Nonlinear Extrinsic Noise Model for HEMT Mixer Suitable for CAD Software

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Abstract

In this paper, two temperatures equivalent noise model was used to predict the noise figure performance and was applied to HEMT gate mixer in which a contribution of each noise source is implanted in ADS simulator. The extracted non-linear elements of equivalent model by measurements are interpolated to provide a description of the HEMT’s nonlinearities in a CAD software. The accuracy of the non-linear noise model and noise figure simulation has been verified and we obtain a good agreement between measured and simulated noise figure results.

1. Introduction

HEMT mixers are one of the most promising candidates for mm-wave MMIC mixers [1]. Potential for conversion gain and easy integration capability with other circuits such as LNA’s and VCO’s makes this type of mixer suitable for low-cost mm-wave receivers.

The noise analysis is simple in linear circuits, since a noise source at a given angular frequency $\omega$ induces a noise voltage or noise current at the same angular frequency $\omega$ at any point in the circuit as in the amplifier [2]-[6]. This is no longer the case for non-linear circuits as in mixer, where frequency conversion occurs. The noise power generated in the nonlinear device near the RF frequency is down-converted to the IF frequency. Mixer noise performances analysis has been studied by several authors [7]-[11].

The noise models used for the CAD are generally derived from the linear noise models; this pushed us to create the nonlinear noise model suitable from CAD. The created noise model is implanted in Advanced Design System (ADS) simulator (From Agilent Technologies) [12]. Specially in this simulator, nonlinear HEMT noise was no existed and the non-linear noise simulation to determinate noise figure mixer as it was described in this simulator is not adequate for noise figure gate HEMT mixer because we need separate input generator between RF and LO signals and it is necessary to define port sources and an output termination (generally set to 50 $\Omega$). ADS noise mixer simulation have not complete circuit (input matching - HEMT - output load) but only circuit with three ports (RF-LO-IF) in which conversion gain and S parameters are defined or need to be defined. In this condition, all three ports are ported directly to 50 $\Omega$. In our case, is not possible to take directly 50 $\Omega$ in input/output ports HEMT circuit to simulated noise figure.
In this paper, we used an extrinsic model based on the experimental values of dynamic parameters measured in the microwave frequency range and extracted by Dambrine method [13]. The Pospieszalski two temperatures (Tg/Td) noise model [4] is used to evaluate the noise figure of the gate mixer according to LO power. Circuit mixer is designed by ADS simulator and the HEMT gate mixer noise figure method is evaluated by this simulator.

2. The HEMT nonlinear noise model

The extrinsic non linear model of HEMT is extracted from small signal measurements by taken into account the transconductance $G_m$, the drain-source conductance $G_d$ and the gate-source capacitance $C_{gs}$ with non-linear profiles as function of gate source voltage. The other circuit elements are assumed to be linear. Figure 1 shows the extrinsic non-linear model used in this work.

![Figure 1: Equivalent circuit of HEMT. Intrinsic noise equivalent temperature are represented by $T_g$ of $R_i$ and $T_d$ of $G_d$. Noise contribution of extrinsic resistance $R_g$, $R_d$, $R_i$ are determined by ambient temperature $T$.]

A non-linear equivalent noise model is shown in Figure 2. Extrinsic resistances contribute only thermal noise and with a knowledge of the ambient temperature ($T$). Their influence is taken into account. The noise properties of an intrinsic HEMT are treated by assigning gate and drain equivalent noise temperature $T_g$ and $T_d$ to the remaining resistive (frequency-independent) elements of the equivalent circuit intrinsic resistance ($R_i$) and transconductance $G_d$. 
Figure 2: Noise equivalent circuit of an extrinsic HEMT.

It is demonstrated that the gate equivalent temperature $T_g$ is within measurement errors equal to the ambient temperature ($T$) [4] and [14]. For that, mixer noise sources definition used to simulated a noise figure are:

$$[e_g^2] = 4 K T B [R_g]$$  \hspace{1cm} (1)

$$[e_i^2] = 4 K T_g B [R_i]$$  \hspace{1cm} (2)

$$[e_s^2] = 4 K T B [R_s]$$  \hspace{1cm} (3)

$$[I_d^2] = 4 K T_d B [G_d]$$  \hspace{1cm} (4)

$$[e_d^2] = 4 K T B [R_d]$$  \hspace{1cm} (5)

where $K$ is Boltzmann’s coefficient, $B$ the frequency band.

$[e_g^2], [e_i^2], [e_s^2], [I_d^2], [e_d^2], [G_d]$ are column matrix defined at all harmonic frequencies of the voltage noise source due to the gate resistance $R_g$, voltage noise source due to the intrinsic resistance $R_i$, voltage noise source due to the source resistance $R_s$, current noise source due to the drain conductance $G_d$, voltage noise source due to the drain resistance $R_d$ and the matrix of the output conductance $G_d$.

The elements of the output conductance matrix $[G_d]$ are obtained by series Fourier decomposition which are the same at all frequencies. Other column matrix are the same at all frequencies (frequency-independence).
In the gate mixer, the RF and LO signals are applied to the gate. The IF signal is taken from the drain. The gate is biased near pinch-off (Vp) that maximize the transconductance $G_m$ [15]. The drain is short-circuited at RF, LO and all harmonic frequencies. Consequently drain-source voltage (Vds) have very small variation. For this reason, the nonlinear elements of equivalent model are taken as function of only gate-source voltage (Vgs) in this work.

The experimental transconductance $G_m$, capacitance $C_{gs}$ and conductance $G_d$ are interpolated using polynomial expressions. The polynomial order are chosen to give the best fit with measured values as [16] :

$$G_m=(a_0+a_1Vgs+a_2Vgs^2+...+a_nVgs^n).F_1(Vgs)$$  \hspace{1cm} (6)

$$G_d=(b_0+b_1Vgs+b_2Vgs^2+...+b_nVgs^n).F_2(Vgs)$$  \hspace{1cm} (7)

$$C_{gs}=(c_0+c_1Vgs+c_2Vgs^2+...+c_nVgs^n).F_3(Vgs)$$  \hspace{1cm} (8)

To obtain quasi-constant representation below pinch-off (Vp), we use a function $F_n(Vgs)$ :

$$F_n(Vgs)=0.5[1+tanh(Vgs-Vp).x]$$  \hspace{1cm} (9)

where $n$ is number equal to 1,2 or 3 and $x$ is constant specified for each nonlinear elements ($G_m$, $G_d$ and $C_{gs}$) obtained by boundary conditions of current ($I_{ds}$) derivation to obtain ($G_m$ or $G_d$) or charge derivation as to obtain ($C_{gs}$).

3. Mixer harmonic balance simulation

All noise source definition are introduced in a HEMT non-linear model created by two port SDD (Symbolically Defined Device SDD2P) in ADS simulator. The transconductance $G_m$ and the conductance $G_d$ are expressed as (6) and (7) (Figure 3 and figure 4) in this two port SDD. Variable capacitance (figure 5) and all linear elements are join to this SDD to defined nonlinear HEMT model.
Figure 3: Nonlinear conductance data as a function of gate-source voltage extracted for ADS simulator.

Figure 4: Nonlinear Transconductance data as a function of gate-source voltage extracted for ADS simulator.
To simulate noise figure by ADS simulator, the mixer is divided in three part in cascade [17] as in Figure 6:

a) **Input matching circuit:**

The input matching circuit is a passive circuit, matched to 50 Ω at RF and LO frequencies.

b) **HEMT model transistor implantation:**

The HEMT model consists of a nonlinear equivalent model of the transistor using nonlinear elements as $G_m$, $C_{gs}$, and $G_d$. This nonlinear elements are implanted in ADS simulator to defined HEMT transistor model. This achieved nonlinear elements are given in Figure 3-4 and 5.

A noise is added to this HEMT model by introduced voltage and current noise source. Voltage noise source are introduced in series with each extrinsic resistance by using Bias dependent noise voltage source ($V_{\text{noiseBD}}$) defined in ADS. Only thermal noise definition at ambient temperature is used for the extrinsic resistance. Intrinsic voltage noise source are placed in series with intrinsic resistance $R_i$. This resistance values is taken constant in this work and was equal to 2.5 Ω.

Bias dependent noise current source ($I_{\text{noiseBD}}$) is placed in parallel with the conductance $G_d$ to define intrinsic output noise source. This noise source is variable with the variation of conductance $G_d$ and drain noise temperature $T_d$.

c) **Output matching circuit:**

The output load was a resistor close to 100 Ω at IF frequency. The passive circuit adaptation does not give a loss if we have a good adaptation.
In Figure 4, $Z_1$ is the output impedance of the input matching circuit. It is calculated using HEMT circuit and output load, seen at RF signal.

$Z_2$ is the input impedance of the output load circuit calculated by inversing HEMT circuit and input matching circuit.

$Z_{in}$ is the input impedance of the HEMT calculated by inversing input matching circuit only at RF frequency.

$Z_{out}$ is the output impedance of the HEMT calculated from output matching. Then the calculation of input impedance of the output load circuit gives the $Z_{out}$. The calculation of the $Z_{in}$ is given in the same manner as $Z_{out}$.

In our case we have not obtained a good short-circuit at all harmonics terminations. For that we have used ADS file ($S_1P$) to found all harmonics impedance at output port. This file is Touchstone type file.

The calculation of the total noise figure pass by application of Friis formula may be by added a linear loss of the input matching circuit to the noise figure of the equivalent non-linear HEMT only or directly to applied a formula while taking a three four-port.

![Figure 6: Mixer circuit used for noise figure ADS simulation.](image)

4. Results and discussion

The noise figure simulation method was applied to the HEMT gate mixer. The LO, RF, and IF frequencies chosen for this test were 24.5, 28.5, and 4 GHz, respectively. The measured parameters of HEMT transistor are given in [16]. The noise figure of HEMT gate mixer is measured in single side band (SSB). This mixer is designed for high conversion gain. The circuit was microstrip patterned on 254 µm thick alumina substrate.

In order to validate the simulation method, the simulated noise figure data was compared with measurements in Figure 7. We can find satisfactory agreement.
5. Conclusion

A simulation method for predicting noise figure of HEMT gate mixers is presented using ADS simulator. This suitability of the method has been verified by excellent agreement between the measured and simulated results. These results show also the importance of the nonlinear profiles of the transconductance $G_m$, the conductance $G_d$ and the gate-source capacitance $C_{gs}$ on the noise figure.

References


[12] Advance Design System simulator


