Bias Dependent, Compact Low-Frequency Noise Model of GaInP/GaAs HBT: Experimental Identification and CAD Implementation

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Abstract—In the present paper, the experimental identification of a compact low-frequency noise model of GaInP/GaAs Heterojunction Bipolar Transistors and its implementation in a widely employed RF CAD software is described. The model is analytical so that its CAD implementation does not require look-up tables. In addition to the usual control of the noise sources through the DC or the mean value of the base current, the model reported in the present work is flexible enough to allows for the control of the noise sources through the instantaneous value of the base current.

Low frequency noise; modelling; CAD; characterization; simulation; HBT.

I. INTRODUCTION

The application of compact low-frequency noise models of heterojunction bipolar transistors, both on silicon and GaAs substrates, to simulate the phase noise of microwave oscillators has recently received large interest in the international technical literature [1-2]. In particular, in these circuits the low-frequency noise encounters large signal conditions leading to the problem of correctly accounting for the noise sources modulation, whose theory is still today in progress [2-4].

The noise source modulation topic can be approached in several ways spanning from a system level interpretation [4] to a physics level [3]. A very interesting approach consists in the use of compact low-frequency noise model [1-2], which stays in the middle between a pure physics based and a system-level approach. The development of compact low-frequency noise model typically faces the great difficulties of localizing the intrinsic noise sources inside the transistor small signal schematic. The number of intrinsic noise sources are indeed larger than the typically available experimental data, that are two auto-spectra and one cross-spectrum: the base current fluctuations spectrum (S_{IB}), the collector current fluctuations spectrum (S_{IC}), and their cross-spectrum (S_{IBIC*}), respectively, when the noisy device is described through noise short-currents and the voltage spectrum (S_{V}), and the current spectrum (S_{IV*}), and their cross-spectrum (S_{IV*}), respectively, when the noisy device is described through input referred equivalent noise generators.

In the praxis, the models are therefore developed forcing the noise sources to be an as small as possible subset of the intrinsic noise sources usually recognized to be present in a small signal model (see for instance [2,5]). This task can be done by exploiting additional measurements performed under different experimental conditions (e.g. by changing the value of an emitter degeneration resistor or the transistor configuration) with the aim of gaining a larger amount of experimental data [2,6]. These praxis lead to identify approximated models at the cost of large experimental time and of “ad-hoc” characterization set-up.

Aim of the present work is the identification of compact low-frequency noise model without the application of approximation and/or “ad-hoc” experimental set-up. The proposed method is based on the so-called correlation resistance (R_{Cor}), which is defined when the noisy bipolar transistor is described in terms of S_{I}, S_{V}, and S_{IV*}. The idea of using R_{Cor} to identify compact low frequency noise models stems from its property of being a useful indicator of the relative weights of each intrinsic noise source [7].

Even if at a first glance it may appear trivial, a very important passage for the model release is to get a clear and effective implementation of the identified low frequency noise compact model in an EDA tool.

The paper is organized as follows. First the experimental set-up employed to carry out the characterization is presented. Then how the correlation resistance can be used to extract a low-frequency noise compact model will be reminded and some results will be presented. The obtained model will be then presented and its implementation in the Agilent ADS simulator described. A conclusion section closes the paper.

II. EXPERIMENTAL SET-UP

When one desires to perform a low-frequency noise characterization of a bipolar transistor accounting also for the correlation properties, two approaches are possible: the multi-impedance technique or the short currents method [2,8]. The former replicates the noise characterization methodology typically employed in the microwave.

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frequency range; it is a highly time consuming experimental approach, that makes sense when one only or at least few bias points should be addressed. On the other hand, the identification of the compact noise model required for large signal applications needs the characterization of the devices on a large number of bias points. This leaves the multi-impedance approach still possible but scarcely advisable. On the other hand, the short currents method is very well suited to address a large numbers of bias points, because it allows for a large reduction of the characterization time [8]. The operation principle of the experimental set-up is based on the noise short-current description of a noisy devices as depicted in Figure 1. The base and collector current fluctuations of the bipolar transistor are drained and amplified in voltage fluctuations by two low noise transimpedance amplifiers (EG&G5182). In order to make the characterization more comfortable and less time consuming, the experimental set-up has been automated as described in [9,10].

Figure 1. Experimental set-up operation principle sketch. These voltage signals at the output of the two low noise transimpedances are acquired by a Dynamic Signal Analyzer (Stanford Research RS785), which is controlled by a home written LabView code running on a PC. Further duties of the control software are to report at the transistor base and collector planes the measured noise signals by taking into account the gain of the transimpedance amplifiers and by de-embedding from the brutal experimental data the noise contributions of the transimpedances as well as of the bias networks. These networks are home fabricated circuits automatically controlled through electromechanical actuators implemented using stepper micro-motors driven by a specific driver (National Instrument MID7602) [9]. In particular, it is worth here pointing out that in the base channel, between the transimpedance amplifier and the base terminal of the transistor under investigation, an analog conditioning stage (not indicated in Figure 1), essentially constituted by a common-base and an audio transformer connected in cascade, is inserted. When high noise, low dynamic input impedance bipolar transistors have to be measured, this precaution is mandatory, in order to avoid that the $S_{ic}$ and $S_{ibc}$ spectra are corrupted by the transimpedance noise and by a fraction of the base current fluctuations, as better detailed in [11]. This countermeasure do not apply to silicon-based bipolar transistors, that exhibits indeed lower low frequency noise magnitudes and higher dynamic input impedances. Of course, the bias networks as well as the transimpedance amplifiers are battery powered, to minimize the impact of the 50Hz interferences on the final measurements.

III. MODELING STRATEGY
The home written LabView code, equipping the experimental set-up, does not only make automated the characterization step, along with the related control and data acquisition and elaboration, but it does also offer a modeling environment, which allows a direct access to the de-embedded experimental data, in order to make quicker and comfortable the extraction of low-frequency noise models. The modeling environment supports all the three most employed low-frequency noise models, that is the input referred equivalent noise sources model ($S_{V}, S_{ib}, S_{ibc}$), the short current noise sources model ($S_{ib}, S_{ic}, S_{ibc}$), and the compact noise model, depicted in the following Figure 2. In this way it is provided guarantee that the three extracted models are all equivalent, leaving therefore to the final user the freedom to choice one among them on the basis of the specific needs. The extraction procedure is based on the $R_{Corr}$, whose expression in terms of the compact model noise sources reveals that it is the weighted mean of four resistances where the weights are the intensity of each noise source as pointed out by the following expression:

$$R_{Corr} = \frac{\{r_{ib1} + r_{ib2}\}S_{ib} + \{r_{ib1} + r_{ib2}\}S_{ib} + \{r_{ib1} + r_{ib2}\}S_{ib} + \{r_{ib1} + r_{ib2}\}S_{ib}}{\{\beta + 1\}S_{ib} + \{\beta + 1\}S_{ib} + \{\beta + 1\}S_{ib}}$$

(1)

The $R_{Corr}$ spectrum acts thus as an useful indicator of the relative importance of each source at each frequency, effectively guiding thus towards the model identification without a priori neglecting any source and without invoking additional measurements carried out under several experimental conditions.

IV. EXPERIMENTAL DATA
The experimental set-up briefly described in the previous section has been applied to GaInP/GaAs Heterojunction Bipolar Transistors (HBT’s). The characterization was carried out at wafer level, contacting the device under test through microwave coplanar microprobes. Since the low-frequency noise properties of a bipolar transistor are practically independent of the collector-emitter voltage ($V_{ce}$), the bias base current ($I_b$) was spanned from 20 $\mu$A to 40$\mu$A while $V_{ce}$ was kept fixed at 1 V.
Figure 3 compares the measured and simulated spectra of R_corr at I_B=30 μA as obtained in the modeling environment. A good agreement was obtained by suitably tuning the contribution provided by each source. In particular, for each source is possible to act on one white noise component, one flicker noise component, and two lorentzian noise components:

\[ S_i = \text{white} + \frac{K_{f_i}}{f} + \frac{K_{GR1}}{1 + \left( \frac{f}{f_{c1}} \right)^2} + \frac{K_{GR2}}{1 + \left( \frac{f}{f_{c2}} \right)^2} \]  

(2)

The white noise components account for the theoretical values of shot and thermal noise. The procedure has been repeated on all the investigated bias points obtaining similar good agreements. Then an analytical expression reproducing the coefficient (K_{f_i}, K_{GR1}, K_{GR2}) of each noise component for each noise source was identified. Table I reports, as an example, the coefficients for the S_{se1} noise source. Similar tables were obtained for the other noise sources.

![Table I. Analytical Model of Sibe1 Source](image)

V. MODEL IMPLEMENTATION

Figure 4 depicts the implementation of the model in the Agilent ADS software. One can note that the schematic in Figure 4 reproduces as close as possible the compact low-frequency noise model in Figure 2 where the sub-network identified by the dashed rectangle has been replaced by the non-linear noiseless HBT model in Figure 4. It is here worth noticing that the low-frequency noise implementation proposed in Figure 3 does not access the transistor non-linear model, which is often provided by the foundry in a form non accessible to the final user.

Each of the four controlled current generators implements the corresponding noise source of the compact noise model. Concerning the noise contributions due to the S_{Ree'} and S_{Rbb'}, the extraction revealed that their contributions were negligible. The analytical dependences on I_B of the different noise components of each source (see Table I for the S_{be1} source) is introduced through Symbolically Defined Devices (SDD). In this way, the noise sources can be made controlled by any form of the base current, ranging from the mean value to the instantaneous value [2,13,14]. The model leaves therefore to the user the freedom of choosing how to modulate the noise sources. It is here worth reminding that, as already stated in the introduction, the modulation of the noise sources in cyclostationary model is still an open matter of discussion.

The value of the correlation resistance modeling for I_B=30 μA.

The value of the correlation resistance in Figure 3 is well below the value of the dynamic base-emitter resistance indicating that the noise sources associated with surface recombination mechanisms occurring in the extrinsic region of the devices (S_{se1} and S_{bc} in Figure 2) are important. These sources indeed weights low value resistances in the analytical expression of the correlation resistance. It is here worth reminding that in the past the decrease in the correlation resistance value was employed to detect the hot carrier induced damage of the extrinsic surface in the base-emitter junction of SiGe bipolar transistor [12].

![Figure 3. Correlation resistance modeling for I_B=30 μA.](image)

![Figure 4. ADS implementation of the compact low frequency noise model.](image)
The identified low frequency noise model has been then applied to a 4GHz Colpitts oscillator depicted in Figure 7. In this schematic, the intrinsic noise sources $S_{\text{ib1}}$, $S_{\text{ib2}}$, $S_{\text{ibc}}$, $S_{\text{ice}}$ are modulated by the instantaneous extrinsic base current flowing in the base. In order to gain a sensibility to the impact of each source on the phase noise, the phase noise was simulated through an Harmonic Balance analysis by accounting for all the intrinsic noise sources or by enabling one intrinsic noise source at a time. Figure 8 compares the obtained phase noise spectra. The bold black line is the simulation carried out accounting for all the intrinsic noise sources. The figure points out that the $S_{\text{ib1}}$ source contribution is moderate on all the frequency offset while the $S_{\text{ice}}$ source contributes always important, specially for frequency offset higher than 10kHz, where it becomes the dominant source. It is worth reminding that the $S_{\text{ice}}$ source represents the most important contribution to the $S_{\text{IC}}$ source, which in its turn is directly related to the $S_V$ generator by the following equation:

$$ S_V = \left( \frac{Z_{\text{in}}}{\beta} \right)^2 S_{\text{ice}} $$

where $Z_{\text{in}}$ and $\beta$ are the dynamic input impedance and the current gain, respectively, of the bipolar transistor.

The pushing factor approach, which evaluates the phase noise in terms of sensitivity of the phase to the voltage applied at the extrinsic base-emitter junction [15,16], forecasts that the phase noise can be reduced by placing a high-value capacitance on the base-emitter junction, so that the $S_V$ noise generator remains the only extrinsic generator of interest [1,17]. The phase noise spectra in Figure 8 suggest therefore that the phase noise of the Colpitts oscillator for frequency offset higher than 10kHz can not be reduced through this capacitor. The phase noise in this frequency offset range is critical in the applications, because the low pass filtering effect of the Phase Locked Loop may be no more effective, and the synthesizer phase noise remains established by the Voltage Controlled Oscillator phase noise [18], as a consequence.

At frequency offset lower than 1kHz the sources $S_{\text{ibc}}$ and $S_{\text{ib2}}$ become important. It is worth noticing that these sources are both related to fluctuation mechanisms occurring at the extrinsic base surface of the transistor [19,20]. Figure 8 shows thus that close to the carrier the quality of the extrinsic base surface is the main factor limiting the oscillator spectral purity.
VI. CONCLUSIONS

Thanks to the use of a home-developed, automated experimental set-up the low-frequency noise model of GaInP/GaAs HBT’s has been identified adopting the correlation resistance methodology. The model is released in the form of a compact model where the noise sources are embedded into the transistor equivalent circuit. Each source exhibits white, flicker and generation-recombination noise sources. The dependence on the bias base current of these components has been provided through analytical expressions allowing the implementation of the model in a RF simulator without invoking look-up tables.

The got model has then been implemented in the Agilent ADS EDA software. A good agreement has been obtained between measured and simulated low-frequency noise spectra for all the investigated bias points. The result shows that the experimental identification and the following implementation of the low-frequency noise model adopted in the present work can be a promising procedure to get models allowing reliable prediction of phase noise in oscillators and noise figure in mixers. One of the most outstanding property of the obtained intrinsic source analytical compact noise model is that it permits to choose the kind of modulation to be applied to the noise sources (DC, mean value, or instantaneous value). This flexibility turns out in an interesting tool to investigate the modulation of the noise sources, which is still today an open matter of discussion.

The identified compact low-frequency noise model has been applied to the design of a 4GHz Colpitts oscillator. The simulations revealed that for offset frequency higher than 10kHz the $S_{11}$ intrinsic noise source dominates the oscillator phase noise while closer to the carrier the oscillator spectral purity is limited by the quality of the extrinsic base surface of the HBT via the $S_{22}$ and $S_{12}$ noise sources.

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