New Trends in Characterization and Modeling of High Power Devices

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Abstract — *In this paper, we present some non exhaustive measurement techniques used for characterization and modeling of high power devices. Capabilities offered by pulsed measurements can be an efficient approach to deal with self-heating effects and sometimes trapping effects encountered in microwave high power devices. Pulsed techniques allow to separate self-heating and trapping effects, making like this the modeling process easier. A pulsed RF and pulsed bias load-pull system is then described as well as a time waveform measurement system. Capabilities of these two characterization tools are illustrated with results obtained on a high power silicon bipolar transistor and on a GaAs MESFET device.*

INTRODUCTION

The design and the optimization of high power amplifiers are based either on non-linear simulations and/or on load-pull measurements. Accurate large signal nonlinear models, including self-heating effects, are required to achieve successful designs. These electrothermal models can be extracted from pulsed I(V) and pulsed [S] parameters measurements under controlled thermal conditions. The characterization of self heating and trapping effects by using a 40GHz/150ns pulsed measurement system is described in the first part of this paper. In the case of very high power amplifiers (up to 10 W and more) or amplifiers working under pulsed excitations (radar applications for example), the lack of models makes load-pull techniques an efficient way to optimize such circuits and to reduce like this the number of prototypes. The second part of this paper presents an active pulsed RF and pulsed DC load-pull system allowing measurements of power performances during RF pulses (power droop, phase shift). Voltage and current time waveforms measurements in the RF and microwave frequency range are described in the last part of this paper.

PULSED MEASUREMENTS FOR ELECTROTHERMAL CHARACTERIZATIONS

Pulsed measurement techniques have proved their advantages to test high power transistors [1]-[3]. For such components, DC measurements are not well suitable for the extraction of the models due to great self-heating effects and sometimes trapping effects.

Characterization of thermal effects:

To extract the electrothermal model of a transistor, both pulsed I(V) and pulsed [S] parameters measurements are performed for various temperatures of interest. Here, the junction temperature of the device is only imposed by an external heating source such as a thermal chuck (no quiescent bias point). Duration and repetition of the pulses are chosen small enough to ensure a quasi-isothermal characterization. (pulse width: < 1 µs ; duty cycle: $< 5\%$). For each temperature of test, an isothermal non-linear model is extracted. The electrothermal model is finally obtained by fitting constitutive elements of the isothermal model versus junction temperature. Figure 1 illustrates pulsed I(V) measurements. These results are obtained on a silicon carbide (4H-SiC) MESFET developed by Thales-LCR. This device is made of two gate fingers and presents a total gate development of 2 x 150 x 1 μm^2.

The thermal resistance is evaluated by measuring the increase of the junction temperature due to an applied DC dissipated power. The key point is to make use of a diode existing inside the component (base-emitter junction in bipolar transistors or grid-source junction in FETs) and working like a thermometer. In order to calibrate this thermometer, the quasi-isothermal pulsed I(V) characteristics of the diode are measured at different temperatures and will be used as reference curves. An example of isothermal reference curves concerning the SiC MESFET is shown on figure 2. The temperature of the component, for any quiescent bias point, is then obtained graphically with the measured value of the pair voltage/current of the diode and the set of reference curves. The determination of the temperature associated to the dissipated power (quiescent bias point) allows the computation of the thermal resistance.

Characterization of trapping effects:

FET transistors developed on new materials, such as Gallium Nitride (GaN) or Silicon Carbide (SiC), are still in a research and development phase and their performances are reduced by trapping effects [4]. Surface traps are mainly sensitive to the gate quiescent bias point while substrate traps are sensitive to the drain quiescent bias point. To observe traps sensitivity towards the quiescent drain voltage Vdso, the quiescent gate voltage Vgso is chosen so as to pinch-off the component and avoid like this any self-heating effect. The drain current versus drain voltage characteristic is then measured during short applied pulses. In a same way, the dependence of traps towards the quiescent gate voltage Vgso is obtained with a quiescent drain voltage Vdso equal to zero. Figures 3 and 4 show influence of Vdso and Vgso quiescent voltages on trapping effects of a 2*150µm GaN MESFET.With other specific pulsed measurements, it is possible to evaluate thermal time constants and also capture and emission traps time constants [3]. Pulsed measurements, with their capabilities to separate trapping and thermal effects, provide a powerful tool to characterize and model microwave components.

PULSED RF AND PULSED DC LOAD-PULL MEASUREMENTS

The implementation of a pulsed RF and pulse DC active load-pull system is a possible approach to observe the influence of low frequency phenomena (heating, traps, biasing circuits,…) on power performances of transistors. Moreover, such a system can be an efficient tool for the test and optimization of high power devices, which sometimes work only under pulsed RF signals and cannot be continuously biased.
Our pulsed RF and pulsed DC measurement system [5] is based on the use of a Wiltron pulsed vector network analyzer (VNA) and a two channel HP8115A DC pulsed generator (fig. 5). RF and DC pulse widths down to 250ns and duty cycle down to 1% can be used. An analysis RF window (profile pulse) of 50ns minimum width can be swept within the RF pulse stimulus(fig. 6). This capability is useful to measure performances of amplifiers (carrier phase shift, power droop, …) within the output RF pulse. These pulsed RF and pulsed bias subsystems are coupled to an active load-pull setup. A conventional thru-reflection-line (TRL) calibration procedure is used to correct measured power wave ratios. The absolute power calibration procedure is performed by measuring incident powers at reference planes with a power meter. The RF power variations and the RF carrier phase shift within the RF pulse, obtained on a class C MACOM 8W silicon bipolar matched amplifier, are presented figure 7. The RF pulse was set to 200 µs with a duty cycle of 10%. A 20 µs acquisition window width (profile pulse) was used. Measurements were performed when the position of this window is shifted from the beginning to the end of the 200µs RF pulse.

TIME DOMAIN MEASUREMENTS OF VOLTAGE/CURRENT WAVEFORMS

Voltages and currents time waveforms provide sometimes interesting indications during CAD amplifier optimization. For example, in addition to usual performances (output power, gain, PAE, IP3,…), time waveforms, RF load-lines, signal swings or overshoots are often useful parameters to evaluate the success of an amplifier design. In the system described below [6], the voltage/current waveforms are reconstructed from measured harmonic frequency components of power waves. The VNA is used in its “receiver operation mode” and provides measurements of any complex power wave ratio at fundamental and harmonic frequencies. Absolute magnitudes of power waves are measured by using the selective power-meter capabilities of the VNA. Conventional VNA’s do not allow the measurement of the power wave absolute phases. To overcome this difficulty, a modified VNA test-set with an additional input (phase reference signal input) has been developed (fig. 8). This modification needs the measurement of five power waves (four usual power waves for the DUT: a_1 , b_1, a_2, b_2 and the phase reference wave a_{REF}). Since the VNA has only four IF channels ($R_{A,}$ T_A, R_B, T_B), a programmable switch has been inserted to selected in turn reflected waves b_1 or b_2.
The external phase reference signal a_{REF} comes from a step recovery diode (SRD) fed with the microwave synthesizer signal. This SRD is phase calibrated by using a specific HP-Agilent procedure [7]. As far as the reference signal a_{REF} remains constant during the calibration and measurement procedures, the phase relationships between all frequency components of wave $b_2(t)$ can be determined. Then, time-domain waveforms $a_1(t)$, $b_1(t)$ and $a_2(t)$ can be deduced from the other conventional power wave ratios measured with the modified VNA.
This system is coupled to an active multi-harmonic load-pull set-up (fig. 9). Three active loops at fundamental, 1st and 2nd harmonic frequencies allow to control load impedances. Results concern the optimum operating conditions of an 800-µm gate periphery GaAs MESFET for maximum power added efficiency at L-band.
Measured input and output voltages/currents waveforms are plotted figure 10 as a function of time at three input power levels. In this example, measurements on the first five harmonics are sufficient to reconstruct reliable time waveforms. In these conditions, the device exhibits an optimum PAE of 81%, a power gain of 13 dB and an output power of 192 mW at 1.8 GHz. These time waveforms can also be used to validate non-linear models.

CONCLUSION

With appropriated adjustments of pulsed and quiescent bias levels, self-heating effects and surface or substrate trapping effects can be observed separately. A pulsed RF and pulsed bias load-pull measurement system reveals to be an efficient tool to characterize and to optimize operating conditions of power amplifiers. This system is particularly well suited in the case of pulsed radar amplifiers that can not be measured in CW mode. Phase shifts and output power droops can be measured during the RF excitation pulses. Finally, an active load-pull set-up combined with a modified VNA has been presented. With the use of a phase calibrated reference SRD diode, the whole system provides voltage and current time waveforms at both ports of nonlinear devices. RF load-lines or time waveforms are often used to optimize power amplifiers during the CAD process. The proposed system provides experimentally the same optimization criteria.
Current and future investigations concern the time domain characterization of transistors under pulsed RF and DC conditions and also under complex modulated carriers. These investigations are developed from the measurement techniques presented in this paper and on a new time domain measurement technique based on the Agilent Nonlinear Network Measurement System (NNMS) [8].

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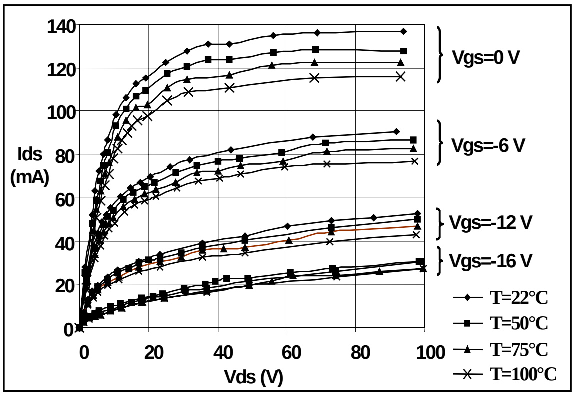
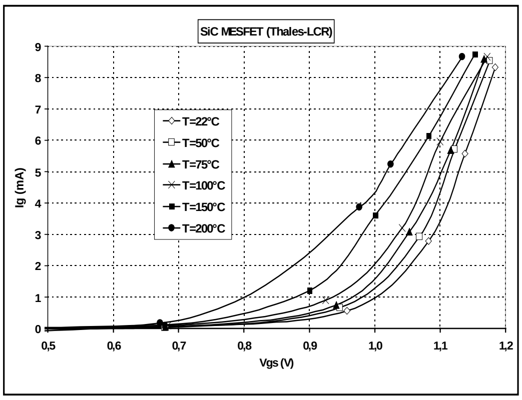
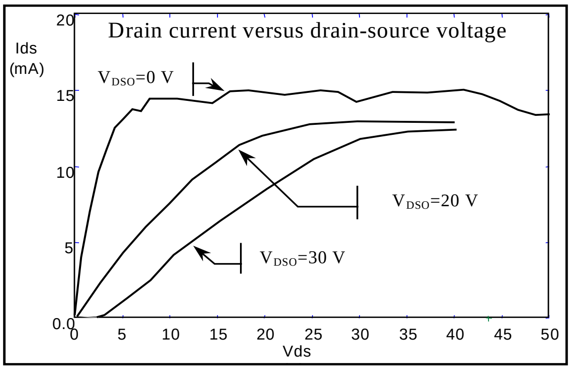


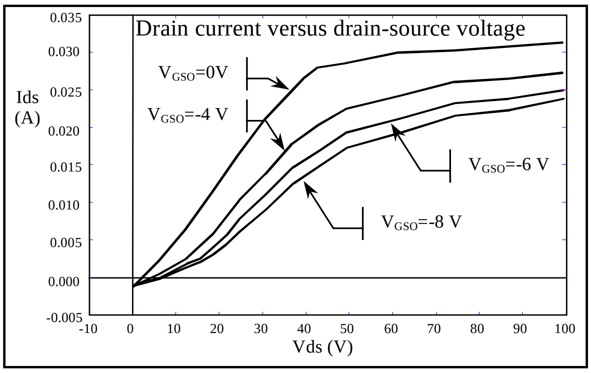
Quasi-isothermal pulsed I(V) characteristics (SiC MESFET)
Figure 1



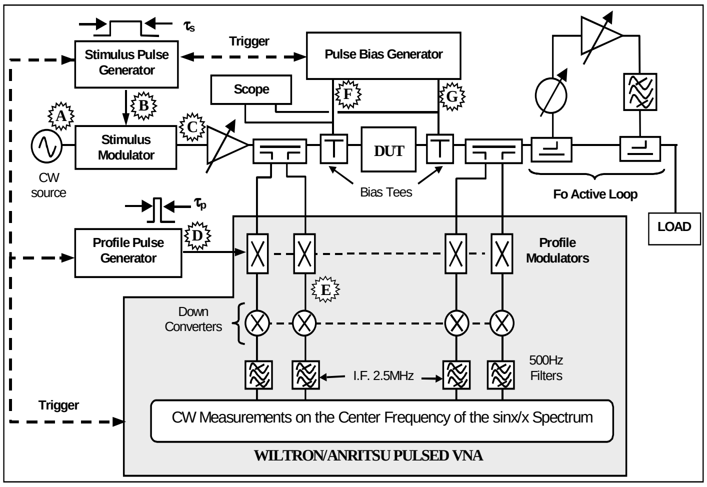
Diode reference curves (SiC MESFET)
Figure 2



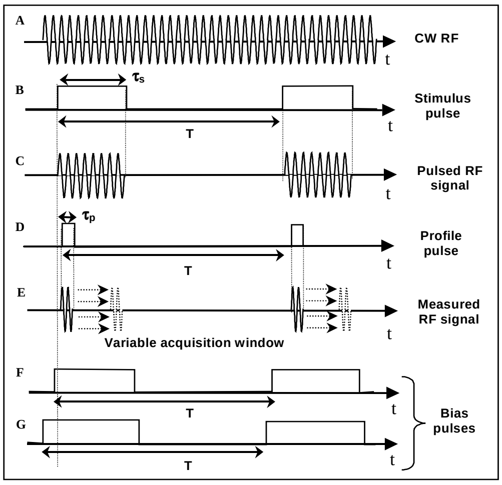
Influence of drain quiescent bias voltage Vdso on traps
Figure 3



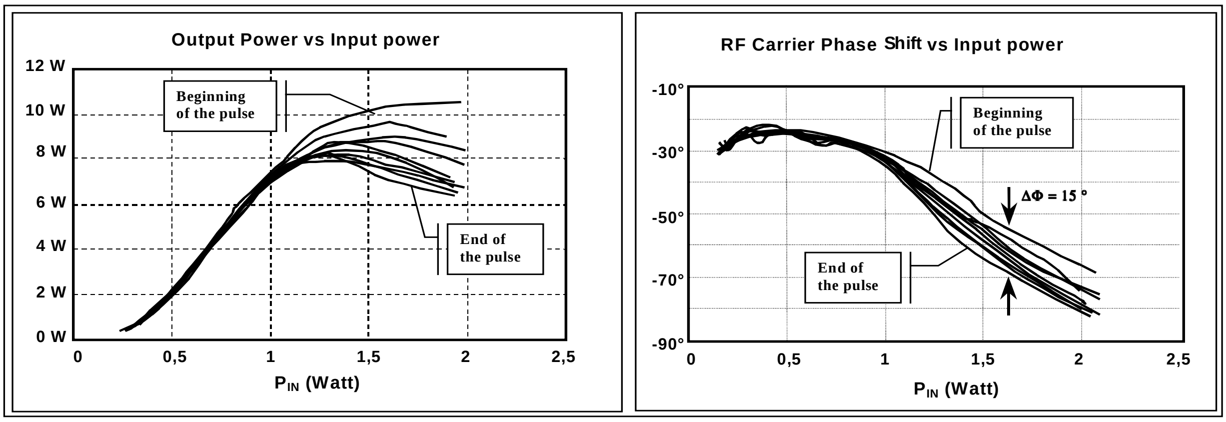
Influence of gate quiescent bias voltage Vgso on traps
Figure 4



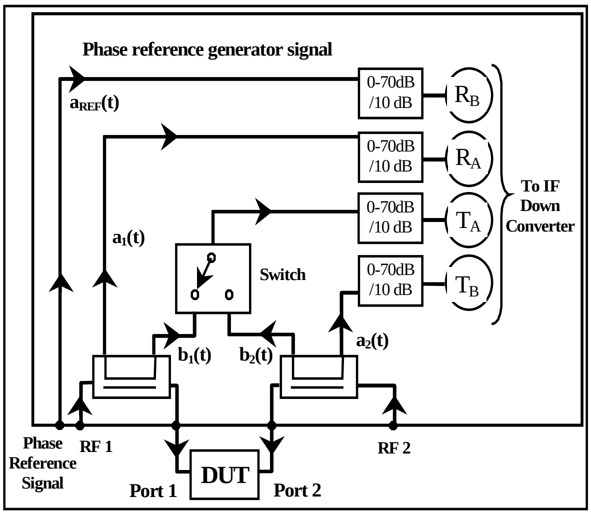
Block diagram of the active pulsed load-pull system
Figure 5



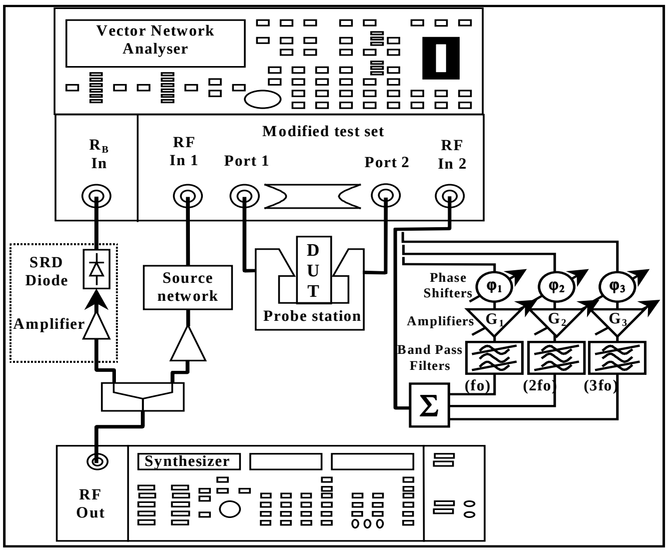
Pulsed RF and pulsed bias signals timing
Figure 6



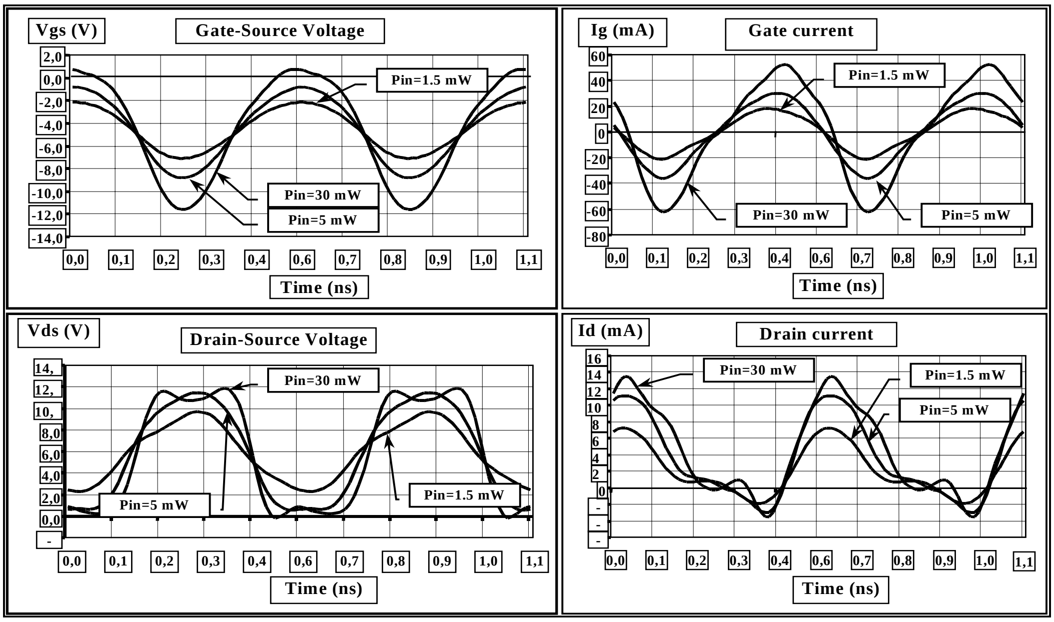
2.7 GHz Pulsed Load-pull measurements on a 8 W class-C MACOM silicon bipolar amplifier
Figure 7



Modified VNA test-set
Figure 8



Time waveforms measurement system
Figure 9



GaAs MESFET time waveforms at three input power levels
Figure 10