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# SiGe HBT Nonlinear Phase Noise Modeling – X-band amplifier design

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**Abstract**— A nonlinear noise model of a SiGe bipolar transistor is presented. This model includes a nonlinear noise source and is able to predict the noise conversion phenomena in circuits using this transistor such as oscillator phase noise. It is based on two main low frequency noise sources, which are extracted thanks to noise measurements under large RF signal superposition. An original low phase noise X band amplifier is also presented. This amplifier features a phase noise performance of  $-160$  dBrad<sup>2</sup> · Hz<sup>-1</sup> at 10 kHz offset frequency together with a low consumption of 50 mW.

**Index Terms**— phase noise, nonlinear modelling, SiGe HBT

## I. INTRODUCTION

Microwave sources 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.

However it is difficult to model accurately the phase noise, because it is the result of a complex interaction of many noise sources in a nonlinear behavior. It 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 separate papers [1], [2]. It 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 up conversion of the LF noise [3], [4], and on its dependence on  $P_{IN}$  (input microwave power).

This paper extends a previous study [5] based on equivalent extrinsic noise sources measured at different microwave input powers on the device. This approach has led to excellent results to predict amplifier or oscillators phase noise, but the transistor was supposed to be placed in the same HF load conditions in the final device as the ones used for noise characterization and modelling.

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.

A first model based on an extrinsic voltage noise source has been proposed [5], in which this noise source was parameterized by the microwave input power. However, for more precise circuit optimization, an intrinsic nonlinear noise modeling approach is required, and different models of this type have been proposed recently [6], [7], [8]. The technique described in these papers is based on the mapping of the noise sources spectral density versus the bias current. Then this mapping is used to extract the equations describing the nonlinear behavior 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 [9]. Thus, in these cases the multi-bias approach fails in describing the noise spectrum shape.

Then this nonlinear LF noise source is included 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).

The phase noise is simulated using Agilent ADS software and 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.

Then an amplifier design is presented. The goal was to design an X band amplifier with sufficient gain to sustain an oscillation on a resonator with a middle range coupling factor (typically, 6 dB losses) and featuring the best possible phase noise performance. Our amplifier provides 8.6 dB gain at 10 GHz and a phase noise performance of  $-164$  dBrad<sup>2</sup> · Hz<sup>-1</sup> for a 100 kHz offset frequency. The different optimizations steps performed during the design are discussed. To conclude, an overview of the different applications of this amplifier type is given.

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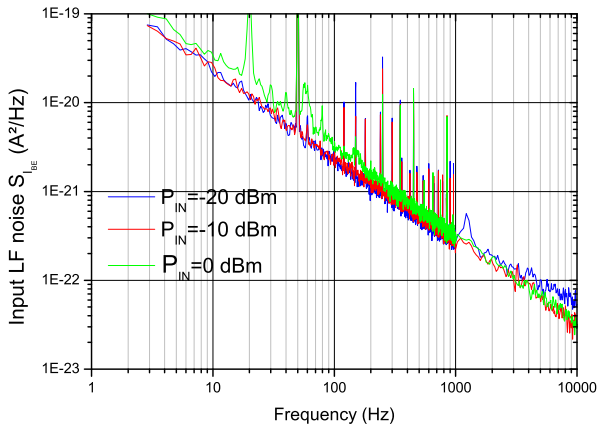


Fig. 1. Input current noise spectral density  $S_{I_B}$  for three different microwave power levels onto  $50 \Omega$  @  $3.5 \text{ GHz}$ , Quiescent bias:  $V_{CE} = 2 \text{ V}$  and  $I_C = 10 \text{ mA}$

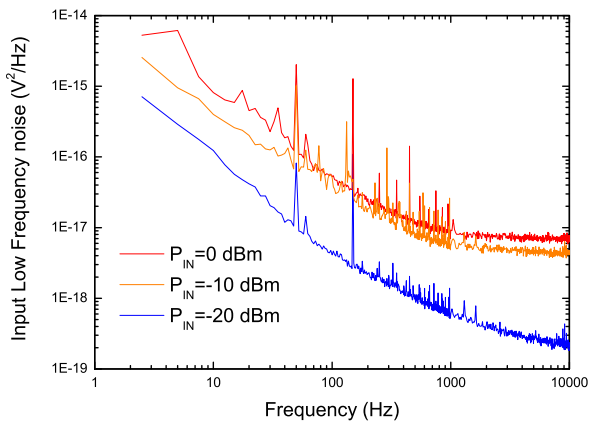


Fig. 2. Input voltage noise  $S_{V_{BE}}$  spectral density from  $P_{IN} = -20, -10$  and  $0 \text{ dBm}$  onto  $50 \Omega$  @  $3.5 \text{ GHz}$ , Quiescent bias:  $V_{CE} = 2 \text{ V}$  and  $I_C = 10 \text{ mA}$

## II. 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 Agilent ADS software.

To perform our nonlinear noise modeling, we have first investigated on the current noise spectral density  $S_{I_B}$  at the transistor input. This noise source has been measured versus the input microwave power (transistor loaded onto  $50 \Omega$  and submitted to a variable microwave power level up to  $1 \text{ dB}$  compression) thanks to the technique described in [10] and in the Figure 4 with the transimpedance amplifier. As shown in Figure 1, the  $1/f$  noise source level does not change with the increase of the microwave power. Thus, this noise source

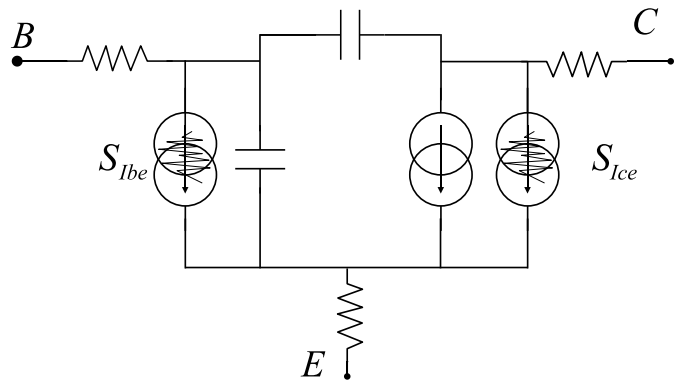


Fig. 3. Model used to implement noise sources into Agilent ADS software

can be considered as constant (or simply bias dependent, in our model). This constant  $S_{I_B}$  differs from the nonlinear noise models already published for the GaAs devices. This important property may be specific to Silicon devices.  $S_{I_B}$  corresponds to a physically well localized noise source 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 of an oscillator or an amplifier (at least for Silicon devices).

However, if one chooses to short circuit this noise source using a low impedance bias on the base (or, more easily, 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[11].

We have thus carried out a measurement in these conditions (using a high value capacitance on the base) of the equivalent voltage noise spectral density at the transistor input  $S_{V_{BE}}$ .

Figure 2 shows the evolution of this equivalent voltage noise spectral density for a superposed microwave power level varying from linear to  $6 \text{ dB}$  compression conditions. Indeed, these measurements of the equivalent voltage noise spectral density, use a high value capacitor placed in parallel with the base, as shown on the Figure 4.

An important 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 and emitter electrodes, and the collector current 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  $S_{I_C}$ . The LF noise  $S_{I_C}$  has been related to the square of the instantaneous current  $I_C(t)$  using the capabilities of the symbolically defined devices of the Agilent ADS software, with an approach close to the one described in [4], [7], [8].

The measured data of the Figure 2 have been used to

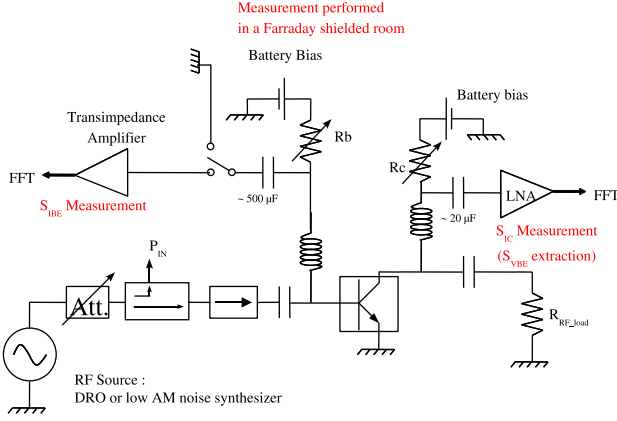


Fig. 4. Test setup for the measurement of the low frequency noise under nonlinear conditions

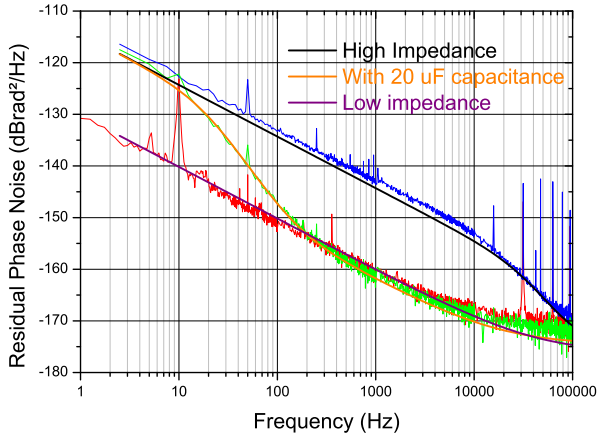


Fig. 5. Simulated and measured transistor residual phase noise @ 3.5 GHz for different bias configurations,  $P_{IN} = 0$  dBm, onto  $50 \Omega$  @ 3.5 GHz, Quiescent bias:  $V_{CE} = 2$  V et  $I_C = 10$  mA

extract the parameters of this nonlinear noise source, which is described with an equation of the following type:

$$S_{I_C} = S_{I_{C_0}} + S_{I_{C_1}} \cdot i_c^2(t)$$

where  $S_{I_{C_0}}$  is a constant (white) noise spectral density and  $S_{I_{C_1}}$  is a constant  $1/f$  noise spectral density.

$$S_{I_{C_0}} = K_0 \text{ and } S_{I_{C_1}} = \frac{K_1}{f}$$

Using this model, we have performed various simulations to compare to already available measurement data. These data have been obtained from phase noise measurements performed at 3.5 GHz using an open loop (or residual) phase noise measurement bench [1], [11]. This measurement bench is a phase bridge, realized with two phase detectors (for cross-correlation analysis), which is able to measure the phase fluctuations added by the transistor thanks to a comparison

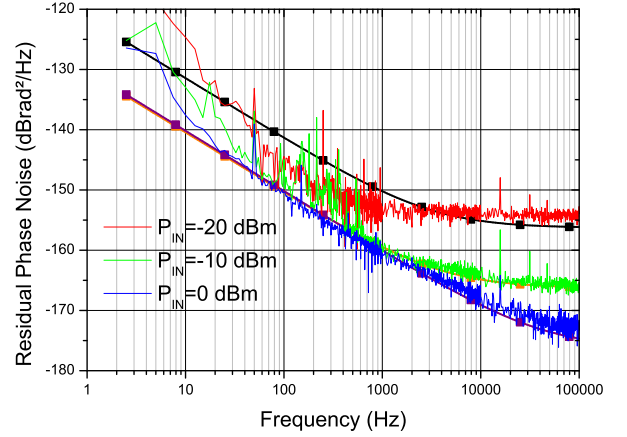


Fig. 6. Simulated and measured transistor residual phase noise @ 3.5 GHz Low impedance biasing with  $P_{IN}$  level from  $-20$  dBm to  $0$  dBm onto  $50 \Omega$  @ 3.5 GHz, Quiescent bias:  $V_{CE} = 2$  V et  $I_C = 10$  mA

to a reference path. The sensitivity of this experiment is very high and the measured phase noise floor is lower than  $-180$  dBrad<sup>2</sup> · Hz<sup>-1</sup> at 10 kHz offset (3.5 GHz frequency).

Firstly, in Figure 5, the phase noise added by the transistor at 3.5 GHz is measured, using three different base bias network configurations for the transistor: low impedance, high impedance and high impedance short circuited with a  $20 \mu F$  capacitance. The measurement agrees very well with the simulation (continuous lines). The observed reduction of noise using the low impedance bias is directly related to the cancellation of the contribution of  $S_{I_B}$  to the phase noise. In Figure 6, the low impedance bias on the base is used in all cases, but the microwave power is changed from  $-20$  dBm to  $0$  dBm. As shown in the figure, the model is able to describe the evolution of the phase noise versus the microwave power level.

### III. APPLICATION TO THE DESIGN OF A LOW PHASE NOISE AMPLIFIER FOR HIGH SPECTRAL PURITY OSCILLATORS APPLICATION

Considering a feedback loop oscillator using an amplifier and a resonator placed in transmission, the optimized resonator coupling losses for phase noise performance are 6 dB ( $Q_L = Q_0/2$ ) [11]. This is true both for the two components of phase noise: additive and  $1/f$  noise. If we take into account the additional circuit losses and the necessary compression (about 1 dB); the amplifier small signal gain must be of about 9 dB. This gain level is easily reachable in the low microwave range with a single SiGe HBT transistor, keeping a low level of phase noise. However, at X band, the transistor must be matched for its maximum small signal power gain, which corresponds to one of the worst conditions for phase noise generation in bipolar amplifiers [11], [12]. We have thus investigated a circuit topology including two transistors: a two stages amplifier. This approach had been first tested cascading two devices loaded onto  $50 \Omega$  [13]: the resulting phase noise was very close to the phase noise of a single device, and

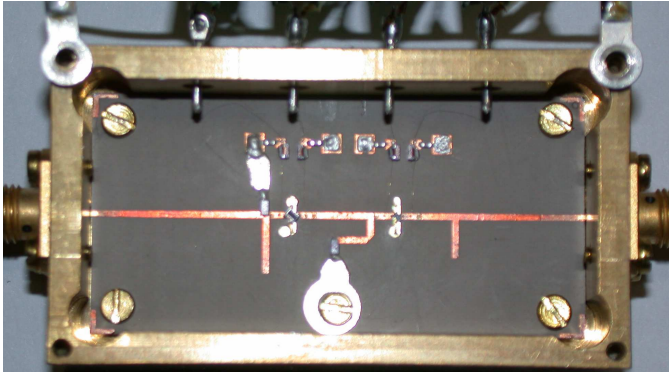


Fig. 7. Picture of our two stages amplifier with stability optimizations

mainly related to the phase noise of the first device (not only for the additive noise contribution, but also for the  $1/f$  phase noise). The two devices for the amplifier design have been selected with this experimental approach. The first stage is realized with a SiGe HBT from Infineon (BFP620) and the second stage using a BJT device from Nec (NE894M13).

#### A. Spurious oscillations

A first amplifier has been designed thanks to a nonlinear model based on RF power parameterized external noise sources, as described [5]. Such a model has been extracted for the two transistors chosen for this design. Nevertheless, several stability issues appear with such a configuration. The main cause of instability is the matching between the two stages. Actually, our two transistors feature respectively only 2.5 dB gain for the SiGe one and 2 dB for the Si one at 10 GHz when they are loaded onto  $50 \Omega$  ( $S_{21}$ ). The inter-stages matching is thus mandatory, but a high level gain, particularly at low frequencies, may result in transistor instability.

We thus need to take into account this parameter when we optimize the gain and the noise of our circuit. The possible oscillations conditions at low frequencies (between 1 MHz and 1 GHz) have been theoretically studied, and various filtering capacitors and inductors have been added on the bias access to prevent these parasitics oscillations. A low phase noise X-band amplifier has then successfully been realized. It features 8.6 dB gain at 9.65 GHz and is shown in Figure 7. Measured and simulated results are presented in the section III-B.

#### B. Two stages amplifier

Figure 8 depicts the phase noise results obtained with our amplifier and the comparison with the simulated data obtained with the model presented in part II. It is a post design simulation because the amplifier had been optimized thanks to the first model using the extrinsic equivalent noise sources approach. However, a good agreement between post simulated and measured data is found. As a consequence, we can assume that our model using a nonlinear noise source is reliable even in this case where the transistors HF load is different from  $50 \Omega$ .

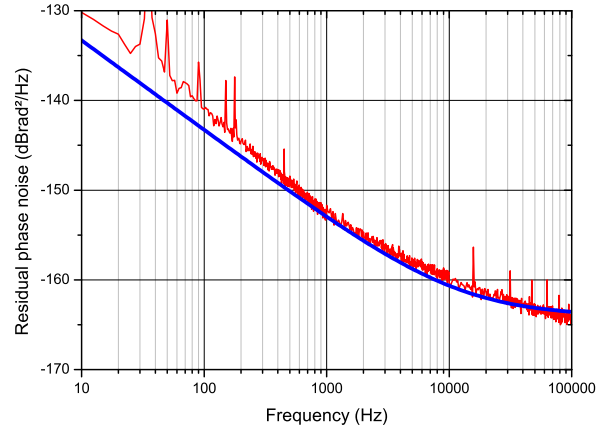


Fig. 8. 10 GHz phase noise measured and retro simulated for the two stages amplifier with the input power  $P_{IN} = 0$  dBm, Quiescent bias:  $V_{CE} = 2$  V et  $I_C = 10$  mA for each transistor

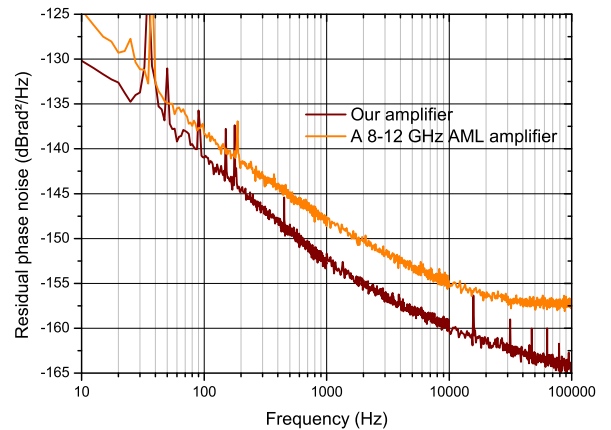


Fig. 9. Phase noise comparison between our two stage amplifier ( $V=2$  V and  $I=20$  mA) and an AML amplifier ( $V=15$  V and  $I=600$  mA) with  $P_{IN} = 0$  dBm 10 GHz

These results have been obtained with an input microwave power level of 0 dBm at 10 GHz. The phase noise performance of our amplifier is compared in Figure 9 to the phase noise of one of the best commercially available low phase noise amplifier at this frequency (AML Communications). Our amplifier features a better phase noise performance, but with a smaller gain (8.6 dB compared to 26 dB) and a smaller operating bandwidth. However the power consumption of our amplifier is also much smaller (50 mW compared to 900 mW) and the gain performance is sufficient to start an oscillation on a moderately coupled resonator.

#### IV. CONCLUSION

In this paper, an original SiGe HBT nonlinear model including a nonlinear noise source has been proposed together with the related parameters extraction technique. 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. Another difference with these models rely on the choice of the noise sources nonlinearity ( $S_{I_C}$  instead of  $S_{I_B}$ , as an example), but it must be pointed out that these models had been extracted on III-V HBT devices, while our work is on SiGe HBT devices.

The proposed model is quite simple, easy to extract, and is able to describe the phase noise behavior at different input RF power or using different bias circuits. Coupling this technique with an accurate physical modeling of the device [14], [15] should be advisable for a better understanding of the phenomenon considered.

This model has been successfully used to simulate the phase noise of a two stages amplifier. It may be used to optimize the phase noise performance of amplifiers and oscillators realized with this device.

To conclude, an amplifier using an original topology has been presented. This amplifier features good skills for X-band applications, and particularly for embedded applications for which a low power consumption and a low phase noise performance is required. It could also be used in a very high spectral purity oscillator based on a sapphire resonator for metrology applications.

In this case, the expected phase noise is as low as  $-145 \text{ dBc} \cdot \text{Hz}^{-1}$  at 10 kHz offset from 10 GHz (with a loaded  $Q$  factor,  $Q_L = 60000$ ).

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systems for signal transmission with low additive noise". His interests are in the study of microwave sources, and more generally nonlinear circuits, both with theoretical and experimental approaches. He has proposed different techniques to investigate the phase noise in microwave oscillators, and designed ultra low phase noise microwave sources. He is now also involved in the development of optical-microwave systems for time & frequency applications. He is the author or co-author of more than 100 papers, either on scientific journals or international conferences.