Modeling and Measurement of Phase Noise in GaAs HBT Ka-Band Oscillators

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Abstract — Accurate oscillator phase-noise simulation is a key problem in MMIC design, which is not solved satisfactory so far and needs further investigation. In this paper, a Ka-band MMIC oscillator with GaInP/GaAs HBT and on-chip resonator is treated as an example. Measured phase noise reaches -90 dBc/Hz and below at 100 kHz offset. To evaluate phase-noise prediction, the circuit is simulated using different commercial simulation tools and HBT models. Considerable differences in simulation results are observed.

I. Motivation

Low phase-noise oscillators are key components in communication as well as sensor systems for the emerging markets in the 20 GHz to 80 GHz range. In order to meet the low-cost requirements, monolithically integrated solutions (MMICs) with on-chip resonators are highly favorable. This demands for both transistors with low 1/f-noise and accurate CAD tools for circuit optimization. Regarding the transistor, the GaInP/GaAs HBT is particularly suited since its 1/f-noise is considerably lower than for GaAs HEMTs, but the frequency potential is higher than that of SiGe HBTs. Phase-noise prediction, on the other hand, involves too much uncertainties so far to be a reliable basis for circuit design. Further investigations are required on this subject.

The purpose of our paper is to contribute results in this field. As an example, we study a GaAs-HBT-based 36 GHz oscillator. Attention focuses on the phase noise at 100 kHz offset-frequency. From the measurements, it can be seen that this frequency is in the transition region between $1/f^3$ and $1/f^2$ phase-noise behavior. Phase-noise modeling, therefore, needs to be composed of the following issues [6]:

- Modeling and parameter extraction of the 1/f-noise of the active element used in the circuit. Measuring 1/f-noise of the GaInP/GaAs-HBTs at different source impedances and bias states, we found two independent low-frequency (LF) noise sources. The two noise sources are implemented in an in-house HBT large-signal model. The results are compared to simulations with a standard Gummel-Poon model, which includes only a single LF noise source.
- Calculation of the conversion from LF noise into oscillator phase-noise. The simulations of the 36 GHz oscillator are performed using 3 different commercial design tools (MDS and ADS of Agilent and Serenade of ANSOFT).

II. 1/f-Noise HBT Description

In standard HBT models (e.g. Gummel-Poon) only the base current includes 1/f-noise. However, measurements of the spectral current density of 1/f-noise at the output of GaInP/GaAs-HBTs with different source resistances R_s show that this description is not sufficient. In the low-frequency range, all of the extrinsic reactive elements can be neglected. Hence, the equivalent circuit of the HBT simplifies to a Y matrix with R_{be}, and β and an additional Z matrix containing the parasitic resistors R_b, R_c, and R_e (see Fig. 1) The 1/f-noise model should be consistent with the high-frequency noise model, so we suppose voltage sources at the extrinsic resistors and current sources at base and collector current.

Using the simplified equivalent circuit, the influence of each noise source on output noise can be calculated as a function of the source resistance. In general, measurements for *n* different source-resistance values allow the separation of up to *n* independent noise sources, but for the simplified HBT equivalent circuit the voltage sources at base and emitter cannot be separated. From the simulation point of view, both contribute the same noise at the output, but from physical considerations one can conclude that the emitter layer acts as the relevant LF noise source [1]. In Fig. 3, measured LF noise at the output is plotted together with the modeled data. All bias and source resistance conditions are well described.

III. Circuit Simulation and MMIC Fabrication

The oscillator is designed as a negative resistance circuit in coplanar environment. Fig. 2 provides a chip photo. Lumped elements are used as blocking capacitors only. The resonator is formed by a short-circuited line at the emitter.

All coplanar line elements are simulated with the model according to [2]. For HBT description the in-house model [3] extended by two 1/f-noise sources is employed. For the original design, MDS of Agilent was applied using both the in-house HBT model [3] and the built-in Gummel-Poon one. Fig. 4 presents the results together with measured phase noise. Both models fail to predict phase noise correctly. The in-house model yields reasonable agreement at 100 kHz offset, but frequency dependence does not fit.

The circuits are fabricated using the 4 inch GaAs-HBT MMIC process at the FBH. For details see [4,5]. To suppress recombination at the surface of the GaAs-base layer, a fully depleted GaInP ledge technology is applied. The electroplated Au metalization is 3 µm thick, i.e., the process does not involve special measures to improve Q factor of the passive elements.

IV. Phase-Noise Simulation and Measurements

To evaluate mm-wave phase-noise prediction, the circuit is simulated employing three different commercial design tools: MDS and ADS of Agilent and Serenade of Ansoft. Furthermore, the large-signal HBT model as well as the CPW model is varied applying the built-in models and the user-defined CPW [2] and HBT model [3], respectively. Tab. 1 provides the results.

The first observation is the large spread in the simulation results, mainly with regard to output power and phase noise. Using the in-house CPW model instead of the ADS built-in one, for example, does not influence output power and frequency greatly, as expected, but leads to more than 17 dB deviation in phase noise. Similarly, comparing the ADS and MDS data for identical in-house models, only phase-noise results vary, though by not less than 30 dB. For the GP model, on the other hand, both power and phase noise changes considerably. Given the deviations in power, i.e., in the noiseless nonlinear analysis, it is not surprising that the spread in phase-noise data is even larger. In this regard, the influence of the HBT large-signal model should be emphasized. Difficult to explain, however, are the differences between the three simulators for otherwise identical models.

V. Conclusions

Ka-band MMIC oscillators based on GaInP/GaAs HBTs yield excellent phase noise values exceeding -90 dBc/Hz at 100 kHz offset. Large-signal and phase noise simulations using the common design tools, however, fail to predict this and show an unexpectedly large spread in data. Even an advanced 1/f-noise description of the HBT does not lead to adequate results. This finding points out the high sensitivity of these quantities to details in transistor modeling and simulation approach.

References

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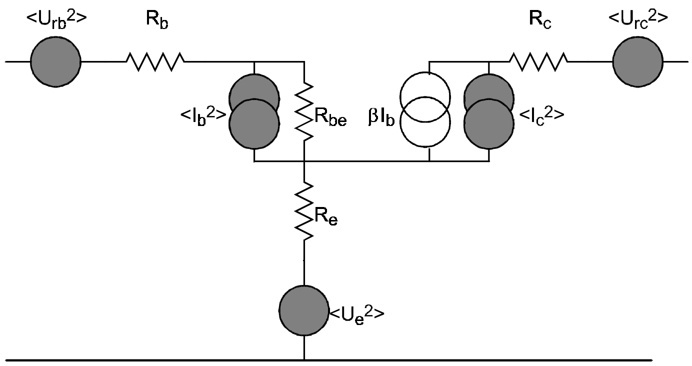


Fig. 1 Equivalent noise circuit of the HBT (reactive elements are neglected).

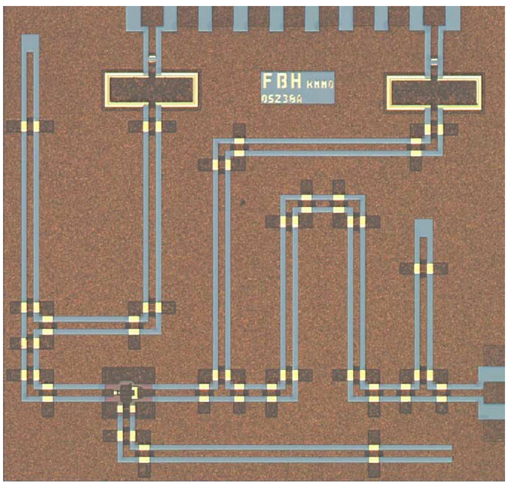
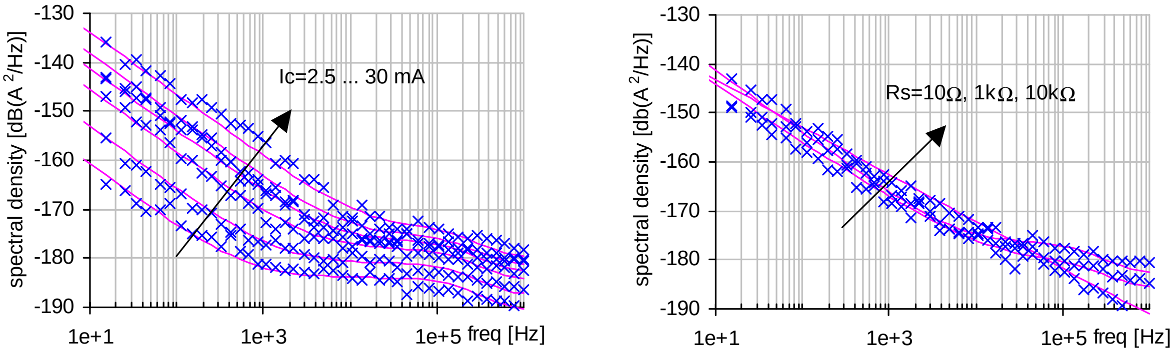


Fig. 2 Chip photo of the MMIC oscillator (size: 1.42 x 1.34 μm^2).



(a) (b)

Fig. 3 Measured (symbols) and modeled (lines) LF current-noise in dB(A^2/Hz) vs. frequency at the output of a 1x3x30 µm^2 HBT; (a) input resistance R_s=10 kΩ and collector current I_c as parameter; (b) collector current I_c=15 mA and source resistance R_s as parameter.

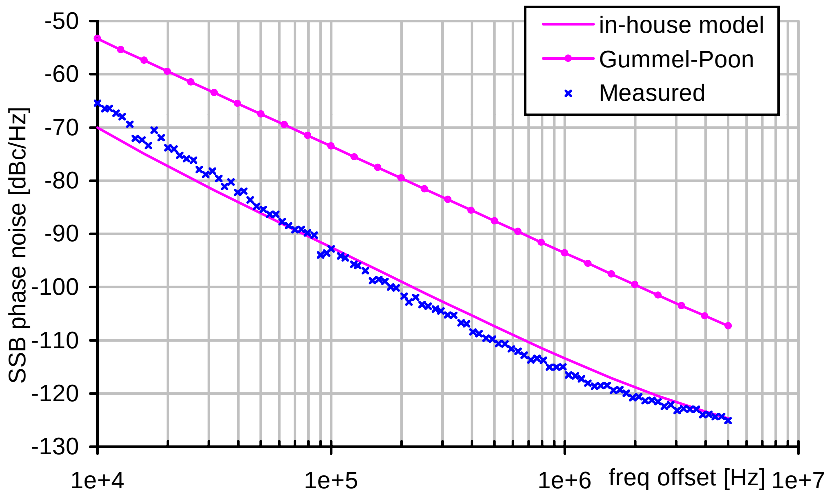


Fig. 4 Phase noise vs. frequency: measured (symbols) and modeled (lines) data using Gummel-Poon and in-house HBT model.

CPW model	HBT model	Simulation-tool	Output power [dBm]	Frequency [GHz]	Phase noise @ 100 kHz [dBc/Hz]
std.-CPW	in-house	ADS	2.475	35.15	-82.299
std.-CPW	GP	ADS	10.532	35.76	-89.333
in-house	in-house	ADS	2.435	35.05	-63.349
in-house	GP	ADS	10.91	35.82	-72.090
in-house	in-house	MDS	2.242	34.90	-92.540
in-house	GP	MDS	2.610	35.79	-82.541
in-house	GP	SERENADE	8.280	35.80	-82.950
measurements			0.3	35.1	-91

Tab. 1 Simulation results for Ka-band oscillator.