Noise Modelling of Microwave Bipolar Transistors

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ABSTRACT

In this paper we present a stochastic approach to study the noise modelling of bipolar microwave transistors. Starting from experimental on-wafer measurements of the scattering and noise parameters of these bipolar devices we obtain the corresponding Giacoletto model with the noise internal sources. We write down then the stochastic differential equations of the Giacoletto model for a short-circuited output in order to study the noise properties of these devices. From the power spectrum of the output current we obtain the behaviour of the noise figure as a function of the operating frequency.

Our theoretical results are in good agreement with experimental ones. The present approach allows to study the statistical properties of the output current for different statistics of the internal noise sources of the bipolar transistors (BJT and HBT).

Keywords: noise modelling, stochastic differential equation, microwave transistors.

1 INTRODUCTION

The bipolar transistors have been characterised *on wafer* in terms of scattering parameters and noise figure by varying the collector current (Ic): (i) between 0.7 and 10 mA at collector-to-emitter voltage (Vce) value of 1 V over 1-2 GHz frequency range for BJT, (ii) between 0.5 and 1 mA at collector-to-emitter voltage value of 2 V over 0.5-40 GHz frequency range for HBT.

The test devices and measurements have been furnished by ST-Microelectronics (BJT) and Daimler Benz (HBT). Such device is a 2-finger emitter structure, or better, the BJT tested is realised with two 1-finger devices in parallel configuration. Both devices exhibit a current gain β in excess of 100 but the BJT reach this value for low bias point (0.7 mA). Therefore the BJT has an extrinsic base resistance value larger than that of HBT. This aspect, together with an high transconductance value (g_m), causes the HBT to have a lower noise figure (NF) value than BJT for fixed collector current and collector-emitter voltage values.

To characterise the noise behaviour of transistc different noise quivalent circuits are used. In these circu the noise properties are modelled as noise voltage a current generators in order to design microwave devices low noise applications.

In this paper we present a new approach to study noise modelling of bipolar microwave transistors. consider a stochastic differential equation for the Giacole model of the bipolar devices obtained by experimental wafer measurements of the scattering and noise paramete We obtain the probability distribution and the pov spectrum of the output current of the transistors. We give analytical temporal behaviour of the second moment of output current, assuming particular given correlat functions between the internal noise sources. We obt finally the behaviour of the noise figure versus the operat frequency.

The agreement between our theoretical results and experimental measurements is good.

2 GIACOLETTO MODEL

For our initial purpose we consider a very sim topology of Giacoletto model because of: (i) on wa measurements which allow us to neglect some eleme connect with the package, (ii) the very low and narr frequency range which allow us to neglect the collector emitter resistance especially when compared to values device impedance matrix. Therefore, we extract this model from scattering and DC measurements at each b condition (Ic=0.7 and 1 mA). Noise generator has b added to the noise-free circuit [1].The values of generators have been fixed according to the transistor nc theory. The model network is reported in Figure 1, where:

-$\langle v_b^2 \rangle$ is a source that takes into account the fluctuations to the thermal noise of the base resistance $R_{bb'}$,

$$\langle v_b^2 \rangle = 4KTR_{bb'} \cdot \Delta f \qquad ($$

-$<i_b^2>$ is the shot noise generator that takes into account of the random diffusion of holes and electrons through a potential barrier of semiconductor,

$$<i_b^2>=2qI_b\Delta f \qquad (2)$$

-$<i_c^2>$ is the source that take into account the fluctuations in the collector current due to the random process of the time arrival of the diffusion and drift carriers at the collector-base junction,

$$<i_c^2>=2qI_c\Delta f \qquad (3)$$

Some adjustment have been requested by the complex correlation coefficient existing between emitter and collector shot noise generators for the best fitting of the measured noise figure NF.

We show the model results versus frequency and the element values of the model respectively in Figure 1 and Table 1.

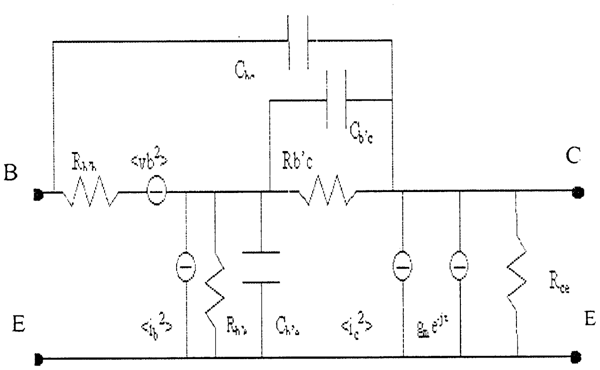

Figure1: Giacoletto Model with noise sources added.

Transistor	BJT	HBT
Bias Point	V_{ce}=1 V I_c=1 mA	V_{ce}=2 V I_c=1 mA
$R_{bb'}(\Omega)$	104	24
$R_{b'e}(\Omega)$	3000	1260
$R_{b'c}(K\Omega)$	18	20
$R_{ce}(K\Omega)$	25	30
g_m(mS)	26	30
$C_{b'c}$(pF)	0.0075	0.0015
C_{bc}(pF)	0.0077	0.024
$C_{b'e}$(pF)	0.1809	0.1264
$Coef_{REAL}$	0.7213	0.6131
$Coef_{IMM}$	0.7213	0.6942

Table 1. Element values for the Model

Starting from the Giacoletto model obtained w: MMICAD software and applying Kirkhhoff's laws to t equivalent circuit (Figure 1), we obtain the expression of t output current as a function of the circuit parameters and t noise sources, with R_L=0 and Y_s=G_s. To do this, we use t Laplace transform method [2]. We get finally an integ stochastic equation for the output current:

$$i_{out}(t)=ai_{sn}(t)+bv_{bn}(t)+ci_{bn}(t)+i_{cn}(t)+$$

$$\int_0^t [i_{sn}(\tau)a(t-\tau)+v_{bn}(\tau)b(t-\tau)+i_{bn}(\tau)c(t-\tau))d\tau \qquad ($$

where the coefficients a, b and c and the functions a(t-τ), b τ) and c(t-τ) have different expressions depending on t source admittance.

3 LANGEVIN APPROACH

From equation (4), by assuming some given correlati function between the internal noise sources, it is possible calculate all the moments of the output current. The correlation functions are directly related to the physi pictures of the microscopic internal structures of the bipo transistors.

To calculate the second moment of the stochastic proc of the output current we consider:

(a) all the noise sources expressed in terms of the Wie process;
(b) no correlation between the external noise sources a with the internal ones;
(c) the internal noise sources are δ–correlated:

$$<v_{bn}(\tau)i_{bn}(\tau')>=\sigma_{vb}\sigma_{ib}\,\delta(\tau-\tau')$$
$$<v_{bn}(\tau)i_{cn}(\tau')>=\sigma_{vb}\sigma_{ic}\,\delta(\tau-\tau')$$
$$<i_{cn}(\tau)i_{bn}(\tau')>=\sigma_{ic}\sigma_{ib}\,\delta(\tau-\tau')$$
$$<i_s(\tau)V_{bn}(\tau')>=0$$
$$<i_s(\tau)i_{bn}(\tau')>=0$$
$$<i_s(\tau)i_{cn}(\tau')>=0 \qquad (\text{:}$$

By using the statistical properties of the Wiener proc we obtain the second moment of the output current

$$<i_0(t)^2>=\sigma_{is}^2+b^2\sigma_{vb}^2+c^2\sigma_{ib}^2+\sigma_{ic}^2+$$

$$\int_0^t(\sigma_{is}a^2(t-\tau)+\sigma_{vb}b^2(t-\tau)+\sigma_{ib}c^2(t-\tau)+2\sigma_{vb}\sigma_{ic}b(t-\tau)c(t-\tau))d\tau+$$

$$+2b<v_b(t)i_b(t)>-2b<v_b(t)i_c(t)>-2c<i_b(t)i_c(t)>-$$

$$+2\sigma_{is}^2a(t)+2b[\sigma_{vb}^2b(t)+\sigma_{vb}\sigma_{ic}c(t)]+2c[\sigma_{ib}\sigma_{v}$$

$$_b b(t)+\sigma_{vb}\sigma_{ic}c(t)]-+2[\sigma_{vb}\sigma_{ic}b(t)+\sigma_{ic}^2c(t)]. \qquad ($$

Where we use a short-circuited output and the following correlation functions between the different internal noise sources:

$$<i_b i_c>=\sigma_{ib}\sigma_{ic}e^{-t/\tau b}$$
$$<v_b i_c>=\sigma_{vb}\sigma_{ic}e^{-t/\tau bc}$$
$$<v_b i_b>=\sigma_{vb}\sigma_{ib} \tag{7}$$

where τ_{bc} is the carriers transit time from base region to collector region.

4 Noise Figure

In order to obtain the noise figure at 50 Ω from temporal series of the output current, we consider the noise figure definition

$$NF=\frac{\frac{S_{IN}}{N_{IN}}}{\frac{S_{OUT}}{N_{OUT}}} \tag{8}$$

where S_{IN} and N_{IN} are signal and noise source power and S_{OUT} and N_{OUT} are signal and noise output power. After straightforward calculations we obtain, in decibels, the following expression:

$$NF=10\log\frac{N_{OUT}}{G_a N_{IN}}=10*\log\frac{N_0}{N_s} \tag{9}$$

where G_a is the maximum available gain which is independent of the load. Therefore from output current temporal series with and without internal noise sources, we obtain respectively N_0 and N_s and for each frequency we calculate the noise figure (equation 9). The noise behaviour of the bipolar transistor versus bias point show that the NF increases with collector current increase.

5 Results

In Figure 2 we plot the probability distribution of the output current, which is Gaussian as we expected from equation (4). In order to calculate the noise figure by FFT method we calculate the output current power spectrum with and without internal noise sources.

For each frequency value, we calculate the output power level, obtaining the noise figure as a function of the operating frequency. In the same figure we report the noise figure behaviour obtained from experimental measurements with bias points Ic=1 and 0.7 mA for the BJT (see, Figure 3), and Ic= 1 mA for the HBT (see, Figure 4).

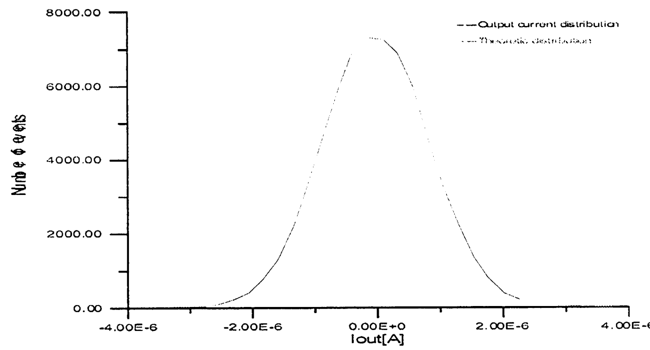

Figure 2: Probability distribution of the output current.

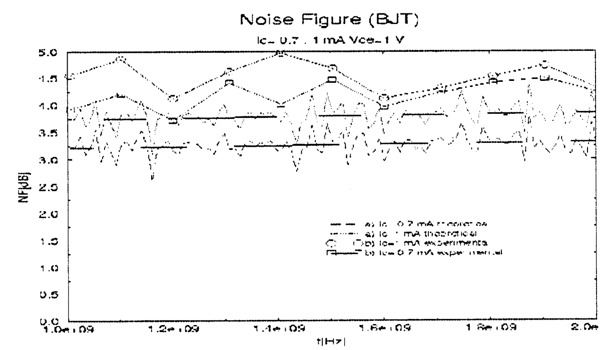

Figure 3: Noise Figure at o.7 and 1 mA: a) theoretical, b)experimental.

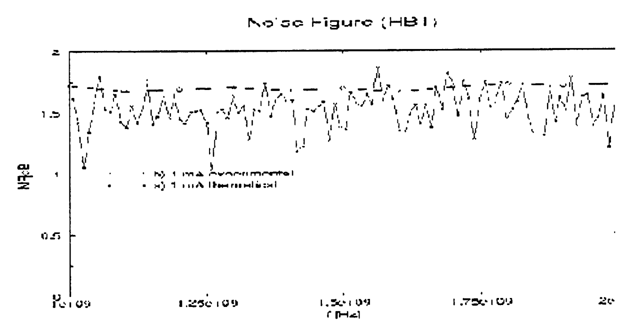

Figure 4: HBT Noise Figure at 1 mA: a) theoretical, b) experimental.

We can see that our theoretical results are in go agreement with experimental ones. Finally, we consider correlation between collector and base noise sources and observe that our fitting of the noise figure improves as module of correlation coefficient increases.

In figure 5 we show the BJT noise figure behaviour for different values of the correlation coefficient.

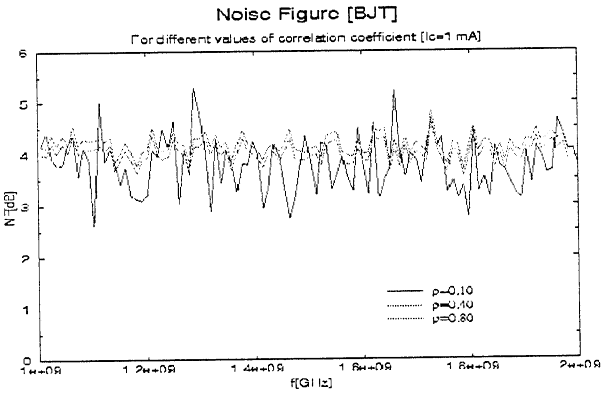

Figure 5: BJT Noise Figure at 1 m A for different correlation coefficient.

6 CONCLUSIONS

This approach, after few adjustments and improvements, will permit to predict noise figure device from only scattering parameter measurements and to avoid the main problems connected to perform additional measurements [3,4,5]. On the other hand we will obtain also more information about the statistical properties of internal noise sources of Bipolar transistors.

Conventional approaches analyse all noise sources into an equivalent noise voltage and assume Gaussian white noise, limiting therefore the analysis only to the knowledge of the first and the second moment of the stochastic processes associated to the noise sources.

As an alternative approach we derive a generalised Langevin equation, or more exactly a stochastic differential equation, for the Giacoletto model of bipola transistors. The output current is a stochastic process as a consequence of the fluctuations due to the different internal noise sources of the transistor.

Applying the Langevin approach to the Giacoletto model we can know the statistical properties of the output current from the knowledge of the probability distribution of the noise sources and the correlation functions between the internal sources of the bipolar transistors.

Concerning the effect of the correlation between the noise sources we study only the case of a correlation between collector and base noise sources and we find that a greater correlation coefficient between these noise sources improves the noise figure of our device, as it can see from the last figure 5.

We can improve our noise figure fitting with the experimental measurements, by changing the probability distribution of the noise sources and testing the effect of the correlation functions between all the noise sources of the microwave transistors considered.

Finally we can apply our method for a wide variation (the bias point and, after changing our simple circuit, 1 different devices and for a wider frequency range (Figure 5).

Although the study in this paper has been restricted to bipolar transistors, the described methodology should t applicable to a wider class of microwave devices.

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