A test set-up for the analysis of multi-tone intermodulation in microwave devices

J.P Teyssier(1), J. Sombrin(2), R. Quéré(1), S. Laurent(1), F. Gizard(3)

(1)XLIM-CNRS-University of Limoges, France,

(2) LABEX-ΣLim University of Limoges, France,

(3)CNES Toulouse, France

Abstract — This paper proposes a multi-tone signal pattern designed for accurate and easy measurements of nonlinear devices linearity factors of merit. The stimulus signal we propose ensures that DUT's third order intermodulation products won't overlap. Thus, the relative phases of source tones do not affect the amplitudes of intermodulation products. The usual metrics for linearity factors, ACPR (Adjacent Channel Power Ratio) or NPR (Noise Power Ratio), can be acquired with a greater accuracy only with amplitude measurements. This work has been carried out with a sampler-based receiver, using FFT (Fast Fourier Transform) filtering for tone separation.

Index Terms — ACPR, Linearity factor, Multi-tone, Nonlinear devices, NPR.

I. INTRODUCTION

Multi-tone intermodulation (IM) analysis still represents a challenge for linearity assessment of microwave devices, notably when they are fed by complex modulated signals, like those involved in Orthogonal Frequency Division Multiplexing (OFDM) systems. Investigations on efficient stimulus signals for linearity tests have been made for a while [1]. In OFDM case it is interesting to separate the IM products from injected frequencies. Many attempts have been made to draw formula from multi-tone signals constituted of a number of equally spaced frequencies [2]. However the separation of the different IM products which appear at the same frequencies is only possible for well-known nonlinearities. Recently it has been proposed [3] to generate a frequency pattern which allows separating all the IM products of third order (IM3) both from the injected signals and the different IM3 products themselves.

This paper describes a measurement set up that allows to generate a signal with this tone frequency pattern and to measure accurately the different IM products both in amplitude and phase. Moreover the four channels system allows performing network measurements on wafer for microwave transistors. Then it will be possible to evaluate the impact of low frequency memory effects on the linearity of transistors and to improve their models.

II. THE INPUT SIGNAL

Generally the input signal is constituted of n equally spaced frequency tones such as the kth frequency is given by:

$$f_k = f_1 + (k-1)\Delta f \qquad 1 \leq k \leq n \tag{1}$$

We make use of random phases; f_1 is the first microwave frequency; and Δf can be adjusted depending of the number n of frequencies and the bandwidth. Intermodulation products can be measured directly if their frequencies are different from carrier frequencies, e.g. in a notch for NPR or outside the signal bandwidth for ACPR. They can also be computed from correlation of input and output signals. In both cases, a large number of random throws of carrier phases must be performed to achieve correct values of the intermodulation ratio after averaging the results of the different throws because the standard deviation on each measurement is quite high.

We propose a set of frequencies chosen such as the kth frequency is given by:

$$f_k = f_1 + (k-1)\Delta f + \varepsilon_k \qquad 1 \leq k \leq n \tag{2}$$

The frequency shift ε_k is small, so that all the IM3 products appear at frequencies that are different from each other and also different from carrier frequencies. The separation frequency Δf as well as the frequency shifts $\varepsilon_k = n_k \varepsilon$ are integer multiples of a base frequency ε. This ε frequency is the Fourier transform grid tone spacing of the measurement system, so that an exact Fourier Transform without any windowing (i.e. no amplitude error) can be performed on the signal to be measured. Moreover those frequency shifts are chosen as small as possible to keep some compatibility with classical signal and to keep the size of the Fourier Transform reasonable. An example of a three-tone signal is given in table I, we show the RF frequency column, together with the relevant IM3 products; our list of n_k for this example is {0, 9 and 27}. We get 9 IM3 frequencies for such a three-tone signal. We propose different measurement columns, depending on the source power setting. The more we increase the source power, the more the RF amplifier is nonlinear and produces intermodulation products.

TABLE I

FREQUENCY TABLE FOR 3 STIMULUS FREQUENCIES, $\varepsilon = 976.6625\ Hz$, FFT SIZE = 131072

Carrier type	$RF\ frequency$	Meas 1, -10 dBm	Meas 2, +6 dBm	Meas 3, +13 dBm	Meas 4, +16 dBm	Meas 5, +16 dBm, pre-distortion
f_1	2002500000.000	-25.2	-9.25	-2.33	+0.64	+0.64
f_2	2002776367.188	-25.4	-9.28	-2.36	+0.61	+0.61
f_3	2003237304.688	-25.5	-9.33	-2.40	+0.56	+0.56
$2f_i - f_j$	2002223632.813	-84.3	-79.2	-63.4	-54.9	-74.4
$2f_i - f_j$	2001762695.313	-82.5	-79.5	-63.2	-54.8	-74.9
$2f_i - f_j$	2003052734.375	-83.7	-81.8	-64.4	-56.2	-70.9
$2f_i - f_j$	2002315429.688	-85.5	-79.6	-62.6	-54.7	-71.9
$2f_i - f_j$	2003974609.375	-84.2	-81.8	-64.5	-56.1	-68.8
$2f_i - f_j$	2003698242.188	-81.5	-79.1	-64.7	-56.3	-70.0
$f_i + f_j - f_k$	2002039062.500	-86.0	-82.3	-57.1	-49.1	-66.9
$f_i + f_j - f_k$	2002960937.500	-84.3	-82.1	-58.2	-49.9	-65.7
$f_i + f_j - f_k$	2003513671.875	-81.9	-81.4	-58.7	-50.3	-64.0
Fig of merit		+63.4	+68.2	+58.5	+53.2	+68.9

If we move to an 8-stimulus tone signal, we end up with 224 RF frequencies; this is still compatible with our hardware. It has been shown by [3] that with 8 stimulus tones, the signal statistics in terms of spectral density and peak to average are almost perfect (like a continuous spectrum signal). Another result from our experiments: the figure of merit we get is not sensitive to the phase of the stimulus frequencies. There is a good reason for that: there is no addition of tones anywhere. The figure of merit is derived from the ratio of IM3 power over the stimulus frequencies power.

III. THE TEST SET-UP

The test set-up consists in a AWG (Arbitrary Wave Generator) RF source with IQ modulation capabilities, a sampler-based NVNA (we are proposing here VTD/Agilent SWAP results. We have checked we achieve the same results with HP/Maury LSNA). We are using the pretty flat IF bandwidth of the SWAP (10 MHz IF bandwidth) and its one-shot acquisition capability to get, thanks to an inverse fast Fourier transform, all the frequencies of interest amplitudes and relative phases information from a single large ADC record.

This approach is suitable for 50 Ohm matched devices or real transistors with an impedance tuning system in a network approach.

For the purpose of this summary, our nonlinear DUT is the power amplifier of the AWG source, when we increase the output power, we get more and more power at IM3 products (see table 1, meas. 1 to 4 columns). Obviously, next step consists in measuring an external amplifier. With the network capability of the system, we can measure simultaneously the input and output of the DUT. We can compensate for the AWG nonlinearities with a pre-distortion algorithm (see below).

For meas1, the amplifier is driven to provide -10 dBm, the IM3 frequencies are in the floor noise of the system. Meas2 gives the best figure of merit, as we can see the stimulus frequencies have higher amplitudes but the IM3 products are still in the vicinity of the noise level. When we reach 13 dBm, the power amplifier is clearly in nonlinear mode. We get an expected result: the f1+f2-f3 products are 6 dB higher than 2f1-f2 products. At 16 dBm, the 6 dB law is not so well respected. It means we just begin to have IM5 products popping up. This is illustrated in fig. 2 that shows the measured spectrum. One can notice the 3 stimulus tones, the 9 IM3 products, 3 of them are -49dBm and 6 of them are 6 dB below. The first IM5 products are roughly at -61dBm.

We have to note here that some nonlinear effects can come from the receiver part of the system if we drive the receivers in the vicinity of their compression. We have checked for that to avoid such an issue. Adding a fixed wideband attenuator at the receiver input lets us know if the IM3 products popping up are coming from the DUT or the receiver system.

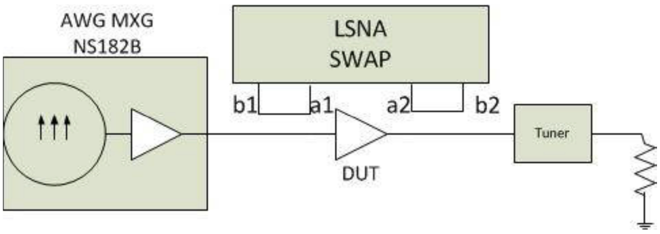

Fig. 1. Measurement set-up with sampler-based receiver.

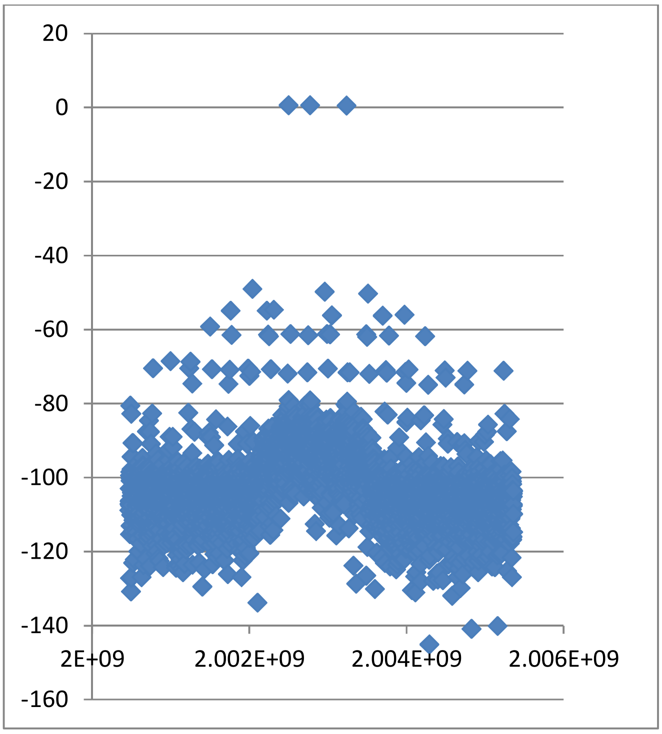

Fig. 2. Measure 4, source set to +16dBm, no pre-distortion.

IV. DIGITAL PRE-DISTORTION

As the generated multi-tone signal is fed through an amplifier, at high power levels this amplifier generates its own IM products. To minimize the input IM products it is necessary to make as perfect as possible the multi-tone generator. This is done by an optimization process where the digital I/Q data sent to the AWG are updated after measurement by the set-up. This pre-distortion is computed from measured amplitudes and calculated phases in the plane of the I/Q generator.

The last column of the table I shows the results we get when driving the amplifier at 16 dBm, with a pre-distortion signal applied at IM3 product frequencies. We have optimized the amplitudes and the phases of 9 small additive tones at the 9 IM3 frequencies, and added these tones inside the AWG.

We can notice that the figure of merit has increased from 53.2 to 68.9 dBs. We show here that we can compensate for a large part of the RF source power amplifier nonlinear effects. This result shows we can pre-calibrate a measurement setup to make it mostly linear, even for high power measurements.

V. CONCLUSION, PERSPECTIVES

We are proposing a new way to get a linearity figure of merit. This approach gives results very consistent with ACPR or NPR measurements. It gives results consistent with EVM measurements of modulated signals too. Our approach is a very good compromise between 2-tone IM3, that is too sensitive to the tone spacing, and real signals that are very complex and require complex stimulus, acquisition and demodulation procedures to get a figure of merit. Our approach is easier to generate and easier to measure than a real modulated signal, it is less sensitive to relative phases of stimulus signal. With a careful choice of $n_k\varepsilon$ values, and 8 stimulus frequencies, it is possible to get a very good coverage of all the low frequency memory effects.

In order to improve our measurement quality, we will need to apply an IF (Intermediate Frequency) calibration.

We think this work paves the way for a better and more general definition of linearity factor for RF active devices.

REFERENCES

[1] M. Begue, “Testing new Digital RF Communications with Smart Stimulus and Analysis”, Hewlett-Packard Tech note, 1995

[2] N.B. De Carvalho, “On the use of multitone techniques for assessing RF components intermodulation distortion”, IEEE trans. On MTT, vol 47, n12, 1999

[3] J. Sombrin, “Future test benches for the optimization of spectrum and energy efficiency in telecom nonlinear RF components and amplifiers”, ARFTG Invited talk, Montreal, 2012