exposed to an optical radiation and the noise wave parameters are modeled by applying artificial neural networks. The validation of the presented approach was done by comparing the simulated and measured noise parameters without and with optical illumination.**

Keywords – **Artificial neural network, GaAs HEMT, Noise parameters, Noise wave model, Optical illumination.**

I. Introduction

GaAs high electron mobility transistor (HEMT) technology has proved to be very suitable for the low-noise applications at microwave frequencies. Indeed, their physical structure makes them very attractive for integrated communication systems, where the microwave transistors are optically controlled to perform various functions of microwave electronic circuits (e.g., gain control of amplifiers, frequency tuning or locking in oscillators, and phase shifting in phase shifters), [1-7]. Therefore, it is very interesting to perform the signal and noise characterization of this type of transistors under optical illumination, as well. The most used way to reproduce the transistor noise behavior at microwave frequencies is to use the transistor noise models within a circuit simulator. In the last few decades, there have been plenty of studies dealing with the modeling of the four microwave transistor noise parameters (F_{min} – minimum noise figure, R_n – noise resistance and Γ_{opt} – magnitude and phase of the optimum source reflection coefficient), [8-19]. However, only a small number of studies is related to the noise parameters modeling for the case of devices under light exposure, [18], [20-22] and to the best authors' knowledge none of them is devoted to wave modeling approach applications.

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At microwave frequencies, a wave representation of noise is advantageous, [9], [15-17], [19], [23-31]. The strength of the wave representation of noise lies in its compatibility with the scattering matrix description of microwave networks. It allows the use of scattering matrices for the noise computations leading to advantages in Computer-Aided Design (CAD) of microwave networks. Therefore, in the case of the wave representation of noise, the noise analysis problems are formulated using scattering (S) parameters. This is very important since the scattering parameters are measured with high precision using vector network analyzers, which further contribute to the accuracy of the noise analysis. Furthermore, the noise wave representation offers alternative measurement techniques, [9], [15].

In this paper, the wave approach for the noise modeling of the GaAs HEMT under optical illumination is presented. The model is developed for a HEMT device based on AlGaAs/GaAs heterojunction, and the model accuracy is verified by comparing the simulated and measured data with and without optical illumination.

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

II. Noise Wave Model of a GaAs HEMT under Optical Illumination

The noise wave model of the GaAs HEMT under optical illumination, whose small-signal equivalent circuit is shown in Fig. 1, [21], is the subject of the research presented in this paper.

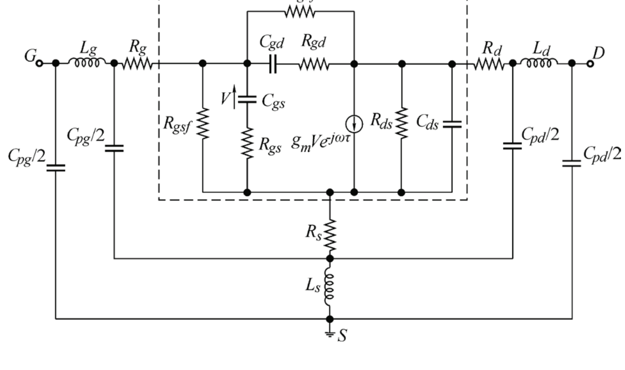


Fig. 1. The small-signal equivalent circuit of the GaAs HEMT under optical illumination

The involved processes are the concurrent photoconductive and internal photovoltaic effects. The former concerns the photo-generation of a current due to excess carriers. It is related with the increase of the electron concentration in the 2-DEG channel and takes place when the energy of the incident photon is higher than the energy-gap of the GaAs layer, while lower than the energy-gap of the AlGaAs layer [18]. The latter is related to the shift of the threshold voltage due to the lowering of the potential barrier between the channel and the source. Instead, it can take place if the energy of the incident photon overcomes also the energy-gap of the AlGaAs layer [18].

As it can be seen in Fig. 1, the equivalent circuit consists of an intrinsic and an extrinsic section. Compared to the standard intrinsic circuit, commonly used in most microwave transistor models, the presented intrinsic circuit (marked with the dashed line) is expanded with two additional gate-source and gate-drain resistances, R_{gsf} and R_{gdf}, due to the significant increase of gate current under light exposure [21]. Their role is negligible when the transistor is not illuminated, so they are not included in the equivalent circuit in that case. It should be pointed out that all the intrinsic circuit elements are bias-dependent and sensitive to the optical illumination. The elements embedded in the equivalent circuit outside the intrinsic circuit (extrinsic elements) represent parasitic effects. Instead, the extrinsic circuit elements can be assumed to be bias-independent and insensitive to the optical illumination.

In the noise wave representation, the transistor intrinsic circuit, which is a noisy two-port network, is considered as a noiseless two-port network with two additional noise wave sources at the input, [9]. These noise wave sources are characterized by its parameters, called the noise wave temperatures – two real temperatures, T_a and T_b, and one complex correlation temperature, $T_c = |T_c| e^{j\omega\tau_c}$. The noise wave temperatures can be expressed in terms of the noise parameters of transistor intrinsic circuit – minimum noise figure, $F_{min,i}$, optimum source reflection coefficient, $\Gamma_{opt,i} = |\Gamma_{opt,i}| e^{j\varphi_{opt,i}}$, and noise resistance, $R_{n,i}$, as follows, [8]:

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

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

$$T_c = \frac{4 R_{n,i} T_0 \Gamma_{opt,i}}{Z_0 |1 + \Gamma_{opt,i}|^2}, \quad (3)$$

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

Since the noise parameters of the transistor intrinsic circuit are not directly measurable, the noise wave temperatures are extracted based on the measured transistor noise parameters usually using optimization procedures in microwave circuit simulators. Nevertheless, it has been shown earlier that the noise wave temperatures should be considered as frequency-dependent parameters to ensure suitable noise model accuracy, [26]. Therefore, it is necessary to extract their values for each frequency separately. In that case, optimization procedures become time-consuming and a quite inefficient extraction tool. For this reason, in this work, the optimization procedures are avoided by applying the analytical noise de-embedding procedure described below, [32-34], for the determination of the noise parameters of the transistor intrinsic circuit based on the measured transistor noise parameters. This further provides a straightforward calculation of the noise wave temperatures using Eqs. (1)-(3).

In order to enable an efficient determination of the noise wave temperatures over the whole frequency range, the artificial neural networks (ANNs) approach has been proposed to model the dependence of the noise wave temperatures on the frequency, Fig. 2. Namely, ANNs have proved to be a very useful modeling tool in the area of microwaves, [27], [30-31], [35-40]. The ANNs considered in this case are based on a multi-layer perceptron (MLP) structure, [35], where the neurons characterized by their transfer functions are grouped into layers: an input layer, an output layer, and one or several hidden layers. Outputs of all neurons in one layer are connected to all the inputs of neurons in the next layer, wherein each connection between the neurons is weighted. ANNs learn relationships among sets of input–output data (training sets) by adjusting network connection weights and thresholds of neuron transfer functions. This process is known as the neural network training. There are different algorithms for ANN training. The most frequently used are the backpropagation algorithm and its modifications with higher convergence order, like the Levenberg-Marquardt algorithm, [35].

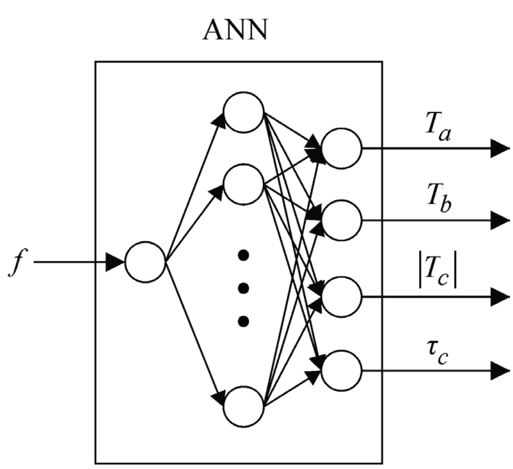


Fig. 2. ANN modeling the noise wave temperature dependence on the frequency

The Analytical Noise De-Embedding Procedure

The analytical noise de-embedding procedure presented within this section is related to the equivalent circuit shown in Fig. 1. The main aim of the presented analytical noise de-embedding procedure is the determination of the noise parameters of the transistor intrinsic circuit based on the measured noise parameters. This is done by removing the noise influence of the series and shunt extrinsic circuit elements using the impedance (*Z*) and admittance (*Y*) representations, respectively, [32-34].

First, it is necessary to determine the *ABCD* noise correlation matrix of the entire transistor based on its measured noise parameters:

$$C_A = 2kT_0 \begin{bmatrix} R_n & \frac{F_{min-1}}{2} - R_n {Y_{opt}}^* \\ \frac{F_{min-1}}{2} - R_n Y_{opt} & R_n \left|Y_{opt}\right|^2 \end{bmatrix}, \quad (4)$$

where k is the Boltzmann's constant and Y_{opt} is optimum source admittance associated to Γ_{opt}.

After that, for removing the influence of the extrinsic elements to the transistor noise, the following equations are used:

$$C_Y^D = C_Y - 2kT_0 \operatorname{Re}\left(Y^E\right) \quad (5)$$

for the shunt elements and

$$C_Z^D = C_Z - 2kT_0 \operatorname{Re}\left(Z^E\right) \quad (6)$$

for the series elements. In Eqs. (5) and (6), C_Y^D and C_Z^D are resulting de-embedded noise correlation matrices, C_Y and C_Z are initial noise correlation matrices, while Y^E and Z^E are *Y* and *Z* matrices of the shunt and series elements embedded in transistor extrinsic circuit, respectively.

As it can be seen, due to the noise de-embedding process, the noise correlation matrices must be converted from *Y* to *Z* or *ABCD*, and vice versa. This is done using the following equation:

$$C'' = T \times C' \times T^* \quad (7)$$

where C' and C'' are the noise correlation matrices before and after the conversion, respectively, and T is the transformation matrix that depends only on the conventional electrical matrix of the network, [32]. 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.

The flowchart of the *core function*, which performs small-signal de-embedding, noise de-embedding, and matrix conversion, is shown in Fig. 3.

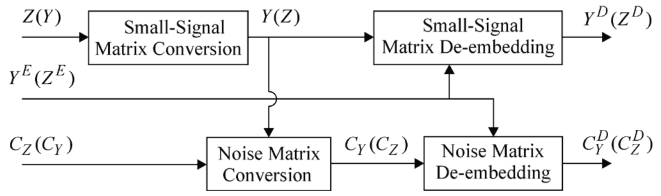


Fig. 3. The flowchart of de-embedding *core function*, which performs matrix representation conversion and de-embeds the small-signal parameter matrix *Z*(*Y*), as well as the noise correlation matrix C_Z (C_Y) from the matrix $Y^E(Z^E)$

Finally, the obtained noise correlation matrix of the transistor intrinsic circuit should take the *ABCD* form in order to calculate the intrinsic noise parameters using the following equations, [32-33]:

$$F_{min,i} = 1 + \frac{1}{kT_0}(\operatorname{Re}(C_{A,i_{12}}) + \sqrt{C_{A,i_{11}} C_{A,i_{22}} - (\operatorname{Im}(C_{A,i_{12}}))^2}) \quad (8)$$

$$Y_{opt,i} = \frac{\sqrt{C_{A,i_{11}} C_{A,i_{22}} - (\operatorname{Im}(C_{A,i_{12}}))^2} + j \operatorname{Im}(C_{A,i_{12}})}{C_{A,i_{11}}}, \quad (9)$$

$$\Gamma_{opt,i} = \frac{Y_0 - Y_{opt,i}}{Y_0 + Y_{opt,i}}, \quad (10)$$

$$R_{n,i} = \frac{C_{A,i_{11}}}{2kT_0}, \quad (11)$$

where $C_{A,i}$ is the *ABCD* noise correlation matrix of the transistor intrinsic circuit and $Y_{opt,i}$ is the intrinsic optimum source admittance associated to $\Gamma_{opt,i}$.

The complete analytical noise de-embedding procedure, which is related to the equivalent circuit shown in Fig. 1, is presented in Fig. 4. Starting from the extrinsic plane, the two capacitances ($C_{pg}/2$ and $C_{pd}/2$) are de-embedded using the *Y* formulation. After that, the *Z* formulation is used for de-embedding the three inductors contribution (L_g, L_d and L_s). The remaining two capacitances ($C_{pg}/2$ and $C_{pd}/2$) are also de-embedded using the *Y* formulation. Finally, after de-embedding the last three resistors contribution (R_g, R_d and R_s) using the *Z* formulation, the extrinsic noise influence ise completely de-embedded, and noise parameters of transistor intrinsic circuit are obtained.

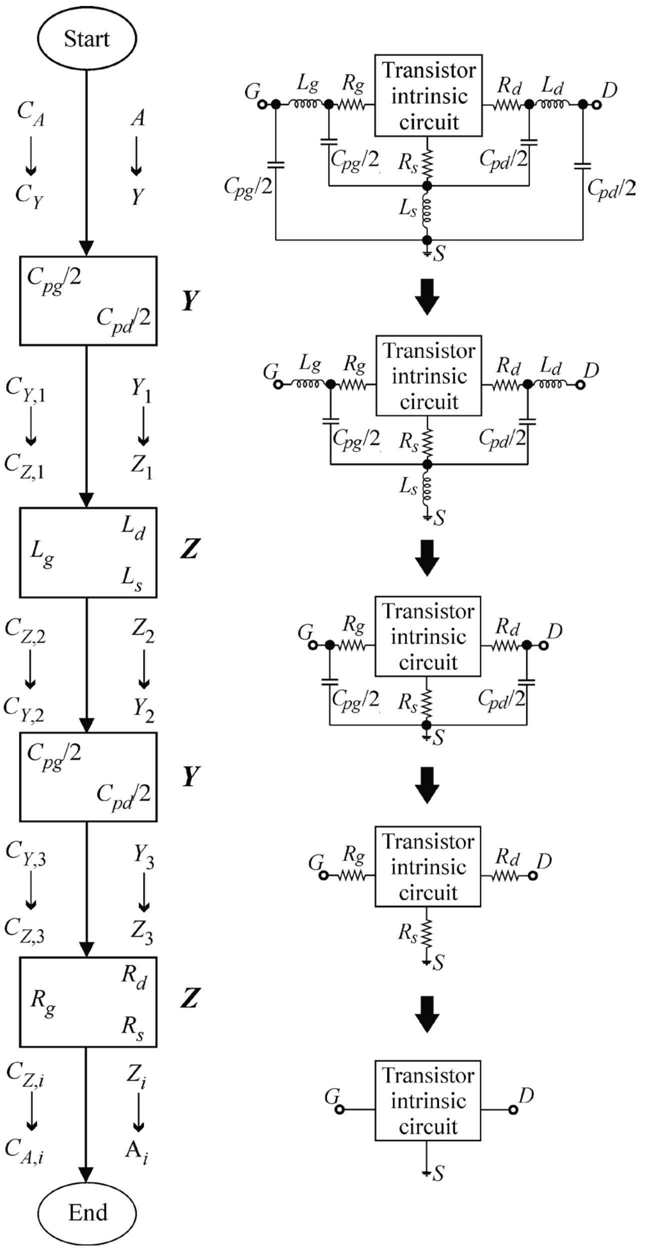


Fig. 4. Noise de-embedding procedure flowchart. The elements to be de-embedded are reported inside the boxes and the obtained matrices and their conversions are shown between the boxes. The formulation used (*ABCD*, *Z* or *Y*) is reported at the right side of the boxes. Beside the flowchart there is illustration of the transistor extrinsic circuit transformation due to the noise de-embedding process

III. Numerical Results and Discussion

In order to validate the presented noise wave model, it was applied for the noise modeling of an on-wafer AlGaAs/GaAs HEMT device. It has a 0.25 µm gate length and a 100 µm gate width, wherein the gate is composed of two gate fingers of 50 µm.

The multi-finger layout leads to an improvement of the microwave behavior, especially in terms of noise performance, thanks to the reduction of the gate resistance. The transistor *S*- and noise parameters were measured both with and without optical illumination, in the frequency range 0.1-26.5 GHz and 2-18 GHz, respectively, by using the measurement procedure and equipment described in [5]. Under illumination, a continuous wave laser beam with a wavelength of 650 nm and an incident power density of about 0.3 µW/µm^2 has been used. The wavelength was chosen to be 650 nm for enhancing the optical effects by allowing transitions in both GaAs (1.4 eV) and AlGaAs (typically around 1.8 eV) layers at the room temperature.

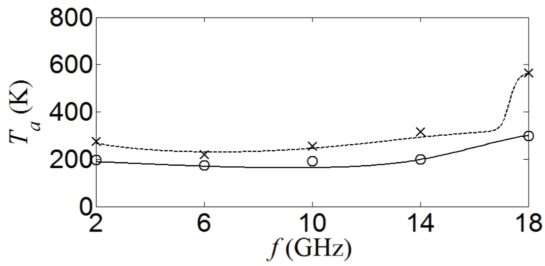
The tested device exhibited a clear worsening of F_{min} and a reduction of the magnitude of Γ_{opt}, due to the increased gate noise current under optical radiation. Indeed, without light exposure, the predominant noise is the channel thermal noise that generates a gate noise through a capacitive coupling. Under optical radiation, the gate leakage current significantly increases owed to the generation of free carriers. This process introduces additional gate noise thus degrading the noise figure values.

First, the analytical noise de-embedding procedure related to the small-signal equivalent circuit presented in Fig. 1 was developed within MATLAB software environment, [41], and further applied for the determination of the transistor intrinsic circuit noise parameters based on the measured transistor noise parameters with and without optical illumination. The extrinsic circuit elements were extracted from the transistor *S* parameters measured under 'cold' bias condition (V_{DS} = 0 V) by using the procedure described in [42]. Their values are the following: $C_{pg} = C_{pd}$ = 15.2 fF, L_g = 118.6 pH, L_s = 11.5 pH, L_d = 127.7 pH, R_g = 4.8 Ω, R_s = 0.5 Ω, and R_d = 2 Ω. On the other hand, the intrinsic circuit elements were extracted from the *Y* parameters of the transistor intrinsic circuit at the considered bias condition (V_{DS} = 2.5 V and V_{GS} = -0.6 V). The values for the device both with and without illumination are given in Table I, [21].

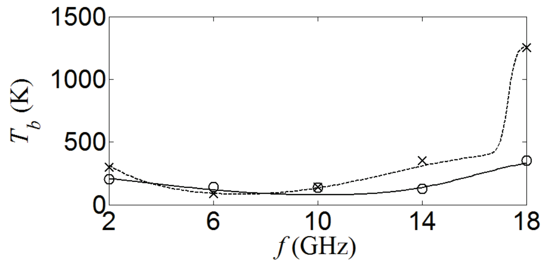
TABLE I
THE EXTRACTED VALUES OF THE INTRINSIC CIRCUIT ELEMENTS AT V_{DS} = 2.5 V AND V_{GS} = -0.6 V

	Without illumination	**With illumination**
C_{gs} (fF)	132.5	147.9
R_{gs} (Ω)	0.3	0.1
C_{gd} (fF)	17.9	21.0
R_{gd} (Ω)	17.0	73.2
g_m (mS)	32.8	40.5
τ (ps)	1.3	1.1
R_{ds} (Ω)	744.5	508.6
C_{ds} (fF)	146.0	152.1
R_{gsf} (Ω)	–	5369
R_{gdf} (Ω)	–	28544

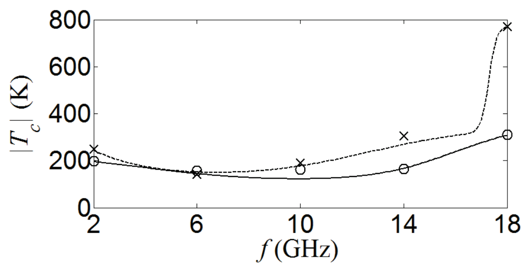
Based on the determined noise parameters of transistor intrinsic circuit, the noise wave temperatures were calculated for both illumination conditions using Eqs. (1–3), in the whole frequency range where the noise parameter measurements were performed. Thereafter, the calculated noise wave temperatures were used for building the appropriate training sets used to train several ANNs with one hidden layer and different number of hidden neurons. The ANN model development was performed within the MATLAB tool. For the process of ANN training the Levenberg-Marquardt algorithm was used, [35]. Among the trained neural networks, ANNs with the highest accuracy have two hidden neurons in the case of non-illuminated device and three hidden neurons in the case with illumination. The ANNs were then described with the corresponding expressions representing their mathematical equivalents, [43], which were generated also within MATLAB. These expressions were further assigned to the noise wave model implemented within ADS (Advanced Design System) circuit simulator using VAR (Variable and Equations) blocks, [44]. The simulator uses assigned expressions to determine the noise wave temperatures in desired frequency range. The obtained noise wave temperature values are presented in Fig. 5. After that, the implemented noise wave model was used to simulate the transistor noise parameters. Finally, the simulated transistor noise parameters were compared with the corresponding measured data in both cases.



(a)



(b)



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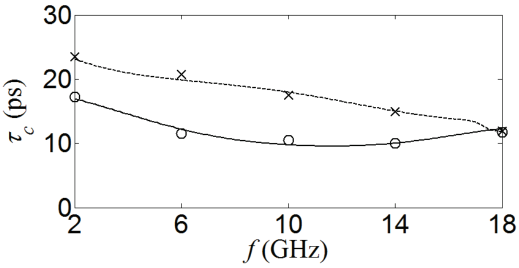
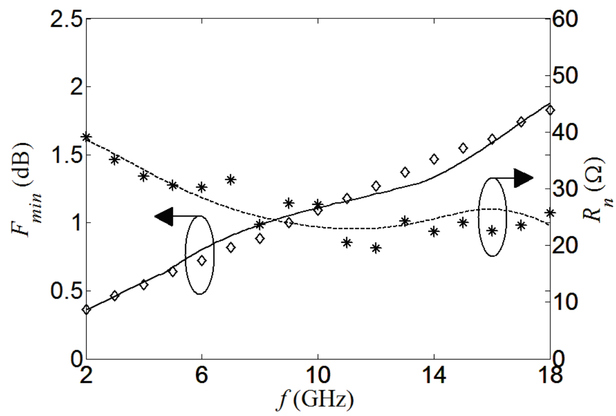


(d)

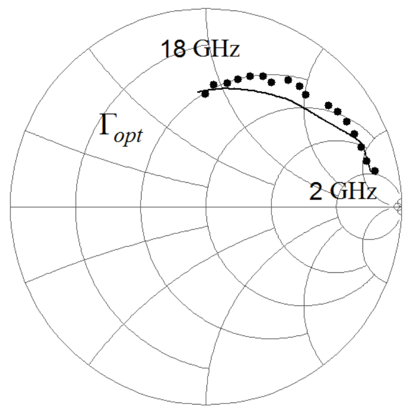
Fig. 5. Calculated noise wave temperatures (circles – without illumination; crosses – with illumination) fitted by ANN (solid lines - without illumination; dashed lines – with illumination):

a) T_a, b) T_b, c) $|T_c|$ and d) τ_c

As an illustration, Figs. 6 and 7 present the simulated noise parameters F_{min}, R_n, and Γ_{opt} and the corresponding measured data. The results shown in Figs. 6 and 7 were obtained in the case of GaAs HEMT without and under optical illumination, respectively, in the frequency range from 2 to 18 GHz. It can be seen that the simulated values of the noise parameters are very close to the measured ones, verifying the noise wave model accuracy.



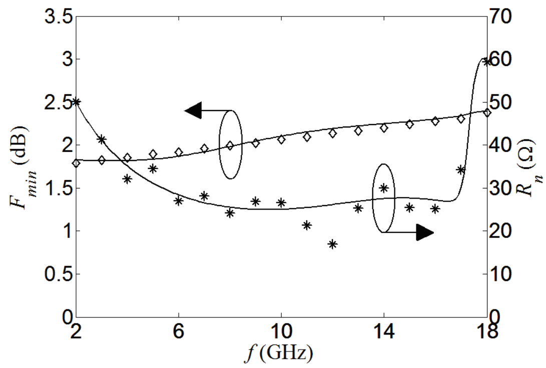
(a)



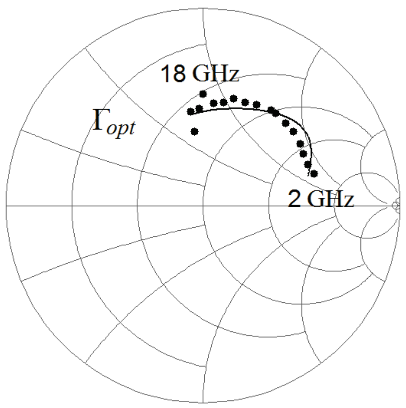
(b)

Fig. 6. Noise parameters obtained by the noise wave model (lines) compared with the measured noise parameters (symbols) in the case of GaAs HEMT without optical illumination:

(a) F_{min} and R_n, and (b) Γ_{opt}



(a)



(b)

Fig. 7. Noise parameters obtained by the noise wave model (lines) compared with the measured noise parameters (symbols) in the case of GaAs HEMT under optical illumination:

(a) F_{min} and R_n, and (b) Γ_{opt}

IV. Conclusion

In this paper, the noise wave approach is applied for the first time to reproduce the noise behavior of a GaAs HEMT under optical illumination. Since the optimization procedures for extracting the noise wave temperatures typical for circuit simulators are time-consuming, the noise wave temperatures were calculated. This task has been accomplished by using the noise parameters of the intrinsic circuit, determined by de-embedding the extrinsic elements contribution from the measured noise parameters. In order to provide the continuous extraction of the noise wave temperatures in the whole frequency range, the calculated noise wave temperatures were fitted using ANNs. In other words, ANNs were trained to model the dependence of the noise wave temperatures on the frequency.

With the aim of validating the presented noise wave model, it was applied to the specific on-wafer GaAs HEMT. The transistor noise modeling was performed in the case without and with optical illumination. A good agreement between the simulated and the measured transistor noise parameters for both illumination conditions proves validity of the noise wave model.

Acknowledgement

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