Abstract—This paper addresses the question how to describe the low-frequency noise sources in a GaAs HBT large-signal model. Devices under test are two HBTs from the same process run, but epitaxially grown under slightly different conditions. Hence they show different low-frequency noise, but almost identical electrical performance otherwise. Residual phase-noise measurements are used to characterize noise upconversion. It is shown that in the large-signal case noise upconversion can only be simulated well if cyclostationary noise sources are considered. In contrast, low-frequency noise sources which are excited by the DC current component only yield severely underestimated noise levels.

I. INTRODUCTION

Due to upconversion effects, low-frequency noise can play an important role also in microwave applications. Most prominent is the contribution to the phase noise of oscillators, where the low-frequency noise dominates the spectrum close to the carrier [1]. But also broad-band amplifiers are affected by upconverted base-band noise, or even the base-band noise itself.

However, it is still a field of intensive research how to formulate a large-signal model which is capable of predicting the noise upconversion effects, especially in case of GaAs HBTs. This paper addresses the low-frequency noise modeling considering both the small-signal and the large-signal regime.

In the small-signal case the question is how to implement low-frequency (LF) noise sources in a way that base-band noise is described well for all source impedances. It will be shown that a single noise source, on which standard BJT models rely on, is insufficient in the general case, although it might seem to be well suited if only a fixed source impedance is regarded.

In a second step, residual phase noise measurements are employed to investigate the optimum implementation of these LF sources for the large-signal case. The question is whether the sources are to be described as low-pass noise sources, i.e., excited by the DC current component only, or if they are cyclostationary sources, which means that they are excited by the instantaneous current. While standard models rely on the low-pass sources provided by the circuit simulator software, it was demonstrated in a recently published paper [2] that oscillator phase noise can only be described accurately with two cyclostationary sources. The present work shows that cyclostationary noise sources are also required when considering residual phase noise, which is measured operating the HBT in an almost linear amplifier mode.

In conclusion, this paper discusses the HBT model prerequisites for simulating low-frequency and oscillator phase noise with a harmonic balance simulator. It also addresses the mechanisms generating noise side-bands under large-signal operation in general.

II. HBT TECHNOLOGY AND MEASUREMENT CONDITIONS

The devices under test were fabricated in the 4” In-GaP/GaAs HBT process line of the FBH [3]. HBTs with an emitter size of 3×30 µm² from two different wafers were measured. The sole difference between the wafers is that the emitter was grown in the MOVPE at a different temperature. Both were processed in the same batch, and no difference in the electrical behavior was observed. However, the low-frequency noise is different, as can be seen from Figs. 2, 3 showing the low-frequency collector short-circuit noise current measured as a function of collector DC current and source resistance.

Phase noise was investigated by means of residual phase noise measurements performed at LAAS-CNRS [4]. This measurement condition allows to determine the noise upconversion mechanisms in an open-loop configuration, i.e., when the transistor operates in amplifier mode. In our case, the full phase-noise spectrum is measured as a function of large-signal power at 3.5 GHz.

Along with this, simulations were performed using a commercial harmonic-balance circuit simulator and the FBH HBT model [5], comparing different descriptions for the low-frequency noise sources.

III. LOW-FREQUENCY NOISE MODEL AND SMALL-SIGNAL REGIME

Traditionally, bipolar large-signal models account for low-frequency noise generated at the base-emitter junction only. In the equivalent circuit, Fig. 1, the location of this noise source is denoted as “base-emitter noise source”. In case of the SPICE Gummel-Poon (SGP), VBIC and UCSD HBT [9] models, the noise depends on current and frequency according to

\[ \langle |i_{n}^{2} | \rangle = K_f \Delta f \frac{f^4}{f^2} \]

with the parameters \( K_f \), \( \Delta f \), and \( B_f \), and the noise bandwidth \( \Delta f \). In case of the SGP model, additionally the parameter \( B_f n \) is fixed to unity.

However, since recombination at the base-emitter junction is more pronounced in HBTs than in traditional silicon bipolar transistors, one commonly observes a Lorentz-spectrum.
In Fig. 3b, e.g., this Lorentz-type spectrum is responsible for the bump in the frequency dependence of the noise powers. The Agilent HBT [10] and FBH HBT [5] models, for example, account for this fact by introducing an additional term in the noise formula:

$$\langle |i_{th}|^2 \rangle = K_f \Delta f \frac{r_{bc}^{Ab}}{f_j^{Ab}} + K_b \Delta f \frac{f_j^{Ab}}{1 + (f/F_b)^2} \tag{2}$$

The corner frequency of the Lorentz spectrum can be defined by the parameter $F_b$, and its noise power and bias dependence are controlled through $K_b, A_b$. In case of the Agilent model, this noise source is split into two in order to account for ideal and non-ideal base-emitter currents.

It has been shown that even this enhanced description is not sufficient to describe the low-frequency noise comprehensively [11]. In case that the base-emitter terminal is connected to a low-impedance source, such a model would predict very low collector noise currents. The reason is that the base and emitter resistances $R_b, R_o$, and $R_e$ are quite low in modern HBTs and, hence, the base-emitter noise source is almost shorted. This effect is shown in Figs. 2, 3. Measurements are compared to simulations using the FBH HBT model. The dotted lines in Figs. 2a, 3a refer to the case when accounting only for a base-emitter noise source, which results in deviations from measurements of beyond 10 dB for a 10 Ω source resistance. In contrast, the model performs well when connected to a high-impedance source (see Figs. 2b, 3b). This, of course, is not surprising since the parameters were extracted under this condition.

Obviously, at least a second source is necessary to describe the noise behavior in general. At this point, adding low-frequency noise sources seems to be ambiguous, since there are many possible locations to locate them: all parasitic resistances, and at the base-collector junction. From the practical point of view, it has to be stated that the number of low-frequency sources which can be distinguished reliably from source-pull measurements does not exceed two [2], [11]. Additionally, due to Friis’ formula, noise sources at the output, i.e., at the collector resistance and base-collector junction, will contribute less to the overall noise than the sources at the input which are amplified. Regarding the remaining possible locations, the emitter resistance noise is expected to exceed the noise generated in the base branch, since $I_e \gg I_b$. Additionally, comparison with measurements of epitaxial resistances has shown that the emitter noise source is quite close to the Hooge noise expected for the emitter layer.

One concludes that a the second low-frequency noise source should be located at the emitter resistance. In the FBH HBT model, the corresponding voltage source is defined by

$$\langle |v_{nfe}|^2 \rangle = K_f \Delta f \frac{r_{ce}^{Af e}}{f_j^{A fe}} \tag{3}$$

with the parameters $K_f, A_f, E_f$. The dashed lines in Figs. 2a, 3a show the improvement in simulation accuracy obtained by this arrangement. The noise simulated for the high-impedance source is not affected, since the emitter branch is almost connected to an open circuit then and, consequently, the voltage noise source does not drive any current.

**IV. LARGE-SIGNAL REGIME**

In the large-signal regime, the current exciting the low-frequency noise is no longer a constant DC current only, but it contains also harmonics with considerable amplitudes which cannot be neglected compared to the DC part. Hence, the question arises: Will the noise be determined by the DC current only, or will the instantaneous current drive the noise sources? The first alternative leaves the spectrum of the noise sources unchanged, independent of the large-signal RF signals. In the second case, the base-band noise is influenced by the large-signal current, which can be understood as
noise power (dB A)

Rs = 10 Ω

Ib

10k 100k 1M 10M

2

f   (Hz)

/Hz)

-220

-200

-180

-160

-140

-120

10 100 1k

Fig. 2. Low-frequency noise of 3×30 µm² HBT, Vcc = 3 V, Ic = 2.5, 5, 10, 20 mA, Wafer A. Measurements (solid lines) compared to simulation with two noise sources (broken lines), and simulation neglecting emitter noise source (dotted lines). (a) 10Ω source resistance (b) 10kΩ source resistance.

10k Ω source resistance

10 Ω source resistance.

Fig. 3. Low-frequency noise of 3×30 µm² HBT, Vcc = 3 V, Ic = 2.5, 5, 10, 20 mA, wafer B. Measurements (solid lines) compared to simulation (broken lines), and simulation neglecting emitter noise source (dotted lines). (a) 10Ω source resistance (b) 10kΩ source resistance.

white noise

S f(I)

(a)

(b)

Fig. 4. Interpretation of current-dependent low-frequency noise as a mixing and filtering process of white noise, resulting either in low-pass noise (a), or in cyclostationary noise (b), after [6].

a mixing process. This means that noise side-bands are generated even without any mixing process external to the noise source, i.e., even in a linearly operating device.

Fig. 4 shows a circuit-oriented interpretation of the alternatives [6]. The low-frequency noise can be thought of as white noise, which is low-pass filtered and multiplied by a function of current. The question is: does the low-pass filtering follow or precede the mixing process? In the following, we will refer to the first type of source as “low-pass” noise source, and to the second one as “cyclostationary” source.

At first glance, it is not obvious why a noise source which shows a distinct low-pass behavior (e.g., 1/f noise) should be controlled by the instantaneous current. It would mean that the physical process causing the noise follows fast changes of the signal, and one would expect white noise from such a fast process and not the 1/f like frequency characteristics observed for LF noise. However, it has been pointed out that e.g. generation-recombination noise indeed is governed by a white noise process. The low-pass characteristics are observed only when expressing it in terms of fluctuations in carrier number or current [7]. Physical simulation of various semiconductor structures has shown that, while the microscopic sources indeed show cyclostationary behavior, this could not be said a priori for the lumped noise sources of the corresponding equivalent-circuit based model [6].

The common circuit simulators use low-frequency noise sources following the “low-pass” concept. Accordingly, the built-in models rely on this formulation. It has recently been shown, on the other hand, that nonlinear noise modeling accuracy could be improved significantly by introducing cyclostationary sources. One example is the noise of resistive FET mixers [8], another one is the phase noise of HBT-based oscillators [2]. These noise models necessarily need to use a nonlinear subcircuit in order to obtain a cyclostationary noise source, as addressed e.g. in [8].

The present investigation relies on residual phase-noise measurements, i.e., on measuring the noise side-bands generated when the transistor is operated as an almost linear amplifier. It is the advantage of this set-up that the large-signal noise performance of the HBT alone is measured, while large-signal power, bias and source resistance can be controlled. Therefore, this measurement condition is able to provide a maximum of information compared to the measurement of circuits. Therefore, it is possible to investigate details such as the influence of a single source on HBT noise performance.

In the simulation, the FBH HBT model is used and the low-frequency noise sources are implemented in four different ways: as low-pass sources, as cyclostationary sources, and one as a low-pass source while the other one is cyclostationary.

Figs. 5, 6 present the results for an input power of −6 dBm. For both wafers, it can be stated that a model
based on low-pass sources is not capable of reproducing the simulation data, since it underestimates the phase noise power significantly, partly by more than 10 dB (dashed lines in the figures). On the other hand, if both sources are assumed to be cyclostationary, the model yields an almost perfect fit (thick solid lines). It is, however, interesting to note that both wafers have one dominating noise source. In case of wafer A, it is the emitter noise source, but for wafer B it is the base-emitter noise source. If only this source is modeled cyclostationary, the result is indistinguishable from the result obtained with two cyclostationary sources (thick solid lines). Vice versa, if this dominant source is described by a low-pass source, while the other one is cyclostationary, only little improvement over the low-pass case is achieved (dotted lines).

The observation that the low-pass formulation yields residual phase noise levels considerably below the measured ones has a further consequence for understanding the origins of phase noise. It means that upconversion of baseband noise due to the device nonlinearities does not significantly contribute to phase noise (at least beyond an offset frequency of 100 Hz) and that the large-signal current causes noise sidebands even if the HBT is still in linear operation. Moreover, one concludes that oscillator phase noise can be optimized only to a certain extent by reducing the low-frequency part of the noise sources, e.g., when selecting special baseband terminations in order to suppress upconversion in the nonlinearly operating device.

V. CONCLUSION

This paper addresses the implementation of low-frequency noise sources in GaAs HBT large-signal models. The following conclusions can be drawn:

- In linear operation, two noise sources are required in order to be able to describe the low-frequency noise for all source impedances. If only a base-emitter source is used as it is the case in traditional bipolar models, the noise power level will be underestimated if the HBT is connected to a low-impedance source.
- In nonlinear operation, both low-frequency sources have to be described by cyclostationary sources in order to describe noise upconversion effects properly. The common simulator software packages, on the other hand, provide only low-pass sources. Thus, relying on the built-in models yields grossly underestimated noise power levels. It has been shown that, depending on the actual device, either of the two sources can dominate phase noise generation. Therefore, in a general model it is necessary to have both noise sources described as cyclostationary sources.

These findings explain why noise simulations relying on common bipolar and HBT models provided by harmonic-balance circuit simulators are generally not capable of describing GaAs HBT phase noise with the expected accuracy. The results are also important for understanding the noise generation processes in GaAs HBT oscillators.

REFERENCES