Comparison of Additive Noise of DAC Technologies for Low Noise Microwave Frequency Synthesizers

Jean-marc LESAGE, Jean-François PENN
DGA – Information Superiority
DGA French MoD
Bruz, France
Email: jean-marc.lesage@intradef.gouv.fr

***Abstract*— In this article are compared different high speed DAC (Digital to Analog Converter) standing for different technologies (CMOS, finFET, Bipolar SiGe). The additive noise of each DAC has been accurately measured, without any contribution of the clock source. These new measurements give a piece of information on the intrinsic noise of each technology. Then the DAC that shows the lowest noise is chosen in order to build an up-converted direct frequency synthesizer. Thanks to the measured improvement of the additive phase noise of high speed DAC, state-of-the-art high frequency local oscillator has to be chosen in order to reach a very low phase noise agile X-band frequency synthesizer.**

***Keywords*— additive noise, high speed DAC, phase noise, amplitude noise;**

I. Introduction

Electronic warfare sub-systems always need wider frequency band agile synthesizer. This one must also show low noise and low spurious level. One can design indirect frequency synthesizer as phase locked loop (PLL) but it is difficult to reach in the same time fine frequency resolution and low spurious level. Moreover, there is a limitation of phase noise by the phase detector in the loop band of the PLL.

We have shown in [1] that combining ULN (Ultra Low Noise) high frequency local oscillator (LO) and one available high speed DAC (Digital to Analog Converter) let us to achieve state-of-the-art frequency synthesizer, outperforming then current established limits.

Recently, a lot of high speed DAC appeared on the market with improved noise performances. All these DAC have been designed in different kind of technology: bipolar silicon-germanium (SiGe), RF CMOS, Fin FET, FDSOI…The question is which one is the best one in order to be used in the proposed simple up-converted direct frequency synthesizer.

Thanks to the availability of new high performance phase noise analyser, absolute phase noise measurement can be achieved but it is difficult to discriminate intrinsic noise of the DAC from the noise coming from the high frequency clock. A simple and efficient measurement method has been set up in order to obtain additive phase and amplitude noise of DAC under test.

Four different high speed DAC have been measured with this test bench in order to choose the best one for build a direct up-converted synthesizer [2]. Moreover, as a DAC is a combination of basic transistors, this kind of additive noise measurement gives a piece of information about the overall performance of used technology.

In the last part are shown the results of the best DAC implemented in the direct up-converted synthesizer [2] and the on the high frequency local oscillator choice is discussed.

II. Comparison of Additive Phase Noise of DAC

A. Additive noise testbench

Fig. 1 shows the test bench for additive amplitude or phase noise measurement. Two more DAC in addition of the DAC under test are used in order to provide the local oscillator of the microwave I&Q mixer of the test bench. The signal coming from the DAC under test is divided in two signals in order to drive the RF input signal of the mixer. Then, the I&Q outputs of the mixer are the digitized thanks to analog-digital architecture. So, the clock jitter induced noise is rejected by the mixer phase quadrature but it is also necessary to use a low noise clock in order to reduce it enough below the measured DAC noise level.

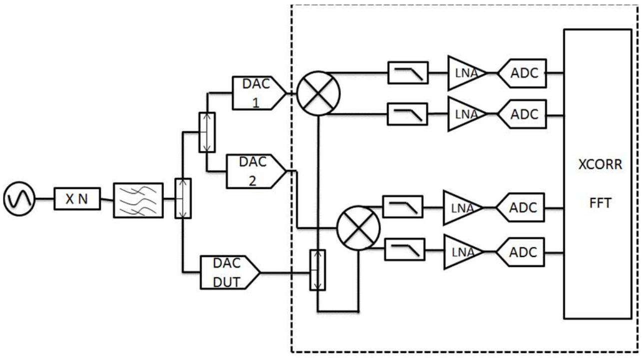

Fig. 1. Scheme of the additive noise test bench

Then, the cross-correlation FFT (Fast Fourrier Transform) allow to removing the noise coming from the two other DAC and from the different amplifiers that can be used. If the three

DAC show quite the same level of noise, the respective noise of the two DAC which play the role of reference (DAC1 and DAC2) can be totally removed in increasing the number of correlation. So, it is possible to measure strictly the additive or residual noise of DAC under test. Moreover, the flexible digital architecture let us to obtain simultaneously amplitude and/or phase noise.

B. DAC Additive phase noise comparison

In this article are compared four different DAC. Two are designed with CMOS foundry with different grid size (28 nm and 65 nm). Other one uses silicon-germanium bipolar foundry. The last uses FinFET technology. As mentioned in part I, the clock frequency is the same for the four measurements and is about 5 GHz.

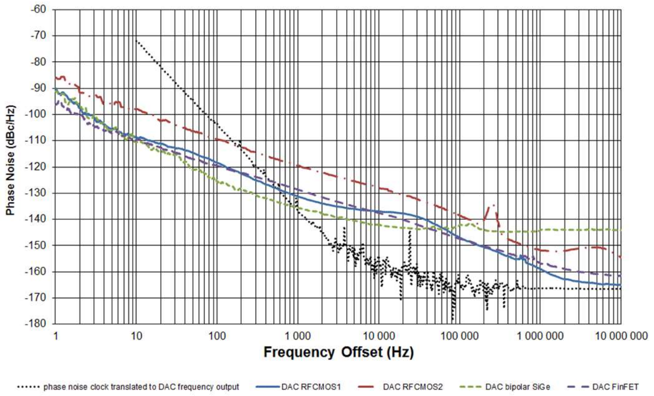

Fig. 2. Comparison of the DAC additive phase noise at Fmax

Fig.2 shows the comparison of the additive phase noise of the four DAC at the maximum frequency (fmax) used in the direct up-converted synthesizer [2].

Concerning the close-to-the carrier additive phase noise, the best is the bipolar SiGe DAC but the RF CMOS1 and FinFET DAC show a phase noise level very closed to the bipolar DAC. The close-to-the carrier phase noise of the RF CMOS2 DAC is the worst among the four DAC. There is a 10 dB difference up to 30 kHz between the two close-to-the-carrier noise of the two DAC in RF CMOS1 technology, whose the grid size is different.

Concerning the additive phase noise floor, the best one is the RFCMOS1 and the worst is the bipolar SiGe one. The difference between the noise floor of each tested DAC could not be explained by quantization noise and thermal noise. These kind of noise are estimated at much lower level than the measured one. Moreover, as shown in Fig 3 for the RFCMOS1 DAC, we measured an output frequency dependency of the additive phase noise level. But there is no dependency of the clock frequency .The same behavior is measured for the four tested DAC. As quantization and thermal noise are theoretically not depending to the DAC frequency output, the measured additive phase noise is clearly a technical noise, giving a piece of information about the technology. The DAC technical additive noise follows a frequency output dependency law in 20 log M, with M the ratio between tested output frequencies.

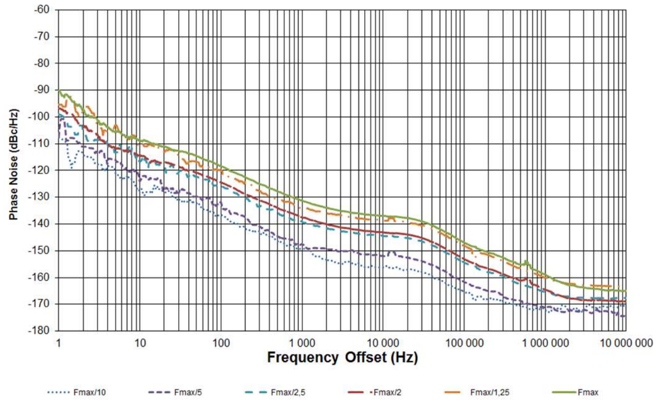

Fig. 3. Comparison of the DAC RFCMOS1 additive phase noise versus output frequency

Finally, in order to build the frequency synthesis, the DAC that shows the best compromise between close-to-the-carrier and floor phase noise is the RFCMOS1. But we have to keep in mind that the DAC FinFET is not so far from the best one.

C. DAC amplitude noise comparison

Thanks to the flexible architecture of the test bench, we can easily measure amplitude noise at the same time as phase noise. As shown in the previous section, the DAC additive phase noise has been hugely improved recently, so it becomes important to look after the amplitude noise.

Fig.4 shows the comparison of the amplitude noise of the four DAC at the maximum frequency (fmax) used in the direct up-converted synthesizer [2]. At first, we measure that there is no difference between additive or absolute DAC amplitude noise. Actually, the DAC amplitude noise is not related to the amplitude clock noise. Contrary to the phase noise, the amplitude noise doesn't show no more frequency dependency than the power attenuation caused by sinc (x) roll-off, with x the ratio between output frequency and DAC clock frequency. No more than 1 dB output power attenuation over the tested frequency span (between Fmax/10 and Fmax) is measured. So the amplitude noise is not considered as frequency dependent and only amplitude noise at Fmax is shown.

Concerning the comparison between the different DAC, the lower close-to-the-carrier amplitude noise is obtained with the bipolar SiGe DAC, like for phase noise. Its amplitude noise is also lower than its phase noise for the chosen minimum DAC output frequency for the synthesizer. The FinFET DAC shows the highest amplitude noise which is 10 dB higher than its additive phase noise at the chosen maximum DAC output frequency (fmax) and it can be bothering. The amplitude noise could be reduced using an amplifier in power saturation after the DAC but this is not always possible. It is difficult to choose a low enough additive phase noise amplifier and especially if current consumption can't be too much increased. Concerning the two RF CMOS DAC, their additive phase noises are not close to their additive phase noises at minimum DAC output frequency for the synthesizer.

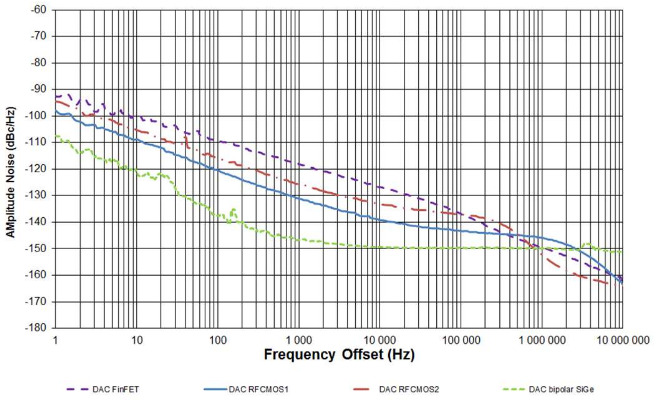

Fig. 4. Comparison of the DAC additive amplitude noise at Fmax

As a conclusion, bipolar SiGe transistor stays the technology with the lowest close-to-the-carrier or 1/f noise (phase and amplitude) but DAC in other technologies are not so far from bipolar SiGe, contrary to all expectation. Nevertheless, the SiGe DAC is not chosen for the synthesizer because its technical noise floor is far from the best one (RF CMOS1). RF CMOS2 DAC is not selected because it shows the worst phase noise. Then, FinFET DAC is not chosen although it shows a very low phase noise level but it shows the worst amplitude noise. Finally, RF CMOS1 DAC is chosen for a new demonstration of state-of-the-art direct up-converted X-band synthesizer because it shows the best additive phase noise floor and nearly the best close-to-the-carrier additive phase noise. But, its amplitude noise is a little bit upper than the additive phase noise at 1 MHz frequency offset and one has to deal with because of the AM/PM conversion in the synthesis scheme (mixer or amplifiers).

III. PERFORMANCE OF THE PROPOSED X-BAND SYNTHESIS

Fig.5 reminds the scheme of the direct up-converted frequency synthesis [2] and Fig. 6 shows the absolute phase noise output synthesizer measurement for the maximum DAC output frequency which is the minimum synthesis output frequency.

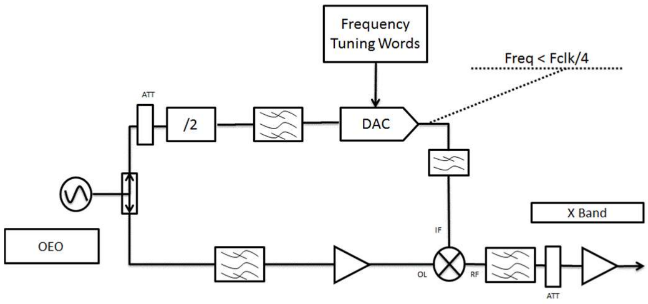

Fig. 5. X-Band synthesis scheme

As we used in this new demonstration a DAC with a best phase noise floor than in [2], the local oscillator noise floor becomes now the most important contributor of the frequency synthesizer. We compare the phase noise results when using a frequency multiplied oscillator (for example state of the art OCSO) [3] and an OEO (Opto-Electronic Oscillator) [4], which is direct high frequency oscillator. As shown in Fig. 7, the best phase noise floor of a direct high frequency oscillator (OEO) gives the best synthesizer phase noise floor.

As demonstrated in [2], this is also the local oscillator that limits the close-to-the-carrier phase noise. Henceforth, there is no more contribution of the DAC phase noise in the frequency synthesis phase noise than in the 10 kHz to 100 kHz offset frequency range.

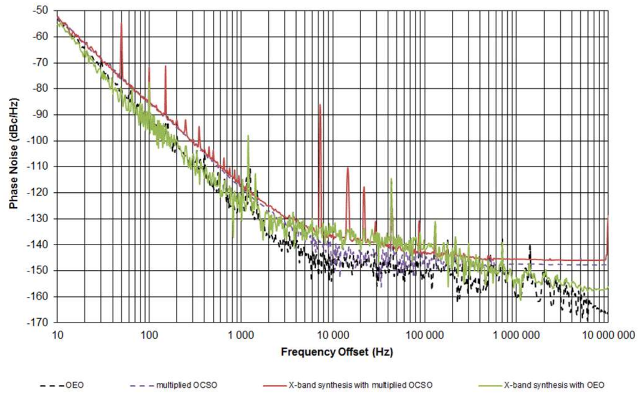

Fig. 6. X-Band synthesis phase noise at the maximum DAC frequency

As a conclusion, thanks to the phase noise floor improvement of high speed DAC, low noise high frequency local oscillator has to be used in order to reach the lowest phase noise level. As demonstrated in II.c, amplitude noise has to be taken in consideration. As there is a little contribution of DAC amplitude noise at 1 MHz frequency offset, we reduce it in using and output amplifier in slight power saturation as shown in Fig.7 so that the amplitude noise becomes reduced at the same level than phase noise.

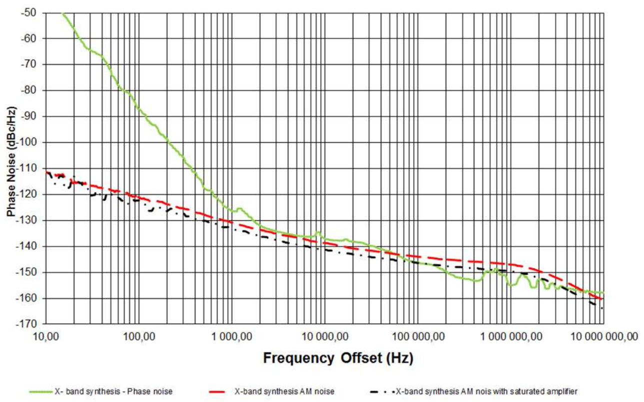

Fig. 7. X-Band synthesis phase and amplitude noise at the maximum DAC frequency

IV. Conclusion

In this article has been presented a comparison between the additive phase noise of high speed DAC designed in different technologies. New DAC in RFCMOS technology shows a 1/f noise very closed to the bipolar one, that still shows the best 1/f additive phase noise. The RFCMOS high speed DAC is even chosen to build an X-band direct up-converted frequency synthesis because its additive phase noise floor is very low. Henceforth, a low phase noise high frequency local oscillator has to be used in order to reach the lowest frequency synthesis phase noise level. OEO is well dedicated for new high frequency low noise synthesized. Finally, one has to deal with amplitude noise that can be reduced under the phase noise level for example with output amplifier in power saturation.

References

[1] Wideband, low noise and low spurious agile direct frequency synthesis based on combination of SAW Oscillator and high speed DAC, Jean-Marc LESAGE, Adrien CAPAINE, Jean-François PENN, Guy JESTIN, EFTF 2014

[2] Wideband and low phase noise up-converted direct frequency synthesis using high speed DAC and Oscillator, Jean-Marc LESAGE, Jean-François PENN, IFCS-EFTF 2017

[3] http://www.rakon.com/products/families

[4] Danny Eliyahu, David Seidel, and Lute Maleki , "Phase Noise of a High Performance OEO and an Ultra Low Noise Floor Cross-Correlation Microwave Photonic Homodyne System", OEwaves Inc, IEEE International Frequency Control 2008