The Influence of Microwave Two-Port Noise on Residual Phase Noise in GaAs-HBTs

Matthias Rudolph, Peter Heymann

Ferdinand-Braun-Institut für Höchstfrequenztechnik (FBH)

Gustav-Kirchhoff-Str.4, D-12489 Berlin. Germany, Phone +4930 6392 2627

Abstract — **We present residual phase noise measurements of GaInP/GaAs HBTs, which are widely used as gain elements in microwave MMIC oscillators. These measurements allow to separate the influence of the noise sources on oscillator phase noise. It turns out that the microwave noise of the device near the oscillation frequency is an important source of phase noise for offset frequencies ≥ 100kHz. Simulation results based on a transistor noise-model show good agreement with experimental results.**

I. INTRODUCTION

With the realization of low phase-noise oscillators playing a key role in developing microwave systems, oscillator design has become the subject of growing interest. At mm-wave frequencies, however, phase-noise description in monolithic circuits is still not satisfactory. Hence, in this paper, the phase noise description based on residual phase-noise is extended to the GaAs-HBT.

Residual phase noise is the noise added to a signal of high purity while passing through a two port, e. g. an amplifier [1]. An oscillator, on the other hand, is a circuit consisting of an amplifier as the gain stage and a feedback loop. This concept is applicable also to reflection-type mm-wave oscillator MMICs, despite the feedback loop may not be visible at first glance [2]. Therefore, the same effect that increases the phase noise of a test signal passing through the gain stage will generate phase noise in an oscillator.

II. OSCILLATOR PHASE NOISE AND RESIDUAL PHASE NOISE

The phase-noise contributions of the gain stage consist of additive and multiplicative noise. Additive noise is the white microwave two-port noise of the amplifying device near the signal frequency f_0 which adds linearly to the signal. Multiplicative noise is generated by direct phase modulation of the signal. In the HBT case, e.g., the transit time of the transistor is modulated by the LF-noise with a 1/f spectral density. In the residual phase noise curves, these two noise spectra are reproduced with their original frequency dependence. In an oscillator, however, they are modified by a factor f^{-2} due to the resonant curve of the feedback stage.

From this, it becomes plausible that residual phase noise of the gain stage is the key feature to estimate the oscillator's phase noise. This is also one basic assumption of the Leeson approach [3]. So far, several authors have investigated the correlation between oscillator noise, LF-noise and residual phase noise for different technologies, e.g. for the GaAs PHEMT [4] and the SiGe HBT [5].

Microwave MMIC oscillators have a great potential as relatively low cost signal sources with low phase noise at offset frequencies f_m beyond 100 kHz. But they suffer from low quality resonators with loaded Q values below 20. Thus, the noise of the transistor as the active device in the gain stage becomes more important for overall phase noise. Experimental data show, however, that technologies (SiGe HBT, GaAs HBT) with low 1/f-noise which are obviously favorable for oscillator applications do not necessarily yield the desired result of excellent phase noise. Moreover, low phase noise oscillators have been demonstrated also with devices which exhibit much higher LF-noise levels (GaAs HEMT). The reason is that the two sources of oscillator phase noise, i.-e., multiplicative LF-noise and additive microwave noise contribute with different effectiveness. For example, using a device with low LF-noise it is of secondary importance to avoid upconversion of this noise, but it is essential to minimize the microwave noise by a circuit design that enables operation near minimum noise. On the other hand, devices with strong LF-noise like GaAs HEMTs which exhibit excellent microwave noise data must be optimized in a different way: Oscillator design must focus on preventing the upconversion of LF-noise because the microwave noise is low, anyway.

III. OSCILLATOR EXAMPLE

We present measurements of a 19 GHz MMIC oscillator to demonstrate experimentally these statements. A comparison of the phase noise spectra at two currents is shown in Fig.1. The slope of the *L(f)* – spectrum provides information about the noise sources. The slope f^{-3} originates from 1/f-baseband noise, f^{-2} from the microwave noise. At I_C = 75mA the spectrum *L(f)* exhibits clearly the two slopes: f^{-3} and f^{-2}. The overall phase noise is minimum and upconversion is strongly reduced. At I_C = 50mA upconversion is enhanced, the f^{-2} part ist completely covered by this effect.

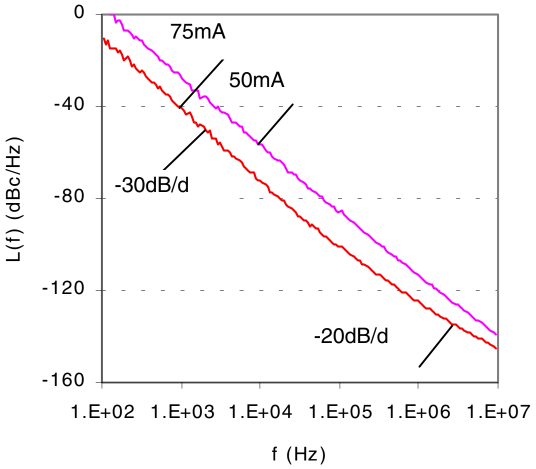

Figure 1: Measured phase noise spectrum of a 19 GHz MMIC oscillator at two collector bias currents. Minimum upconversion at I_C= 75mA, significant upconversion at I_C= 50mA.. The slope – 30dB/dec indicates 1/f-baseband noise, - 20dB/dec microwave noise.

Fig. 2 shows that the phase noise at f = 100 kHz offset strongly depends on the DC collector current I_C. The minimum level of $L \cong$ -100dBc at I_C = 75mA can be calculated from Leeson's formula with reasonable microwave noise parameters of the transistor at f_0= 19GHz. LF-noise upconversion is minimum at this current, because the mechanism of upconversion is weak. At other currents the upconversion of LF-noise is stronger and generates 20 dB more phase noise. The appearance of the minimum at 75 mA can be understood from the upconversion model [6]. It is derived from the oscillation condition: The oscillation frequency is determined by the phase relation of feedback and gain stage. The phase shift of the signal when passing through the gain stage depends on $\angle S_{21}$ of the transistor, which in turn depends on the collector current I_C. As a result of the 1/f–fluctuations of I_C, the phase fluctuates and accordingly the oscillation frequency. This is the source of phase noise with the typical f^{-3}-dependence. The shape of the curve $\angle S_{21}$ versus I_C determines the effectiveness of this process. It is well known for BJT and HBT that the transit time τ achieves a minimum with increasing I_C. As a consequence $\angle S_{21}$ exhibits a maximum. The derivative

$$\frac{\partial \angle S_{21}}{\partial I_C} = 0,$$

i. e. the upconversion of LF-noise, is strongly reduced. Current fluctuations and transit time fluctuations are decoupled [7].

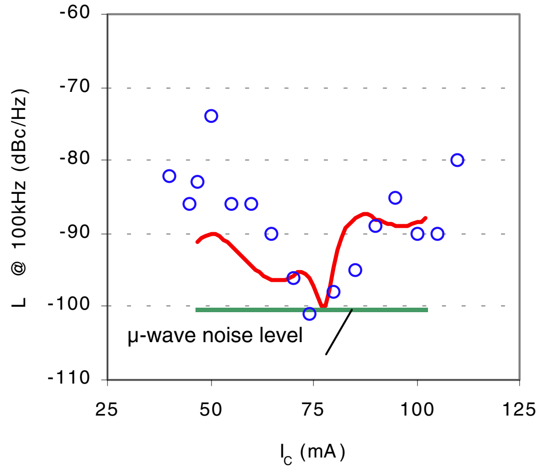

Figure 2: Phase noise at f=100 kHz of a 19 GHz MMIC oscillator. Gain element is a 2(3x30)μm^2 GaInP/GaAs HBT. Symbols = measurement. Thru Line = upconversion using Leeson's formula with the measured $\angle S_{21}$ (I_C) – curve, Noise floor = Leeson's formula with microwave noise only: F= 4; Q=18, G= 10dB; P_{OUT}= 13dBm

IV. LF-NOISE AND TWO-PORT MICROWAVE NOISE

Commonly, when characterizing a transistor for oscillator application, besides the nonlinear model parameters the LF-noise spectra are measured. Calculation of phase noise from these input data requires sophisticated Harmonic-Balance analysis and often there is a lack of understanding of the results [8]. A particularly weak point in this model are the assumptions as to the cyclostationary sources, i.e., the way how the large signal excitation shapes the spectrum of the LF noise sources.
Residual phase noise is closer to the oscillator reality because upconversion and noise addition are already included when the signal is analyzed. Moreover, separation of upconverted LF-noise and added microwave noise is possible. Phase noise generated by upconversion is multiplicative and, to a first approximation, does not depend on the carrier level. It corresponds to the 1/f part of the spectrum. The frequency independent part of the noise spectrum is added microwave noise with a constant power spectral density. Therefore, with increasing carrier power, the signal-to-noise ratio (dBc) increases, too. This criterion may be used to determine whether the added noise originate primarily from microwave noise, as was shown for SiGe HBTs in [5].

V. RESIDUAL PHASE-NOISE MEASUREMENTS

The experimental setup is a modified phase-noise measurement system with delay line. The study is carried out at 5 GHz, although the goal is to understand mm-wave oscillators. Such a high frequency, however, is difficult to manage and not necessary when studying basic effects. We use a 5 GHz, 16 dBm synthesizer

(FSIQ Rohde&Schwarz) as signal source. The reference signal is routed via a line stretcher to the LO-input of the phase detector. The DUT branch contains an attenuator, source impedance tuner, bias tees, wafer probes with the transistor (DUT) and a low-noise amplifier. An Agilent 70420A phase-noise test-set is used as phase detector. The signals from the two branches are adjusted in quadrature by means of the manual line stretcher. The detector constant for different power levels is determined by the ±DC peak sensitivity method [1].

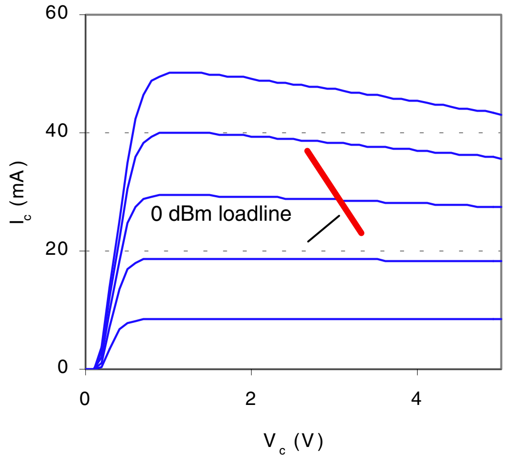

Figure 3: DC-output characteristic and 5GHz load-line of a 1x(3x30)μm^2 GaInP/GaAs HBT from the FBH 4" MMIC-process. The loadline indicates linear operation in a 50Ω environment..

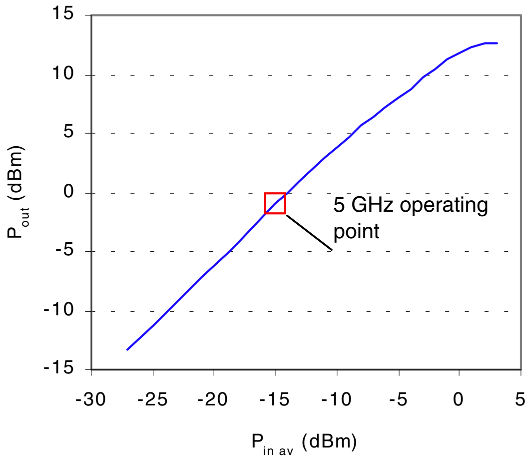

Figure 4: Power transfer curve of the DUT at f_0= 5GHz. The symbol indicates the operating point during residual phase noise measurement. $\Gamma_S \cong \Gamma_L \cong 0$

Transistor VI-characteristic, biasing and RF-power level can be seen from Figs. 3 and 4. There is no clipping of the loadline with harmonic generation; thus, the linear noise theory can be applied.

A typical spectrum and the noise floor of the system are shown in Fig. 5. Despite the disturbances for f < 1 kHz the 1/f and the white noise parts of the spectrum can be clearly distinguished. In the following, we focus on the white noise level for f > 100kHz, which, according to the previous considerations, is caused by microwave noise.

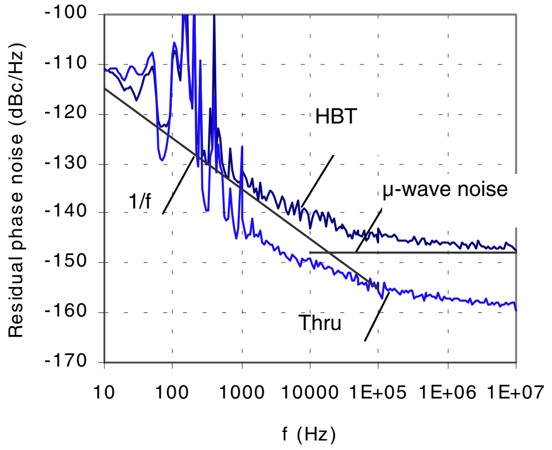

FIGURE 5: Residual phase noise spectrum of the 1x(3x30) HBT at bias conditions according to Figs. 3 and 4. Microwave noise level from (1) with F and G from transistor noise model (F_{50} = 5 dB; G_{50} = 13 dB).

VI. NOISE MODELING

The near-carrier noise power added to the carrier is calculated from the HBT noise model [9]. The DUT is a 1x(3x30) μm^2 HBT from the FBH 4" MMIC-process (f_T = 35 GHz; f_{max} = 80 GHz). The minimum noise figure at f_0 = 5 GHz is $F_{min} \cong$ 3dB and $F_{50} \cong$ 5dB. The normalized noise power at the output is given by:

$$RPN = 10 \times \log\left(\frac{kT_0 \; F \, G}{2P_C}\right) \tag{1}$$

The unit is dBc/Hz. P_C denotes the carrier power, F and G actual noise figure and gain of the device, respectively.

The calculated noise power agrees with the measured RPN (see Fig. 5). The noise power calculated from this linear model is relevant because the device operates in linear regime. Oscillator operation, however, is a typical nonlinear one and a higher noise figure is to be expected due to mixing processes. In this case a nonlinear noise figure must be used, as has been demonstrated in [5]. The microwave noise is added to the carrier. Thus, with increasing carrier power the normalized noise power, i.e. the residual phase noise, decreases. This is shown in Fig. 6. The measured RPN at f_m = 1 MHz follows the calculated values from (1). Even at the highest output power, the device operates in a linear state because the 1dB compression point is around +12 dBm.

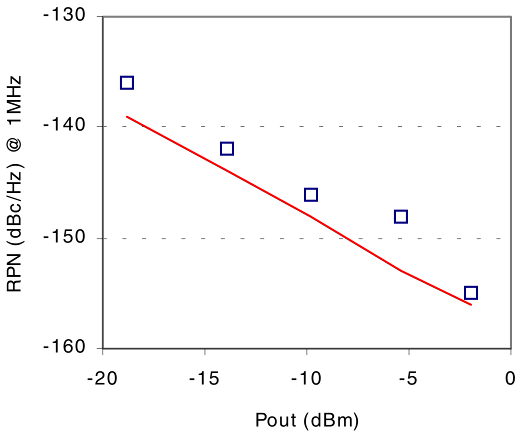

Figure 6: Residual phase noise level at 1 MHz offset versus carrier power. The P^{-1}-slope indicates additive noise, i. e. origin is the microwave noise near the 5 GHz carrier. Simulation according to [9].

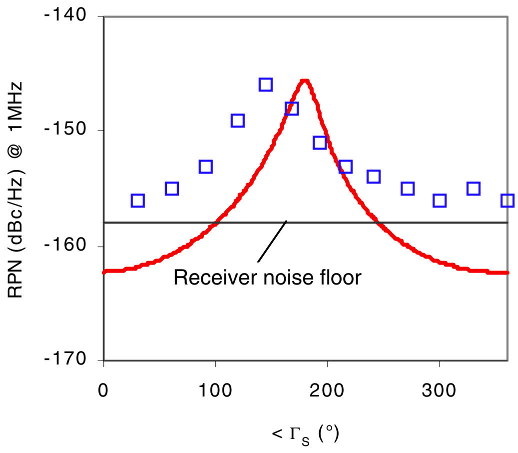

Figure 7: Residual phase noise at f_m = 1 MHz when varying the phase of the source reflection coefficient Γ_S with $|\Gamma_S| \cong 0.8$; simulation according to (1) with F and G from the transistor model; F varies between 5.8 and 12.3 dB, G between 5.6 and 16 dB; the horizontal line indicates the system noise floor.

The source impedance tuner allows to perform source pulling as known from transistor noise-measurements. This is found to cause strong variations of the actual noise figure and gain at 5 GHz. We emulate the impedance presented to the transistor input in a reflection oscillator, typical for microwave oscillator MMICs. The applied source reflection coefficient is $|\Gamma| \cong 0.8$ with the possible phase covering the full range. The result is shown in Fig. 7. The behavior can be reproduced by assuming that microwave noise near the carrier is dominating the phase noise. For calculation the model transistor is loaded by Γ_S = 0.8 and all phases and Γ_L =0. This leads to a strong increase of noise power at the output for $\angle \Gamma_S \cong 180°$.

VII. CONCLUSION

Residual phase-noise measurements of a GaInP/GaAs HBT are performed, which is a device typical for the gain stage of microwave monolithic oscillators. The measurements rely on conditions very close to those under realistic oscillator operation and thus should reveal the contributions of the different noise sources to phase noise. The experimental data indicates that microwave noise near the frequency of oscillation contributes to the phase noise spectrum at offset frequencies above 100 kHz. The level of this contribution can exceed the upconverted LF-noise for proper bias current. The current dependence of superposition of upconverted LF-noise and microwave noise has been demonstrated.

ACKNOWLEDGEMENT

The authors would like to thank J. Hilsenbeck, F. Lenk and M.Schott for providing the devices and oscillators, and W. Heinrich for encouragement and helpful discussions.

REFERENCES

1 T.R. Faulkner and R.E. Temple, „Residual phase noise and AM noise measurements and techniques.“ HP Application Note 1990.

2 F. Lenk, M. Schott, J. Hilsenbeck, and W. Heinrich, „Optimizing MMIC reflection-type oscillators“ , IEEE MTT-S Dig. 2004, TH2A-6.

3 D.B.Leeson, „A simple model of feedback oscillator noise spectrum“, Proc. IEEE, (1966), pp.329-330.

4 O. Llopis, J.B. Juraver, B. Tamen, F. Danneville, M. Chaubet, A. Cappy, and J. Graffeuil, „Nonlinear noise modeling of a PHEMT device through residual phase noise and low frequency noise measurements.“ in IEEE MTT-S Dig. 2001, pp. 831-834.

5 G. Cibiel, L. Escotte, and O. Llopis, „A study of the correlation between high-frequency noise and phase noise in low-noise silicon-based transistors.“ IEEE Trans. MTT, Vol. 52, 2004, pp.183-190.

6 X.Zhang, D.Sturzebecher, A.S.Daryoush, „Comparison of the phase noise performance of HEMT and HBT based oscillators.“ IEEE MTT-S Digest, (1995), pp.697-700.

7 P. Heymann, “Low phase noise monolithic oscillators using GaInP/GaAs HBT-technology.” IEEE MTT-S Workshop Proc. WSI, (2003).

8 F.Lenk, M.Schott, W.Heinrich, „Modeling and measurement of phase noise in GaAs HBT Ka-band oscillators.“ Proc. EuMC (2001), Vol.1, pp. 181-184.

9 M.Rudolph, R.Doerner, L.Klapproth, P.Heymann, „An HBT noise model up to transit frequency.“ IEEE EDL 20, (1999), pp.24-26.