Ultra low phase noise SiGe HBT
Application to a C band sapphire resonator oscillator

G. Cibiel, M. Régis*, O. Llopis, Y. Kersalé**,
V.Giordano**, H. Lafontaine*, R. Plana, M. Chaubet***

LAAS-CNRS, 7 Avenue du Colonel Roche - 31077 Toulouse - France
* SiGe Semiconductor, 2680 Queensview Drive - Ottawa ON K2B 8J9 – Canada
** LPMO-CNRS, 32 av. de l'Observatoire - 25044 Besançon – France
*** CNES, 18 av. Edouard Belin - 31401 Toulouse – France

Abstract — **In this paper, the electrical and noise performance of a 0.8 µm Silicon Germanium (SiGe) transistor optimized for the design of low phase noise circuits are described. The nonlinear model developed for the transistor and its use for the design of low phase noise C band Sapphire resonator oscillator are reported. The best measured phase noise (at ambient temperature) is –133 dBc/Hz at 1 kHz offset from a 4.85 GHz carrier frequency for a loaded Q_L factor of 60,000.**

INTRODUCTION

The design of low phase noise microwave sources is, today, one of the major challenge in telecommunication applications. The spectral purity of this module is driven by the low frequency noise of the active device through up-conversion processes. It is well known that SiGe bipolar transistors are good candidates for low phase noise generation [1-3]. Typically, a phase noise improvement of 10 dB or more can be observed close to the carrier (10 kHz offset) on a SiGe HBT Dielectric Resonator Oscillator (DRO) compared to a GaAs FET DRO [4].

In this paper, an overview of the noise performance of a SiGe HBT technology is proposed and its impact on the performance of a microwave source phase noise is shown. The SiGe HBT technology is presented in Section I, followed by the corresponding phase noise performance in Section II. Then, Section III is dedicated to the device nonlinear modeling. Finally, Section IV and V describe the application of the SiGe HBT for the design of a C band Sapphire resonator oscillator featuring state of the art phase noise performance.

I - SIGE HBT TECHNOLOGY DESCRIPTION

The transistor is constructed using UHV-CVD epitaxial base technology wherein the internal SiGe base is contacted by extending the epitaxial deposition over field oxide. Effectively, the same contiguous epitaxial layer facilitates base contact on field oxide and thereby allows a reduction in the base-collector junction by shrinking the device well. In this manner, high F_T and F_{max} are achieved. Table 1 summarizes the key technical specifications of the technology. This device has been especially developed for low phase noise applications. Its equivalent input low-frequency (LF) voltage noise spectral density at I_c=10 mA and V_{ce}=2 V is plotted in Figure 1. We observe 0.4 nV/Hz$^{1/2}$ at 10 kHz offset frequency and the 1/f corner frequency is lower than 1 kHz.

Emitter width	0.8 µm
BV_{CEo}	> 4.2 V
BV_{CBo}	> 14 V
F_t*	35 GHz
F_{max}*	> 35 GHz
R_b*	< 500(Ω.µm)

Table 1 : Technical specifications of the SiGe technology
(*V_{CE} = 2V, J_c = 1mA/µm²)

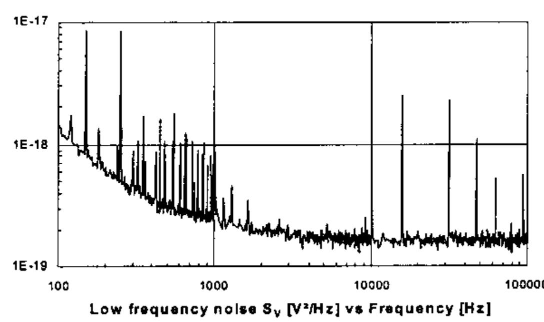

Figure 1: Input low frequency voltage noise spectral density (HBT bias :I_c=10 mA and V_{ce}=2 V)

II. SIGE HBT PHASE NOISE BEHAVIOR

The LF noise characteristics does not give any information on the LF noise to phase noise conversion process. To this purpose, a residual phase noise

0-7803-7239-5/02/$10.00 © 2002 IEEE

measurement bench is used. The open loop phase noise (or residual phase noise) is, indeed, an efficient parameter to evaluate the suitability of a given device for signal generation.

In order to characterize the phase noise of a SiGe HBT, some special techniques must be implemented due to the low noise levels that have to be measured. We use a cross-correlation technique [5], which is based on a cross spectrum measurement on two identical mixers. It allows a substantial improvement of the experiment noise floor by eliminating the uncorrelated noise contributions of the two mixers. But the phase detector noise is not the only challenge in this experimental setup. The source noise can also be a limiting element of the measurement. Its phase noise is theoretically suppressed with a good balance between the two phase detectors arms (no electrical delay). However the rejection of its amplitude noise (AM noise) is more difficult. There are two ways in which this noise can be detected. Firstly, by using an imperfectly balanced mixer or, secondly, in a direct manner by the device under test in non-linear regime. We have proposed some solutions to these two problems previously [6] and we are able to demonstrate a noise floor, represented in Figure 2, of −180 dBrad/Hz at 10 kHz offset.

To attain a high performance with the HBT devices, it is necessary to minimize the effect of the base-emitter current noise source. Previous works have shown that this can be realized with a high value capacitance on the base-emitter junction [2,7]. Figure 4 illustrates the effect of the bias network on the residual phase noise of the SiGe HBT.

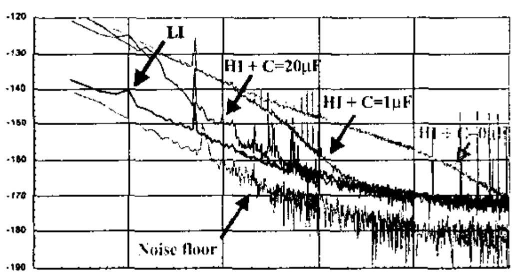

Figure 2 : Open loop phase noise of the SiGe device with different bias network configurations and open loop phase noise floor at P_{IN}(3.5 GHz)=0 dBm (FFT analyzer averaging : 200).

The possible bias network configurations are : low impedance (LI) and high impedance bias network (HI) with different capacitance's value in parallel on the emitter-base junction. The best performance is achieved with the low impedance bias network. The transistor is biased at I_C=10 mA and V_{CE}=2 V. This biasing point corresponds to the optimum measured phase noise.

Considering the excellent residual phase noise level of this transistor, -171 dBrad/Hz at 10 kHz offset and −143 dBrad/Hz at 10 Hz, a very low phase noise oscillator can be designed with this device. However, it is of strong interest to firstly develop a non-linear modeling of the HBT, in order to be able to optimize the oscillator design.

III. SiGe HBT Non-Linear Modeling

The non linear model is based on the SPICE Gummel-Poon model. The transistor high frequency characteristics are taken into account with external resistances and capacitances. The linear validation of this model is shown in Figure 3 where the S-parameters are compared with simulation results. A good correspondence is achieved up to 20 GHz between measured and simulated results. Then, the output power versus the input power sweep is used for the large signal model validation. A good agreement is found, in Figure 4, between the measured and simulated results for the fundamental frequency and the second harmonic.

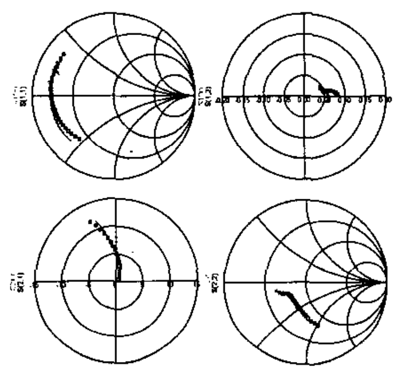

Figure 3 : Comparison between simulated (-) and measured (-) S-parameters from 1 to 20 GHz.

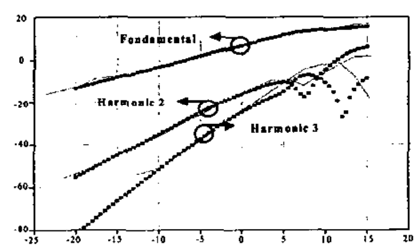

Figure 4 : Comparison between simulated (-) and measured (-) output power versus input power at 3.5 GHz (HBT bias : I_c=10 mA, V_{CE}=2 V).

IV. APPLICATION : SAPPHIRE/SIGE OSCILLATOR

This SiGe HBT device has been used to design a high purity spectral microwave source, dedicated to metrology applications. The goal was to realize a source better than the best quartz based oscillators, in order to lock this source on a cesium clock with a minimum degradation of the time stability of the atomic reference. This work is part of the PHARAO program leaded by the French national space agency (CNES).

The oscillator configuration is based on a parallel feedback topology. The resonator is a monocrystalline sapphire rod used on a 5th order Whispering Gallery Mode (WGM) resonance at 4.85 GHz. The measured unloaded Q_o factor of the resonator is about 290,000. In the first experiment, the transistor bias has been raised to 25 mA in order to get a sufficient gain performance. The total losses in the loop are close to 6 dB, and the loaded Q_L factor of the resonator is about 60,000.

Because the expected performance of the oscillator was much beyond the best available microwave synthesized reference sources, a two oscillators measurement has been performed. Therefore, two identical sapphire/SiGe oscillators have been realized at 4.866 GHz and 4.849 GHz. Their output signal is mixed to generate a 17 MHz beat frequency which is compared to a reference synthesizer (HP8662A) used at 170 MHz and divided by 10 in order to improve its phase noise performance at 17 MHz. The measured phase noise spectrum is plotted in Figure 5.

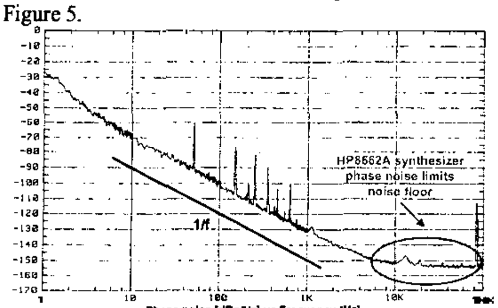

Figure 5: Single sideband phase noise of the 17 MHz beat signal between the two Sapphire / SiGe HBT microwave oscillators (4.866 GHz and 4.849 GHz)

Above 10 kHz offset frequency the observed spectrum is related to the synthesizer phase noise. Under 10 Hz offset frequency, the increase of the noise may be due to a thermal instability. The phase noise of a single 4.85 GHz oscillator can be estimated by subtracting 3dB to this curve. The measured phase noise at 1 kHz is therefore –133 dBc/Hz and by extrapolation close to –160 dBc/Hz at 10 kHz offset. This observed performance is close to state-of-the-art [8] and is compared in Figure 6 versus other published low phase noise oscillators. Some RF quartz sources are shown in this figure. The result that could be obtained at microwave frequencies by multiplying these quartz sources is shown by dotted lines (with the assumption of no additive multiplier noise). It shows that the measured performance of our oscillator corresponds to the best single loop microwave oscillator at ambient temperature. The only other comparable source is the Sapphire-Interferometric oscillator previously reported in [9]. This oscillator, however, makes use of a complex noise cancellation circuit, which requires a fairly high volume and which may be difficult to tune.

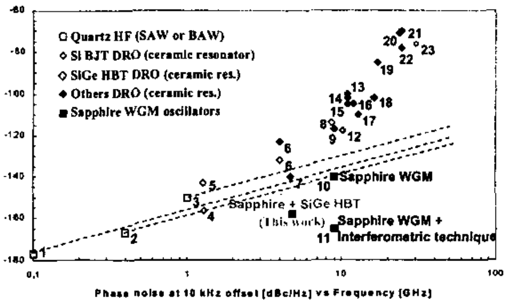

Figure 6: Phase noise comparison at 10 kHz offset with other state-of-the-art oscillators (Reference in Table 2).

1. 100 MHz oscillator, WENZEL, *commercial product*
2. 400 MHz oscillator, Z. Galani, IEEE-MTT Workshop, 1994
3. 1 GHz SAW oscillator, SAWTEK, *commercial product*
4. 1.28 GHz BJT DRO, E. C. Niehenke and P.A. Green, IEEE-MTT S, 1987
5. 1.3 GHz BJT DRO, W. J. Tansky, IEEE Int. Freq. Control Symp 1994
6. 4 GHz FET and Si BJT DRO, M. Régis and al., IEEE trans. on MTT, oct. 1998
7. 4.7 GHz SiGe HBT DRO, M. Llopis and al., IEEE-UFFC S, 2000
8. 8.73 GHz Si BJT DRO, R. Jones and V. Estrick, IEEE Freq. Control Symp, 1990
9. 9 GHz FET DRO, Mizan et al., IEEE-MTT S. Digest, *(loaded Q > 10000)*, 1991
10. 9 GHz WGM sapphire oscillator, Tobar et al., IEEE MGW Lett., april 1995
11. 9 GHz WGM sapphire oscillator, Ivanov et al., IEEE MGW Lett., sept. 1996
12. 10.2 GHz SiGe HBT DRO, M. Régis and al., IEEE-UFFC S, 1998
13. 11 GHz HBT DRO, Tutt et al., IEEE trans. on MTT, 1995
14. 11 GHz HBT DRO, Khatibzadeh, Electron. Lett., 1990
15. 11 GHz FET DRO, EuMC, 1983
16. 12 GHz FET DRO, Graffeuil and al., 1/f Noise Conference, 1983
17. 12,9 GHz SiGe HBT DRO, M. Régis and al., Microwave Journal, October 2001
18. 16.2 GHz FET DRO, Uzawa, IEEE-MTT S, 1991
19. 17 GHz HEMT DRO, K. Kamozaki, IEEE-MTT S, 1992
20. 23.9 GHz HEMT DRO, OMEGA TECH, *commercial product*
21. 24.8 GHz FET DRO, Ogawa et al., Electron Lett., aug. 1990
22. 24.8 GHz HBT DRO, Ogawa et al., Electron Lett., aug. 1990
23. 30.35 GHz FET DRO, Uzawa, IEEE-MTT S, 1991

Table 2: References used in the performance comparison.

V. ULTRA LOW PHASE NOISE SIGE AMPLIFIER DESIGN

Although already comparable with the state-of-the-art, we believe that this result can be improved using a CAD approach and the model presented in Section III. Therefore, a new SiGe amplifier has been designed and optimized for low residual phase noise and sufficient gain performance for this application. The circuit, its phase noise and gain performance are shown, respectively, in Figure 7, 8, 9.

Compared to the amplifier used in the first experiment, this amplifier is operated at lower bias point (I_c=10 mA) where the residual phase noise performance has been found to be improved. A small signal gain performance of 7.1 dB, together with a phase noise of −171 dBrad/Hz at 10 kHz offset have been measured. This preliminary result allows us to estimate that the next Sapphire-SiGe oscillator phase noise will be improved of better than 5 dB compare to the previous one.

. CONCLUSION

The great potential of SiGe HBT devices for low phase noise microwave oscillators has been demonstrated. Both the result achieved for the transistor and the oscillator are quite comparable to the best reported in the literature. Furthermore, the 4.85 GHz Sapphire-SiGe oscillator, is to our knowledge, the best published phase noise result for a single loop microwave oscillator at ambient temperature. Moreover, the transistor non-linear modeling has allowed the design of new SiGe amplifier with optimized characteristics. This amplifier will be soon used in the Sapphire oscillator and this new result will be presented at the conference.

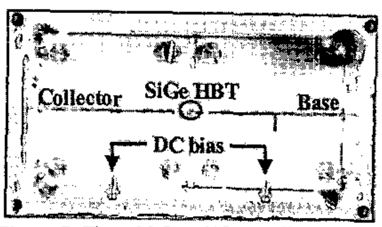

Figure 7: The 4.85 GHz SiGe amplifier circuit.

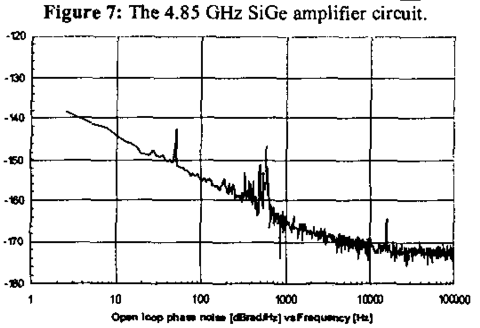

Figure 8 : Open loop phase noise at P_{IN}(3.5 GHz)=0 dB of the amplifier (FFT analyzer averaging : 200).

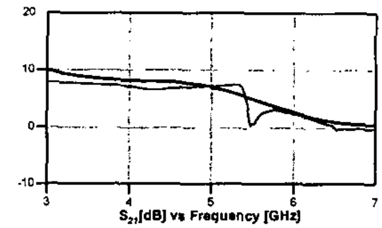

Figure 9 : Comparison between simulated (-) and measured (-) S_{21} magnitudes of the 4.85 GHz amplifier.

ACKNOWLEDGEMENT

The authors wish to acknowledge SiGe Semiconductor for providing the SiGe devices, the CNES (French National Space Agency) for its constant support on phase noise investigations and J. Rayssac from the LAAS-CNRS for his technical help.

REFERENCES

[1] A. Grhule, et al, "Low phase noise 10 GHz DRO with low 1/f noise SiGe HBTs," *28th European Microwave Conf.*, Amsterdam, pp. 391-394, Oct. 1998.

[2] M. Régis, et al, "Ultra low phase noise C and X band bipolar transistor dielectric resonator oscillators," *Proc. of the IEEE int. Freq. Contr. Symposium*, Passadena, pp. 507-511, May 1998.

[3] J. F. Luy, et al, "Si/SiGe MMIC technology," *IEEE MTT Symposium Digest*, pp. 1755-1757, 1994.

[4] Short Course on "Low Phase Noise Oscillators," *European Microwave Week*, 1999 and 2000.

[5] F. L. Walls, et al, "Design considerations in state-of-the-art signal processing and phase noise measurement systems," *Proc. of the IEEE Int. Freq. Contr. Symposium*, pp. 269-274, 1976.

[6] G. Cibiel, et al, "AM noise impact in low level phase noise measurements," *to be published in IEEE Trans. on Ultrason. Ferroelect. and Freq. Control.*

[7] O. Llopis, et al, "Evaluation of two non-standard techniques for the phase noise characterization at microwave frequencies," *Proc. of the IEEE Int. Freq. Contr. Symposium*, Kansas city, pp. 511-515, June 2000.

[8] O. Llopis, et al, "Ultra-low phase noise sapphire - SiGe HBT oscillator", *submitted to IEEE Microwave and Wireless Components Letters*.

[9] E. N. Ivanov, et al, "Ultra-low noise microwave oscillator with advanced phase noise suppression system", *IEEE Microwave and Guided Wave Letters*, vol. 6, no. 9, pp. 312-314, September 1996.