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SiGe HBT Nonlinear Phase Noise Modeling

Sébastien Gribaldo, Laurent Bary and Olivier Llopis

*LAAS-CNRS / University of Toulouse – 7 av. du Colonel Roche
31077 Toulouse Cedex 04 – FRANCE*

Abstract. A nonlinear noise model of a SiGe bipolar transistor is presented. This model includes nonlinear noise sources and is able to predict the noise conversion phenomena in circuits using this transistor and as the phase noise of an oscillator. It is based on two main low frequency noise sources, which are extracted thanks to noise measurements under large RF signal superposition. The model is compared to the experiment thanks to residual phase noise data at different RF power level.

Keywords: nonlinear noise, modelling, SiGe

PACS: 85.40.Qx

INTRODUCTION

Phase noise is an important parameter for many applications. It determines the quality of a telecommunications link, the sensitivity of a radar or may be the absolute limit in a physics measurement.

This parameter is difficult to model accurately, because it is the result of a complex interaction of many noise sources in a nonlinear behavior. However phase noise is mainly the result of two mechanisms: the up conversion of the LF (low frequency) noise and the addition of the HF (high frequency) noise. The last one, has been described in a separate paper [1] and more recently in [2], can be modeled using the HF noise sources (thermal or Schottky) and a precise enough nonlinear model of the device. Our investigations have thus been focused mainly on the conversion of the LF noise, and on its dependence on P_{IN} (input microwave power).

Firstly, a measurement of the base emitter current noise power spectral density S_{Ib} has been performed versus the microwave power. This noise source has been found to be independent of P_{IN} . However, the effect of the base-emitter current noise can be cancelled using a low impedance bias on the base (or a high value capacitance). In this case, it is the input voltage noise which has a predominant effect on the phase noise. Results obtained in this configuration demonstrate a clear dependence of the base LF voltage noise source to the microwave input power. According to these results, we can assume that the nonlinearity takes place on the emitter through a voltage noise source or between the collector and the emitter through the current noise source S_{Ic} . These data have already been used in [3] to implement a nonlinear noise model together with a quasi-static technique to simulate the transistor phase noise. Phase noise was simulated using with an extrinsic input power dependent noise source, which is easy to implement in a CAD software like Agilent ADS but which supposes that the device input impedance is not too much changed between the modeling step and the circuit design step (in order to control the noise dependent parameter P_{IN}).

For further circuit optimization, an intrinsic nonlinear noise modeling approach is required, and different models of this type have been proposed recently [4, 5, 6]. The technique described in these papers is based on the mapping of the noises sources spectral density versus the polarization current. Then this mapping is used to extract the nonlinear

equation of the different noise sources in the transistor.

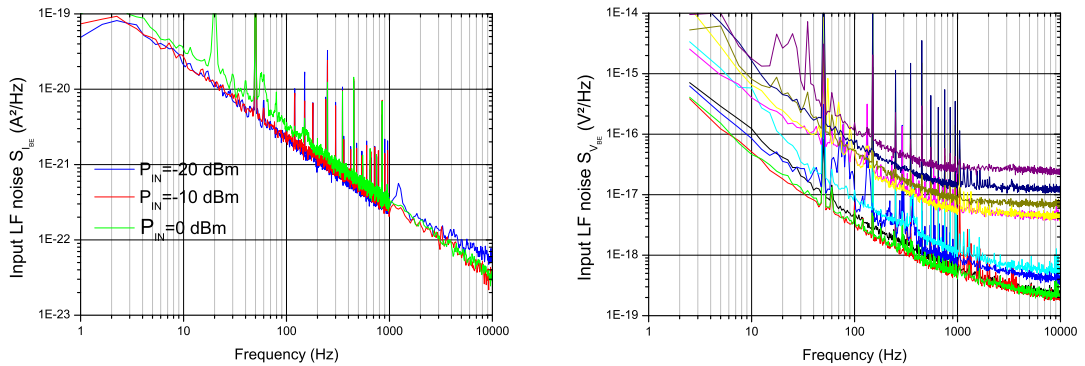
Our approach is close to this type of modeling but differs in the parameters extraction technique. The RF power dependent equivalent input voltage noise data is used to extract the nonlinear LF noise source S_{Ic} . Contrarily to the multi-bias approach, this technique is based on the observation of the real nonlinear behavior of the noise. Indeed in some cases, the noise spectrum can be much different in nonlinear regime than in the quiescent state. Thus, in these cases the multi-bias approach fails in describing the noise spectrum shape.

Then this nonlinear LF noise source is implemented in the transistor electrical model, in which also the S_{Ib} LF noise source is added (this one being a classical bias dependent $1/f$ noise source).

Finally, the complete model is compared to the residual phase noise data, with various microwave input power levels. The simulated phase noise compare well with the measured phase noise, both for high impedance and low impedance bias on the transistor base at low frequency.

SIGe HBT MODELING

First of all static and linear microwave parameters of a SiGe HBT have been measured and fitted thanks to Agilent ADS software. Then the nonlinear model has been extracted and validated. This model is based on the Gummel-Poon model implemented thanks to discrete elements of the ADS software.



a) Input current noise S_{Ib} spectral density for three different microwave power levels

b) Input voltage noise $S_{V_{BE}}$ spectral density for different microwave power levels

Figure 1. LF noise measurements with microwave signal @ 3.5 GHz

To perform our nonlinear noise modeling, we have first investigated on the current noise spectral density S_{Ib} at the transistor input. This noise source has been measured versus the input microwave power level (transistor loaded onto 50Ω and submitted to a variable microwave power level). As shown on the Figure 1 a), the $1/f$ noise source level does not change with the increase of the microwave power. Thus, it is not in this source that the nonlinearity takes place. This source corresponds to a physically well localized noise in the transistor, and is not very sensitive to nonlinear effects. It is the preponderant noise source in an oscillator when the transistor is biased using a high impedance bridge on the base.

These measurements explain why, under these conditions, the classical LF noise models (SPICE) predict with a relatively good accuracy the phase noise.

However, if one chooses to short circuit this noise source using a low impedance bias on the base (or using a high value capacitor), the contribution of this noise source becomes weak compare to the other noise sources in the device : voltage fluctuations on the base or emitter access, current fluctuations on the collector[7].

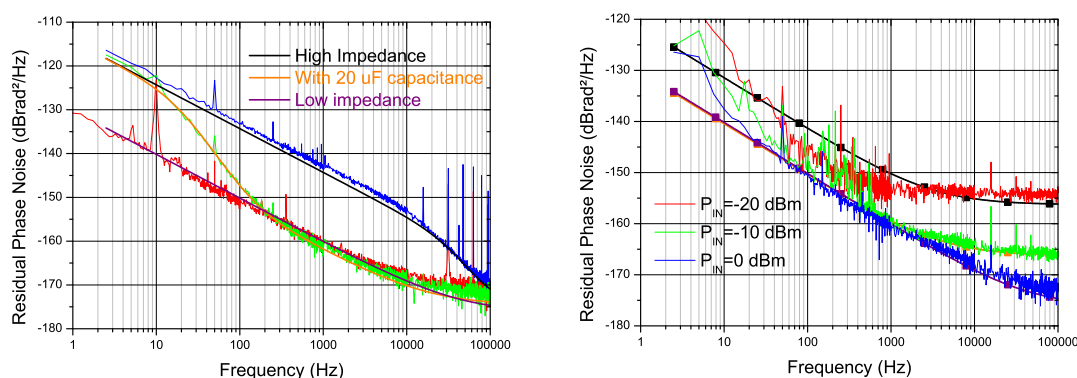
We have thus carried out a measurement in these conditions of the equivalent voltage noise spectral density at the transistor input $S_{V_{be}}$.

Figure 1 b) shows the evolution of this equivalent voltage noise spectral density for a superposed microwave power level varying from linear to 6 dB compression conditions. A very strong noise variation can be noticed (about one decade). As it is the extrinsic equivalent voltage noise fluctuations which are measured, we have to find out the intrinsic cause of this behavior. Such a noise is the superposition of the voltage noise at the base-emitter electrodes and the collector noise flowing into the emitter resistance. We have made the hypothesis that such a strong nonlinear behavior was mainly the result of the variation of S_{I_c} with the RF power, and we have thus implemented in the transistor model a nonlinear noise source S_{I_c} . Indeed, these measurements use a high value capacitor placed in parallel with the base, thus as a consequence S_{I_b} is not anymore preponderant. The LF noise S_{I_c} has been related to the square of the instantaneous current i_c using the capabilities of the symbolically defined devices of the ADS software, with an approach close to the one described in [5, 6].

The measured data of the Figure 1 a) have been used to extract the parameters of this nonlinear noise source, which is described with an equation of the following type:

$$S_{I_c} = S_{I_{c0}} + S_{I_{c1}} \cdot i_c^2(t) \quad (1)$$

where $S_{I_{c0}}$ and $S_{I_{c1}}$ are two fitting parameters.



a) For different bias configurations with $P_{IN} = 0$ dBm

b) Low impedance biasing with P_{IN} level from -20 dBm to 0 dBm

Figure 2. Measured and simulated transistor phase noise on 50 Ω @3.5 GHz

Using this model, we have performed different simulation to compare to already available measurement data. Thus, as shown on the two following pictures, our model predict very well the phase noise level of the studied transistor, even in different conditions for load and applied microwave power.

Firstly, in Figure 2 a), the effect of a change in the base bias network is shown. The observed reduction of noise using the low impedance bias is directly related to the

cancellation of the S_{Ib} related phase noise. In the Figure 2 b), the low impedance is used in all cases, but the microwave power is changed from -20 dBm to 0 dBm. The model describes quite well the evolution of this phase noise versus the microwave power level.

CONCLUSION

In this paper, an original SiGe HBT nonlinear noise model and extraction technique has been proposed. Contrarily to already published papers, the noise model computation is not based on a multi-bias noise measurement but on noise measurements under nonlinear conditions, using the superposition of a microwave signal.

Indeed we are convinced that the multi-bias approach can be insufficient in some cases to accurately describe the nonlinear behavior of the noise, because a nonlinear behavior cannot always be analyzed in this way and because the noise spectrum can be much different at high RF power level.

The proposed model is simple, easy to extract, and describes well the phase noise behavior both versus the RF power or versus different biasing circuits. Coupling this technique with an accurate physical modeling of the device [8] should be advisable for a better understanding of the phenomenon considered. This model can now be used now to optimize the phase noise performance of amplifiers and oscillators realized with this device.

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