Semi-Automated Experimental Set-Up for CAD-oriented Low Frequency Noise Modeling of Bipolar Transistors

M.Borgarino[1], A.Bogoni[2], F.Fantini[1], M.Peroni[3], C.A.Cetronio[3]

[1]University of Modena and Reggio Emilia, Dipartimento di Ingegneria dell'Informazione,
Via Vignolese 905, 41100 Modena, Italy, +39 059 2056168
[2] CNIT, Laboratorio Nazionale di Reti Fotoniche,
Via Cisanello 145/147, 56124 Pisa, Italy, +39 050 9719018
[3] Alenia Marconi Systems, Advanced Research and Technologies GaAs IC Group,
Via Tiburtina Km 12,400, 00131 Roma, Italy, +39 06 41503194

Abstract — **The present work addresses the hardware and software development of a semi-automated experimental set-up devoted to the extraction of low frequency noise compact models of bipolar transistors for microwave circuit applications (e.g. oscillators). The obtained experimental set-up is applied to GaInP/GaAs Heterojunction Bipolar Transistors.**

I. INTRODUCTION

The phase noise $\mathbf{L}(f_m)$ is one of the most demanding specification for the local oscillator of a receiver and even in the transmitter the phase noise is an important parameter to be traded-off with the power amplifier non-linearity [1]. In order to get a reliable phase noise prediction, it is mandatory to use a reliable model not only of the non-linear behaviour but also of the low frequency noise (LFN) properties of the employed active devices. In particular, bias dependent LFN CAD-oriented models of the active device should be provided when the phase noise is predicted adopting a Linear Periodic Time Variant approach [2,3].

The development of such a kind of bias dependent LFN models is usually achieved at the cost of a long characterization time, because of the required extensive and systematic LFN measurements. The adoption of an experimental technique able to reduce as much as possible the characterization time without sacrificing the completeness of the experimental data is therefore highly desirable. It is here worth reminding that a complete characterization should cover the correlation quantities (e.g. correlation resistance or correlation coefficient), that are very helpful data to extract LFN compact models [4]. To this aim, two possible experimental techniques can be employed: the multiple-impedance technique or the direct technique. Even if they are equivalent [5], the direct technique saves a large amount of time, improves the characterization correctness, and gives a physical LFN representation of the device under test (DUT).

In the past, an experimental set-up suited to perform LFN characterizations through a direct technique was presented for SiGe Heterojunction Bipolar Transistor (HBT's) [5] and, more recently, improved for application to GaAs-based HBT's [6]. The greatest limitation of both these set-ups is that they are full manually operated leading therefore to an under-optimised characterization time and to a low user-friendly procedure.

Aim of the present work was to overcome these limitations through the development of a semi-automated experimental set-up.

II. OPERATION PRINCIPLE

A direct technique LFN characterization set-up is founded on the short-current representation of a noisy four-poles as depicted in Fig. 1.

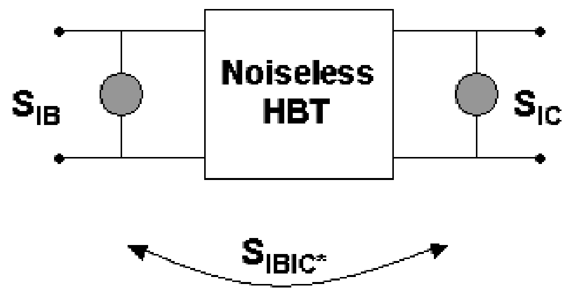

Fig. 1. Base and collector short-current generators representation of a noisy HBT's.

The noisy transistor is modelled as a noisy four-pole where all the noise properties are concentrated in two external partially correlated noise current generators: the base current noise generator S_{IB} and the collector current noise generator S_{IC}; their correlation is described by the cross-spectrum S_{IBIC*}.

In the experimental set-up the stochastic fluctuations of the base and collector currents are drained by two low noise EG&G5182 transimpedance amplifiers (TA's). They amplify these current fluctuations into voltage signals large enough to feed the channels of a SR785 Dynamic Signal Analyser, that computes in real-time the S_{IB}, S_{IC}, and S_{IBIC*} spectra using a Fast-Fourier Transform algorithm.

III. HARDWARE AND SOFTWARE

When the previous principle of operation has to be implemented in the practice, some difficulties rise up, specially due to the noise introduced by the TA's. In the fact, they are optimised in terms of input equivalent noise current but not of input equivalent noise voltage. In particular, for the EG&G5182 transimpedances employed in the present work, it has been demonstrated that the equivalent input voltage generator is physically located at the input of the TA [5]. This location requires the insertion of a common-base amplifier on the base side of the experimental set-up to isolate the TA noise voltage generator from the Device Under Test (DUT). Without this isolation, the measurements of the S_{IC} and S_{IBIC*} spectra would be corrupted by the TA noise. The isolation offered by the common-base amplifier was enough for Si/SiGe HBT's. Nevertheless, when GaAs-based HBT are addressed, because of the difference both in the noise intensity and in the input impedance between a Si-based and a GaAs-based bipolar transistor, the TA noise isolation should be improved introducing a transformer [5, 6]. In order to get an experimental set-up useful for both Si- and GaAs- technologies, the experimental set-up developed in the present work utilizes the common-base amplifier as well as the impedance matching transformer. Since in the practice, these two cascaded stages (amplifier + transformer) has to be properly used depending on the kind of measurements and of the DUT, the first step towards a more user-friendly experimental set-up was the arrangement in one single box (see Fig. 2) of the whole conditioning circuitry of the base channel together with the corresponding configuration switches. In addition, the control circuit for the base bias current too was fitted in the same box. In Fig. 2, the configuration switches and the bias connections are visible on the upper and on the front sides, respectively.

Fig. 2. The configurable box for the analog signal conditioning on the base side of the experimental set-up. It contains the common-base amplifier, the impedance matching transformer as well as the base bias current control.

During the assembly of this box, particular attention was paid to the switches arrangement. It was indeed observed that a bad arrangement can lead to highly undesirable resonances, that may severe corrupt the measurements. Once these difficulties overcome through a suited arrangement, the final user of the set-up should not be made aware of all the above described signal conditioning difficulties and switch configuration cautions. In addition, to make easier the box configuration, the user is assisted by the control software, that step by-step indicates to him the required operations.

The control software is written in LabView™ code [7]. Its mission is not only to interactively operate with the user but in particular to control the operations of the Dynamic Signal Analyser, and the acquisition, the conversion, and, the storage of the experimental data. In addition, the control software also de-embeds from the measurements the noise contributions due to the TA's and the bias circuits. All these time consuming operations are automatically carried out and thus transparent to the user.

The upper of Fig. 3 shows a snap-shot of the control environment, which is mainly covered by the four areas allocated for S_{IB} and S_{IC} on the left side and for the magnitude and phase of S_{IBIC*} on the right side. The three upper software switches in the middle of the window enable to measure every desired combination of S_{IB}, S_{IC}, and S_{IBIC*}, exploiting the flexibility intrinsic of the direct technique. It is indeed here worth pointing out that an experimental set-up founded on a multi-impedance technique forces the user to perform always a full characterization even if the final interesting data would be S_{IB} only. In the practice, this has to be considered as a lost of time. Indeed, during a preliminary phase of a design, when the technology has to be chosen, the most important task is to compare as quick as possible the available technologies. This is usually carried out using the $K_{1/f}$ figure-of-merit of the base current fluctuations [8], whose measurement does not require a full LFN characterization, that will be performed only later on the selected technology.

Another important aspect of the control environment is that it does perform all the measurements on two frequency bands: from 10Hz to 10kHz (lower band) and from 100Hz to 100kHz (upper band). A central frequency span (100Hz-10kHz) results where the spectra are measured two times. If the spectra obtained in the lower and in the upper bands overlap in the central span then the measurement correctly occurred. The experience has demonstrated that this check is precious for S_{IBIC*}, whose measurement is known to be a challenging task. Once the characterization done, the software stores the data and automatically de-embeds not only the noise contributions of the TA's and of the bias circuits but also the gains of the TA's. The user gets thus a real-time access to the S_{IB}, S_{IC}, and S_{IBIC*} spectra reported at the base and collector of the DUT. At the end of the characterization, the data are thus immediately available for the LFN modelling.

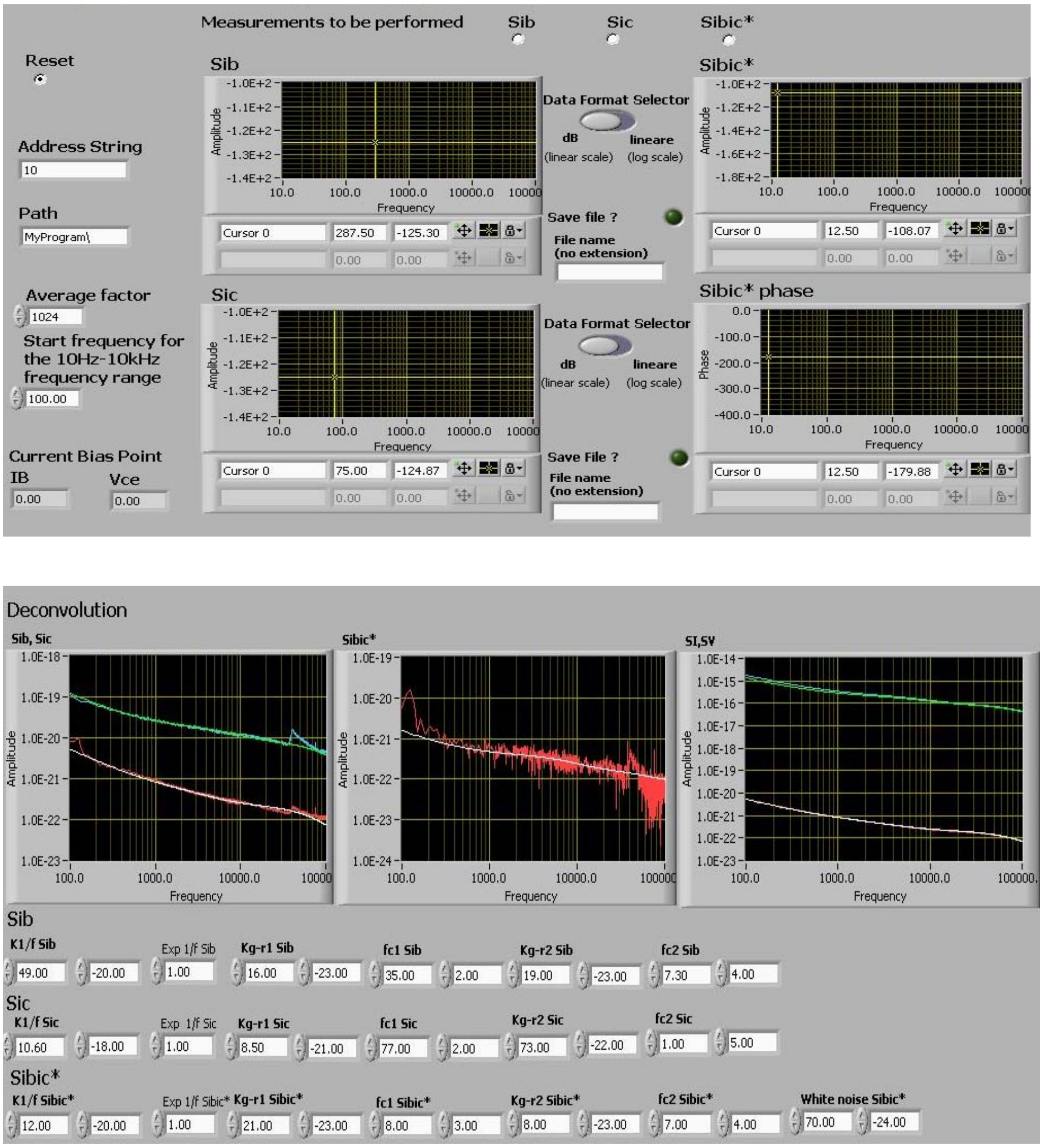

Fig. 3. Snap-shot of the main window of the control environment (upper) and of the model extraction environment (bottom).

In order to make this operation more easy and user-friendly, in the present work a model extraction environment with a direct access to the measurement data has been also developed still using LabView[TM] [7]. A snap-shot of the model extraction environment is reported in the bottom of Fig. 3. In this way the user is not required to transfer the data from a software application to another one. As usually, the extraction environment has been designed paying particular attention to the interactivity with the user.

In the bottom of Fig. 3, the S_{IB} and S_{IC} spectra are on the left, the cross-spectrum S_{IBIC*} is in the middle, and spectra of the input equivalent noise voltage and noise current generators of the chain representation are on the right. It is also possible to observe the software console through which the user tunes the coefficient to fit the experimental data.

Three LFN models, based on the three most widely employed representations, can be simultaneously extracted: input referred equivalent sources, base and collector short-current sources, and intrinsic sources embedded in a Π-topology small-signal models [4]. The intrinsic model extraction uses the correlation resistance method [4]. The simultaneous availability of all three models in a unique extraction environment guarantees their complete equivalence leaving thus to the circuit designer the full freedom of choosing the model most suited for his simulation needs.

IV. APPLICATIONS TO GAINP/GAAS HBT'S

The previously described experimental set-up has been applied to GaInP/GaAs HBT's. A full LFN characterization were carried out and a compact model was extracted using the extraction environment. All the measurements were carried out at wafer level using coplanar probes to contact the DUT.

Fig. 4 shows the S_{IB}, S_{IC} spectra already de-embedded from the TA and bias circuit noise contributions and reported at the DUT terminals. The coloured curves are the measurements and the white ones are the model. The cross-spectrum is reported in Fig. 5; again, the coloured curve is the measurement and the white one is the model.

Concerning the performance of the developed experimental set-up, the data acquisition required about 5 minutes. Then they were immediately available for being sunk in the modelling environment for the model extraction. The overall procedure (measurement plus modelling) required about 20 minutes. One can forecast that during an extensive characterization campaign, where more bias points are addressed on the same DUT, the mean time spent for the characterization and the following modelling for each bias point may be as low as 15 minutes.

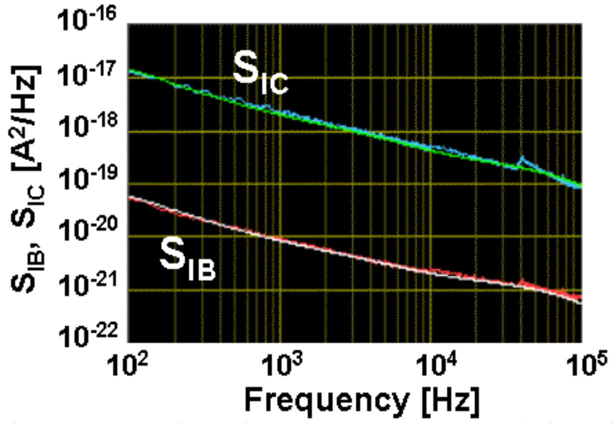

Fig. 4. Comparison between measurement (coloured curves) and extracted base and collector short-current sources model (white curves).

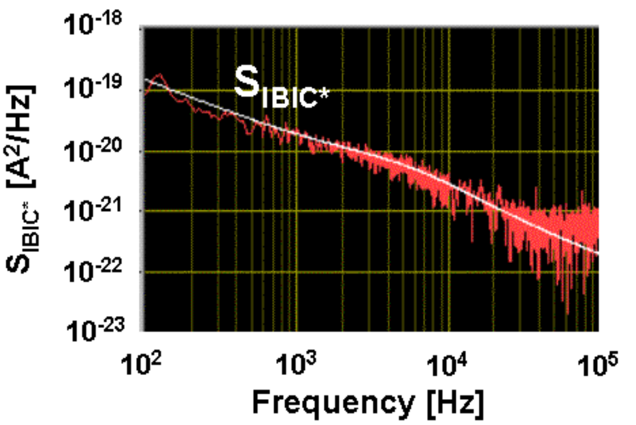

Fig. 5. Comparison between measurement (red curve) and the extracted base and collector short-current sources model (white curve).

V. Conclusions

In the present work a semi-automated experimental set-up devoted to the release of CAD oriented low frequency noise models of bipolar transistors has been presented. The experimental set-up has been tested on GaInP/GaAs HBT's. The attained performance demonstrates that the experimental set-up allows also to an unskilled user to obtain in one work-day the release of a multi bias point low frequency noise model.

Acknowledgement

The work was supported by the national Italian university research program COFIN entitled "Non-linear noise models and design of low phase-noise oscillators for high performance communication systems".

The authors would like to acknowledge ing. C.Angelone for her contribution to the software development.

References

[1] S. Woo, "Combined Effect of Power Amplifier Non-Linearity and Oscillator Phase Noise in IEEE 802.11a Wireless LAN Transmitter", in *Proceedings of the 6th European Conference on Wireless Technology* , Munich, Germany, pp. 399-402, October, 2003.

[2] A. Demir, and A.Sangiovanni-Vincentelli, *Analysis and Simulation of Noise in Nonlinear Electronic Circuits and Systems*, 2nd ed., Kluwer Academic Publishers, 2000.

[3] A. Demir, A. Mehrotra, and J. Roychowdhury, "Phase Noise in Oscillators: A Unifying Theory and Numerical Methods for Characterization" *IEEE Transactions on Circuits and Systems-I: Fundamental Theory and Applications*, vol. 47, no. 5, pp. 655-674, May 2000

[4] M. Borgarino, L. Bary, D. Vescovi, R. Menozzi, A. Monroy, R. Plana, F. Fantini, and J. Graffeuil "The Correlation Resistance for Low-Frequency Noise Compact Modeling of Si/SiGe HBTs," *IEEE Transactions on Electron Devices*, vol. 49, no. 5, pp. 863-870, May 2002

[5] L. Bary, M. Borgarino, R. Plana, T. Parra, S.J. Kovacic, H. Lafontaine, and J. Graffeuil "Transimpedance Amplifier-Based Full Low-Frequency Noise Characterization Setup for Si/SiGe HBTs," *IEEE Transactions on Electron Devices*, vol. 48, no. 4, pp. 767-773, April 2001

[6] M. Borgarino, "Enhanced Set-up for Low Frequency Noise Cross-Spectrum Measurements in GaAs HBTs" submitted to *IEEE Transactions on Instrumentation and Measurements*

[7] LabView™ User Manual 6.1, 2000, National Instrument Corporation

[8] L.S. Vempati, J.D. Cressler, J.A. Babcock, R.C. Jaeger, and D.L. Harame "Low-frequency Noise in UHV/CVD Epitaxial and SiGe Bipolar Transistors" *IEEE Journal of Solid-State Circuits*, vol. 31, no. 10, pp. 1458-1467, October 1996