Very small duty cycles for pulsed time domain transistor characterization

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Abstract – This paper deals with an innovative approach for pulsed measurements, particularly suited for RF time domain transistor characterization. This approach avoids the loss of dynamic range induced by classical methods when the duty cycle decreases. The application of this principle with a LSNA is shown; an additional board has been added into the LSNA to manage all the necessary triggers and clocks. Results are shown with a HEMT AlGaN/GaN, duty cycles up to 0.0001 are demonstrated with 1 μs pulse durations.

Index Terms – Duty cycle, Dynamic range, LSNA, Pulsed measurements, RF transistor, Time domain measurements.

I. Introduction

RF designers need to have complete information about operating conditions of their transistors, particularly when they are used in the saturation region. They can today simulate time domain slopes in their RF software, and particularly load lines, to preview the behavior of the transistors. So, there is an interest in comparing simulations against measurements. It means to be able to measure directly absolute amplitudes and phases relations for a wide number of the harmonic frequencies at both accesses of a microwave transistor [1]. For high harmonic range, the power is very small compared to the power at the fundamental frequency, so keeping the dynamic range of the measurement system is a challenge. Measurement setups which are based on a MTA or a LSNA [2,3] can acquire this type of information, but today the dynamic range of these systems is lower than up-to-date VNAs.

Moreover, working on pulsed conditions is really interesting for RF transistor characterization [4,5]. This excitation mode can be used to identify thermal and traps effects, or to explore the transistor limits [6,7]. So it is a key point to be able to perform time domain measurements in various pulsed modes, e.g. for a wide choice of duty cycles and pulse widths.

This paper presents results of the time domain approach for measuring RF slopes in pulsed mode. A wide domain of duty cycles is explored, up to 0.0001, while keeping all the measurement system dynamic range, even for short pulse widths. This principle has been applied with a LSNA measuring an AlGaN/GaN HEMT.

II. Different measurement methods under pulsed conditions

There are two main different approaches for pulsed mode measurements: the "frequency domain" approach (FDA) and the "time domain" one (TDA).

A) Frequency domain approach

The FDA is very classical and used in a lot of microwaves labs. Two methods are used: measurement of one filtered frequency and wideband measurements [8,9].

Measuring data at only one center frequency implies an inherent dynamic range loss linked to duty cycle. It gives the well known equation (1), where α is the duty cycle, and Δdyn the dynamic range loss.

$$\Delta \mathrm{dyn} = 20 \log(\alpha) \tag{1}$$

Consequently, the noise floor of the measurement system is strongly degraded with the FDA when α decreases. Up-to-date VNAs have very good noise floors, so they can handle pulsed measurements at relatively small duty cycles.

But for time domain measurements, with a LSNA, the following example gives the dynamic loss in this configuration:

Example:	output power (f0) = 20 dBm;
	Dynamic range (CW) = 60 dB;
	$\alpha = 1\,\%$.
Conclusion:	Noise floor ($\alpha = 1\,\%$) = 0 dBm

If the power at a harmonic frequency is lower than 0 dBm, it can not be measured by the system in this pulse configuration, even if in it was possible in CW mode.

The second frequency method consists in a wideband measurement. The dynamic losses still exist because all the frequency lines can not be acquired by the receiver. These losses are lower than the first frequency method; however an important disadvantage is that a minimum pulse width is required, often several microseconds.

But in the context of RF transistor time domain characterization, pulsed measurements have to be performed with enough dynamic range to acquire amplitude and phase of a maximum of harmonic frequencies, for a wide range of duty cycles, and with short pulse widths, typically lower or equal than 1 μs.

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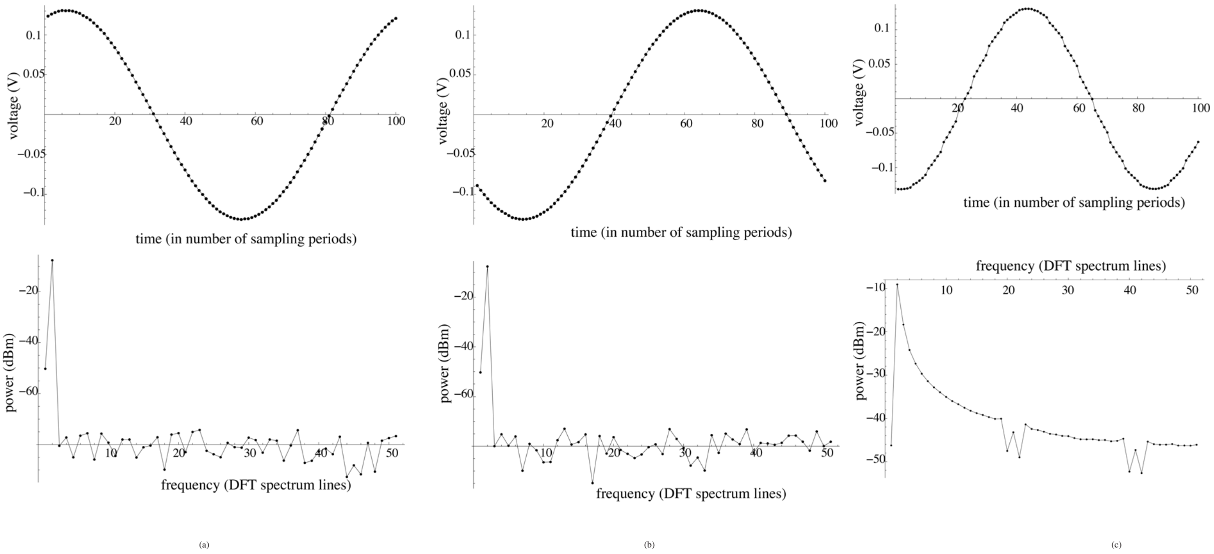

Fig. 1. (a) ADC sampling result with the TDA. 1 period between two acquisitions. (b) ADC sampling result with the TDS. 100 periods between two acquisitions. (c) ADC sampling result with the TDA. 100 periods between two acquisitions and something wrong.

B) Time domain approach

The principle of the TDA was described in [10,11]. It is based on a progressive acquisition of all the points of the signal. Inside every pulse, a defined number of samples is stored, and put together with the precedent ones. This principle is like the stroboscope approach, because the ADC trigger is lightly shifted compared to the observed frequency. The computation of all the related frequencies of the system – ADC sampling, ADC trigger, intermediate frequency from the LSNA – is a key point, to be sure of the phase coherence between the sample groups.

This method implies the acquisition time directly depends on the duty cycle but it has in theory no consequence on the dynamic of the considered system. Another important point is that the TDA needs a common reference for the trigger of the ADCs and for the RF receiver.

III. Time domain approach integration into LSNA

A) Verification of the time domain approach with the ADCs

A preliminary test to evaluate the time domain approach in the LSNA is to check the dynamic range of the ADCs. If all the frequencies computation is well done, no dynamic loss should appear even for very low duty cycles in pulsed mode.

An appropriate test is to sample a CW 100 kHz signal with the ADCs at a sampling frequency at 10 MHz. The ADCs are in pulsed mode, with the TDA, so a trigger at a precise frequency has to be furnished.

Three main points in this kind of integration are to be considered: first the trigger frequency has to be locked to a reference frequency, typically a 10 MHz signal; second the trigger frequency is obtained by a division of the ADC sampling frequency; third, the delay between two sample groups is an integer of the IF period.

The quality of TDA can be checked by a long acquisition of the IF signal: the needed acquisition time depends on duty cycle. So a problem in ADCs settings or triggers could be found by looking at the measured Discrete Fourier Transform spectrum lines. If the TDA is available, time and frequency measurement results have to be the same for a wide choice of duty cycles.

Three different configurations will be showed:

- 5 samples in each period, delay of one period between two sampling triggers;
- 5 samples in each period, delay of one hundred periods between two sampling triggers.
- 5 samples in each period, 100 periods delay and something wrong was introduced in the trigger settings: the ADC sampling frequency was divided by 10106 instead of 10105 to give the trigger frequency.

The Fig. 1 shows the result in the time and frequency domains for each configuration described above.

- Fig. 1a: one period delay;
- Fig. 1b: 100 periods delay;
- Fig. 1c: something wrong

No phase problem in time slopes appears when the duty cycle decreases; it is confirmed with frequency spectra, where no unexpected line appears.

These results are very well suited for microwaves. The ADCs dynamic range becomes independent of the duty cycle choice. It means that a receiver like a LSNA, which has a smaller dynamic range than up-to-date VNAs, can be used with the capabilities of the CW mode. Moreover, it is easy to check the trigger settings computation by looking at the spectrum lines.

B) The “Pulse Controller Board” associated to the LSNA

The measurement setup is based on a LSNA. A dedicated digital board has been created to generate all the triggers we need to work in pulsed mode [12]. The principle is to use a very precise frequency synthesizer (called FracN) to drive the acquisition triggers and all the others devices which need a trigger: oscilloscope, RF source, pulse generators. The Fig. 2 shows the main links between the devices to work in pulsed mode.

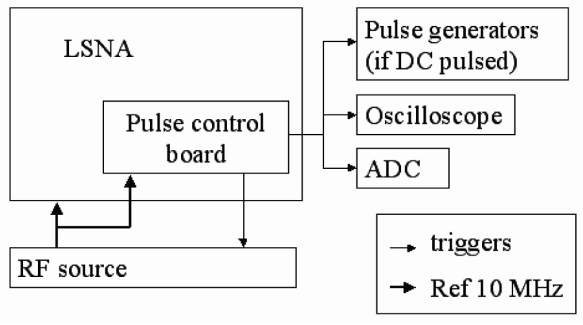

Fig. 2. Clocks and triggers management.

IV. Application to RF transistor measurement

Pulsed LSNA measurements with the TDA approach are now measuring the time domain slopes acquisition at both ports of a microwave power transistor. In fact, when the transistor is in the saturation region, the power levels at harmonic frequencies are increasing, and their precise measurements are required for accessing complete time domain waveforms. The goal is to take benefit of all the pulsed LSNA dynamic range for a wide choice of duty cycles [13].

Measurements are performed on an AlGaN/GaN HEMT processed by Alcatel-Thales III-V Labs ($4 \times 100 \times 0.25\,\mu\mathrm{m}^2$). The fundamental frequency is 3 GHz and four other harmonics have been taken into account. The RF was in pulsed or CW mode. To only look at the measurement approach, the bias is in continuous mode ($Vgs = -4.5$ V, $Vds = 20$ V, class AB). The load impedances presented here are not the optimal ones either for output power or PAE. The Fig. 3 shows results obtained with the RF input power in pulsed mode; the load impedance is $(200-j.5)\Omega$. This sweep of input power at this load impedance on the Fig. 3 shows that the saturation region is reached, slopes are really non linear.

The measurement of amplitude and phase at harmonic frequencies can be compared for different pulsed configurations.

The different pulse configurations for the RF excitation are given below:

- $1\,\mu\mathrm{s} - 12\,\mu\mathrm{s}$;
- $1\,\mu\mathrm{s} - 100\,\mu\mathrm{s}$;
- $1\,\mu\mathrm{s} - 1000\,\mu\mathrm{s}$;
- $1\,\mu\mathrm{s} - 10000\,\mu\mathrm{s}$.

The duty cycle is decreasing up to 0.0001 (0.01 %). The first mean to check up the TDA is to measure amplitudes at fundamental and harmonic frequencies

for each duty cycle. The Fig. 4 gives the measured power at several frequencies – f0 (4a), 3f0 (4b), and 5f0 (4c) – for the same sweep of input power.

The conclusion of this figure is that the dynamic range of the LSNA is unchanged even if the duty cycle reaches 0.0001 (0.01%). For the 5f0 case, for an input power lower than 12 dBm, the LSNA is measuring the noise floor, according to its dynamic range of around 60 dB. For upper input powers, duty cycle has no influence on measurement capabilities.

To compare with FDA measurements capabilities of a LSNA, with a dynamic range of 60 dB, a good example is the RF HEMT measured just before, with an output power of around:

- 32 dBm at f0;
- 20 dBm at 3f0;
- 10 dBm at 5f0.

The Tab. 1 gives the capability – yes or no – of measuring information at these frequencies with the FDA – and eq. (1) – and with this dynamic range, for the given four duty cycles.

The conclusion of this table is that amplitude at 5f0 can not be measured in this example with a FDA system; however the TDA approach keeps this capability.

The second mean to verify the TDA is to look at the load lines. In fact, to build a load line, the system needs of course amplitudes, but the phase information too. The Fig. 5 shows different load lines, with one line corresponding to one duty cycle, at the same load impedance and at a given power gain compression.

This figure proves that the TDA can provide correct amplitude and phase information for a high number of harmonic frequencies. The unchanged dynamic range is validated both from these two kinds of measurements.

V. Conclusion

This paper has presented a powerful approach for pulsed measurements in the context of time domain characterization of microwave transistors. This method is based on a progressive acquisition of samples, in way. The so-called TDA allows for keeping all the dynamic range of the measurement system, even for very small duty cycles, proved here up to 0.0001 and a pulse width of $1\,\mu\mathrm{s}$.

This principle has been applied with a LSNA. The key point to perform pulsed time domain measurements is to manage many coherent triggers and clocks, in order to synchronize RF power, ADCs acquisition, oscilloscope and pulse bias generators. A dedicated electronic board has been created and added to the LSNA.

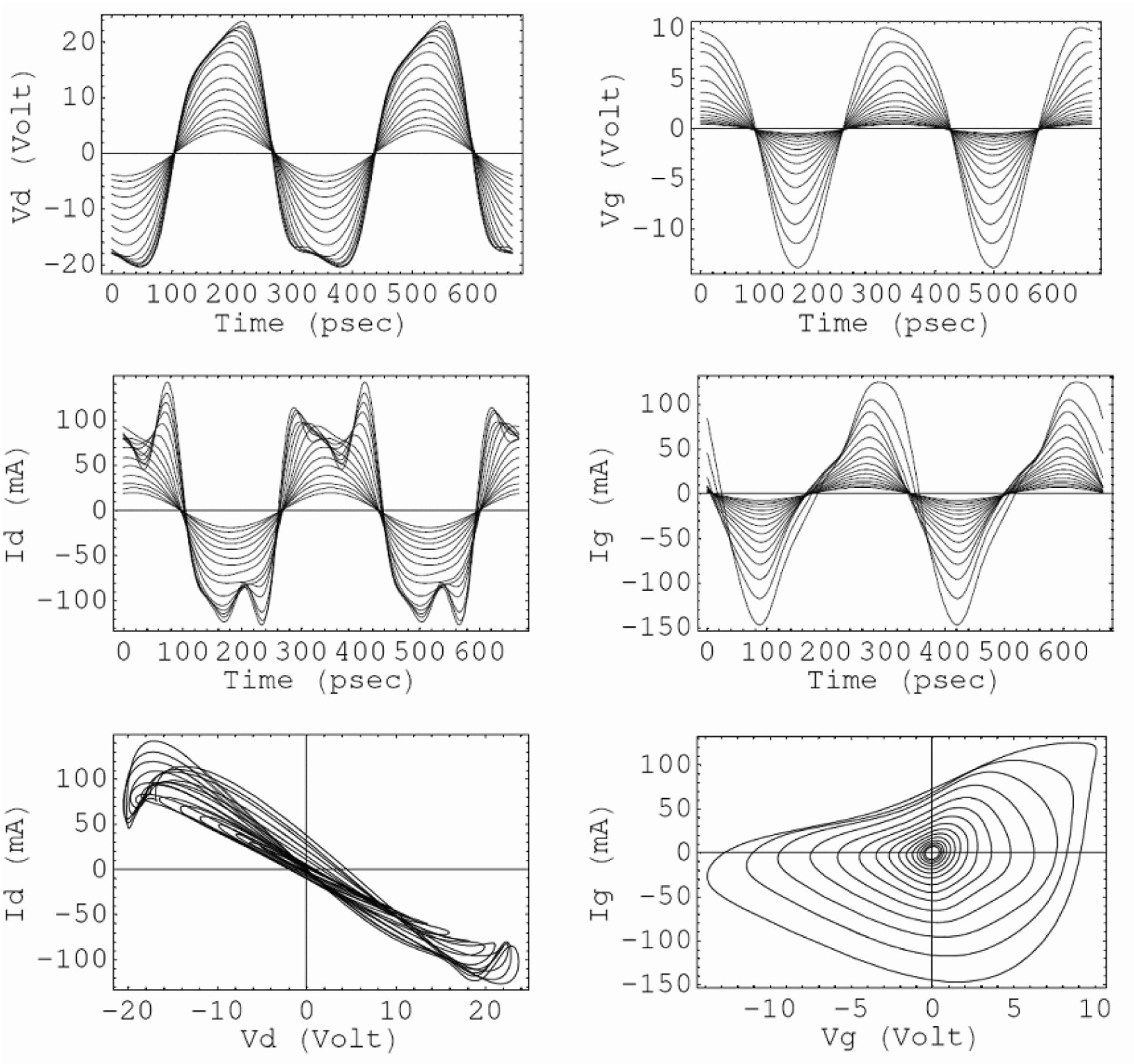

Fig. 3. Time domain slopes in pulsed mode 1 µs/10 µs for a sweep of input powers.

Tab. 1. Simulation of harmonic frequencies measurement capabilities using the FDA.
Output power at f0: 32 dBm ; at 3f0: 20 dBm and 5f0: 10 dBm. Dynamic range : 60 dB

α	Available dynamic range (dB)	Noise floor (dBm)	F0	3F0	5F0
1	60	-30	Yes	Yes	Yes
0.1	40	-10	Yes	Yes	Yes
0.01	20	10	Yes	Yes	?
0.001	0	30	Yes	No	No
0.0001	?	?	No	No	No

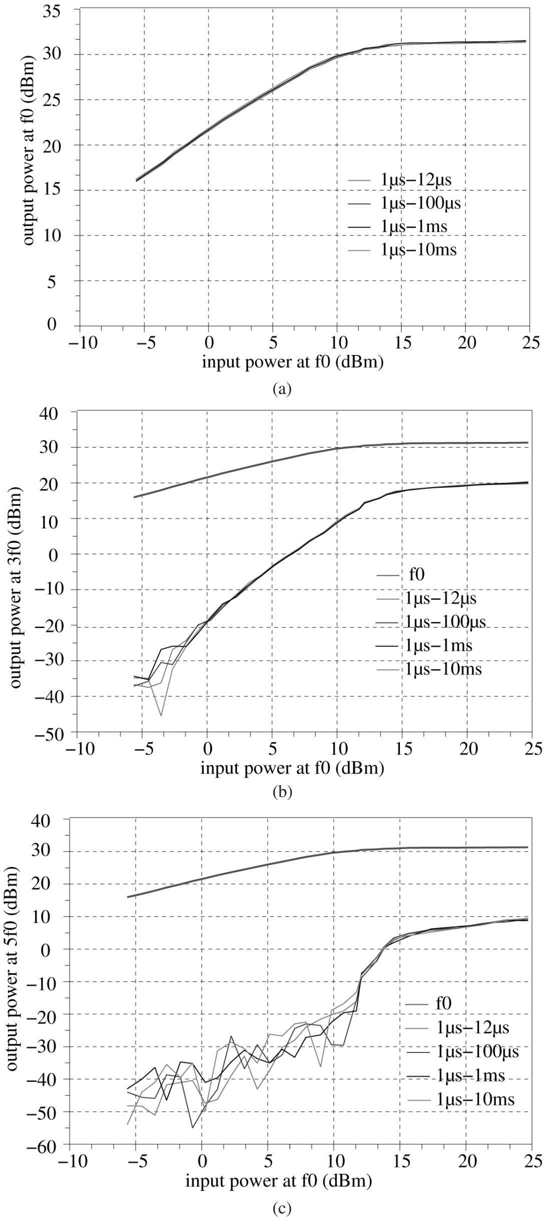

Fig. 4.(a) Output power at f0 for different duty cycles. (b) Output power at f0 and 3f0 for different duty cycles. (c) Output power at f0 and 5f0 for different duty cycles.

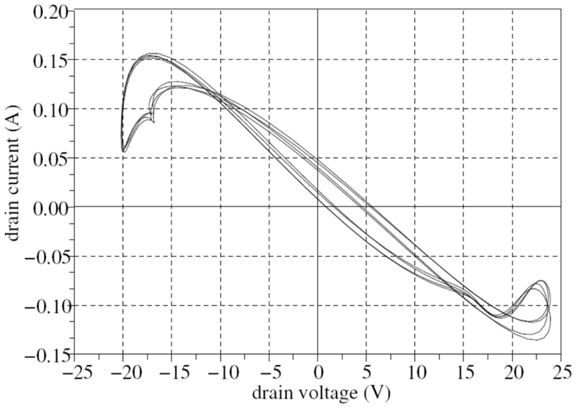

Fig. 5. Five load lines corresponding to the five chosen duty cycles at a given power gain compression.

The new kind of measurements now available with our system provides extremely valuable data for RF engineers, many investigations are now possible: dynamical study of thermal behavior, of traps; reliability and dynamical breakdown measurements.

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