ANALYSIS OF LOW FREQUENCY MEMORY AND INFLUENCE ON SOLID STATE HPA INTERMODULATION CHARACTERISTICS

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Abstract — **Theoretical analysis using two-tone simulations and practical measurements of low frequency memory impact on third order intermodulation (IM3) on HBT as well as HFET power amplifiers is carried out. A particular emphasis is made on thermal origin for a HBT case and electrical origin for the HFET case of these low frequency nonlinear phenomena.**

I. INTRODUCTION

Classical design of solid state High Power Amplifiers (HPA) is usually the result of a fine study and optimization of nonlinear working conditions under constant wave (CW) signals [1]. For a few years, an important amount of work has been undertaken to introduce real world signals (multicarrier signals) in the design process [2].

However in these conditions, nonlinear behavior of solid state circuits is more difficult to understand, because many nonlinear complex phenomena are mixed together.

Of course influence of load and source impedance at fundamental but also at second and third harmonics is still of prime importance for optimum power and PAE. But because of time varying envelopes, new critical design parameters have been discovered, whose influence was impossible to reveal with CW signals.

Among those of prime importance are the very long time constants present in nonlinear microwave circuits, which directly impacts the envelope of modulated signal having a rapidity of a same order.

From a very general point of view, nonlinear low frequency memory effects (low frequency dependence) can be divided into three classes : those related to thermal/heating of the active component, those related to an electrical behavior, and those related to traps in the structure of the device.

At the circuit level, designers need to understand the different characteristics of this new critical parameters to improve amplifier designs, as well as efficiency of predistortion linearization technique [8].

In the same time, for the system and subsystem level simulation, where wide band signals are involved, frequency dependence of circuits for in-band effects (high frequency memory) as well as out-band effects (low frequency memory) is being introduced in the modeling process [3][4].

The first step for understanding nonlinear low frequency memory is to use very simple multicarrier signals, such as a two tones signal. In this article we will investigate the influence of thermal effects and low frequency load and source impedance repartition on intermodulation characteristics of HPA.

II. THERMAL MEMORY EFFECTS

Thermal state of an HBT under two tones excitation has been studied in simulation using a nonlinear electrothermal model [5]. The objective of the simulation was to show how thermal state of the device could change with increasing distance (Δf) between tones as shown in Fig. 1 :

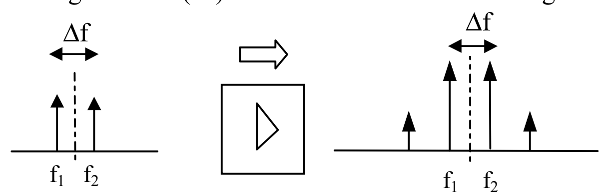


Fig. 1. : 2 Tones simulation with increasing distance between tones

To avoid any frequency dependence of the matching and biasing circuits, input / output optimum impedance are fixed using ideal frequency independent impedance boxes, and biasing circuit is a short circuit up to $f_0/2$ (center frequency f_0=2GHz).

Results of simulations are given in Fig. 2 for a constant input power and a distance of tones from 10Hz to 10MHz. Although there is no frequency dependent component outside the transistor, an important variation of IM3 with frequency distance is remarked (up to 7 dB). Origin of these results are situated in the natural low pass nature of thermal behavior of the transistor.

Indeed as temperature of the transistor does not follow power dissipation simultaneously, thermal behavior of the transistor is represented by a R/C equivalent circuit as shown in Fig.3 :

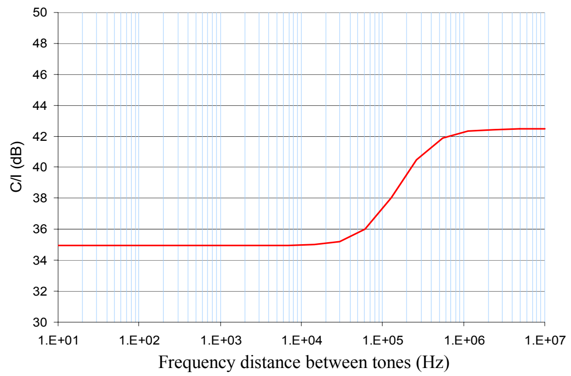
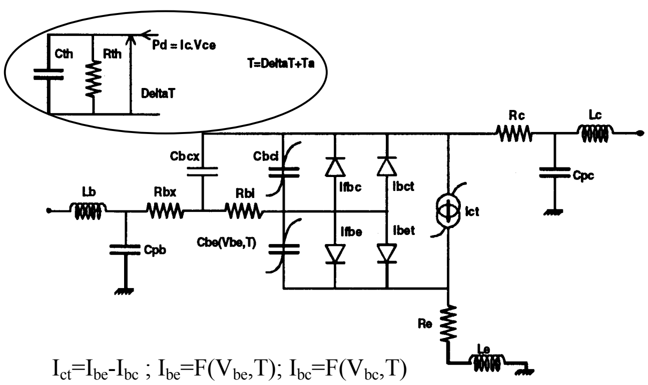


Fig. 2. : transistor IM3 for increasing distance between tones.



$I_{ct}=I_{be}-I_{bc}$; $I_{be}=F(V_{be},T)$; $I_{bc}=F(V_{bc},T)$

$I_{bet}=F(V_{be},T)$; $I_{bct}=F(V_{bc},T)$; $I_{fbe}=F(V_{be},T)$; $I_{fbc}=F(V_{bc},T)$

$C_{be}=F(V_{be},T)$; $C_{bc}=F(V_{bc},T)$

Fig. 3. : Electrothermal nonlinear HBT model[5].

As $R_{Th}=160\Omega$ and $C_{Th}=6.25nF$, the cut-off of the thermal circuit is roughly f=160kHz. Depending of the distance between tones (Δf), intermod f_2-f_1 will fall into or outside the band of the thermal filter.

The consequence of this phenomenon is given in Fig. 4 where three frequency distances have been chosen. For Δf=100Hz, Temperature is modulated by frequency difference f_2-f_1 and amplitude of modulation is maximum. For Δf=100kHz, Temperature is still modulated by frequency difference f_2-f_1 but amplitude of modulation is reduced. Finally for Δf=10MHz, f_2-f_1 is above cut–off of the filter and variations of signal are too fast for temperature to change. Since most of nonlinearities in HBT are strong nonlinear functions of the instantaneous junction temperature, nonlinear behavior of the transistor will be instantaneously modified depending of Δf and resulting on a different output spectrum.

Finally, we can see that a non constant thermal state of the transistor is degrading IM3, and the greater amplitude of modulation the worst degradation is. Degradation of IM3 is in this case closely dependent to a frequency parameter, that's why we can speak of a memory effect. Moreover amplitude of IM3 degradation is varying depending on input power of the 2 tones signal (not shown here) : thermal memory is a nonlinear phenomenon. As an other consequence of thermal memory, an asymmetry between IM3 at $2f_2$-f_1 and $2f_1$-f_2 could sometimes be observed. A detailed study could be found in [6][7].

Let's now go back to a multicarrier (let's say QPSK) signal of about 10 MHz wide. One can understand that part of low frequency intermods (near DC) will fall into filter band and an other part outside. ACPR results will be affected by thermal memory, and will obviously change depending on the bandwidth of the signal.

However here come the difficulty with thermal effects for circuit designers. Even if thermal behavior of component modifies intermodulation characteristics of the amplifier, thermal dissipation is difficult to improve directly inside the component. However a good external thermal conduction would limit amplitude of thermal modulation. An a posteriori modeling could be used to represent this phenomenon at system or subsystem level [3].

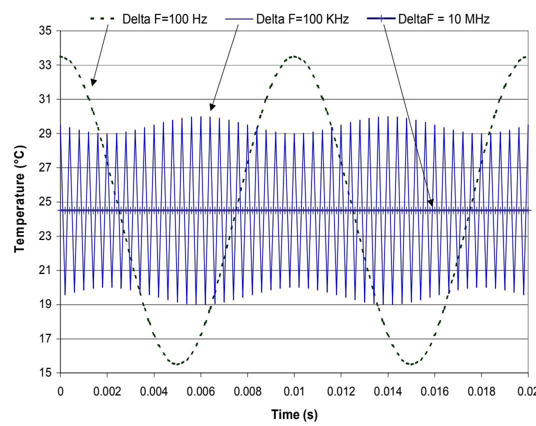


Fig. 4. : Time variation of Transistor Temperature for three frequency distance between tones

II. Electrical Memory Effects

A second origin of nonlinear memory is situated in load and /or source impedance presented to the transistor at envelope low frequency (f_2-f_1) [8].

Using non linear model of transistor, influence of source and load impedance for a two tone signal could be theoretically studied, by simulating a load-pull set up as it could be done for finding optimum fundamental and harmonic loads in CW (Fig. 5). To avoid any frequency dependence of transistor environment every charge used in set up Fig. 5 is a frequency independent impedance box.

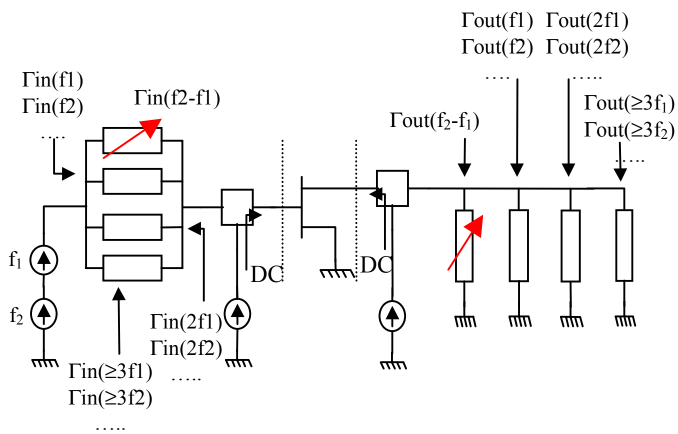


Fig. 5: Simulation of a Source/Load Pull Set up at f_2-f_1

This set-up has been applied to a HFET power transistor under a two tones signal. Impedance at envelope frequency Γin(f_2-f_1) and Γout(f_2-f_1) have been swept for covering the entire Smith chart.

No significant influence of Γin(f_2-f_1) has been found for this transistor (it could have been the case for an HBT where base input is strongly nonlinear). However influence of Γout(f_2-f_1) has been found to be considerable.

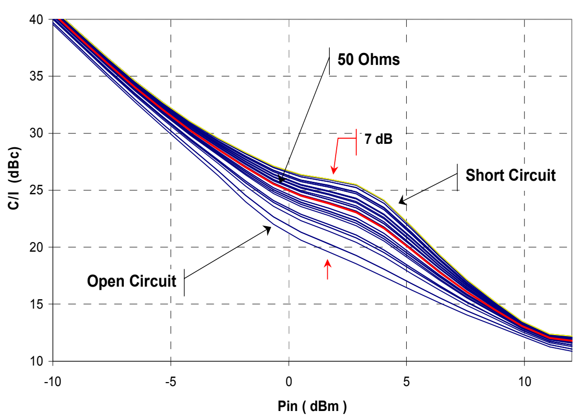


Fig. 6 : IM3 for different output loads Γout(f_2-f_1)

Fig. 6 shows that influence of output load could reach 7 dB on IM3 between the best case (short circuit) and the worst case (open circuit). In the same time, variations on output power leads to an important improvement on optimum PAE in two tones conditions (about 10 points) between the worst case (open circuit) and the best case (short circuit) (Fig. 7). Of course variations of Γin(f_2-f_1) and Γout(f_2-f_1) do not change CW performance of the amplifier.

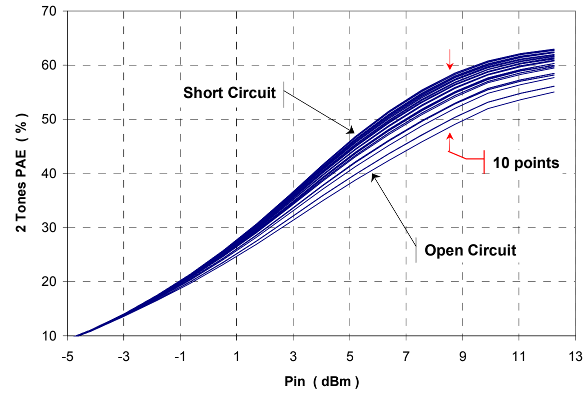


Fig. 7 : PAE for different output loads Γout(f2-f1)

This results show that output load at envelope frequency (f_2-f_1) is of prime importance for HFET. For other type of transistors input load could have been as much important. Maintaining optimum load should be an optimization objective in power amplifier circuit design.

However for wide band amplifier, this means maintaining the output load to optimum from DC to typically 200 MHz in C-Band (3.8 GHz). The use of biasing inductors and decoupling capacitance which are essentially frequency dependent elements is in contradiction with this remark. A careful design of biasing circuit is consequently very important.

Optimum output load has been found here to be the short circuit, which intuitively could be understood as a cancellation of the modulation of the drain biasing point (transistor Ids is a voltage controlled source). As it has been shown for thermal memory, low frequency modulation of transistor state degrades IM3. This result could be found to be in contradiction with those exposed by J. Sevic [9], who found an optimal complex impedance to present to transistor. In fact this is not necessarily the case, because a complex impedance added in series on the biasing network may represent a compensation of both DC bias block and DC bias source used during experiment, to obtain finally the optimum impedance (supposed short circuit) in transistor plan.

Indeed, external biasing cables and biasing source must be carefully checked because of the series impedance added to the amplifier internal biasing circuit. Fig. 8 shows S_{11} presented by a typical DC bias source from DC to 100MHz. As we can see impedance presented by the source is far to be a constant short circuit in DC→100 MHz frequency range, even exhibiting resonance around 26 MHz.

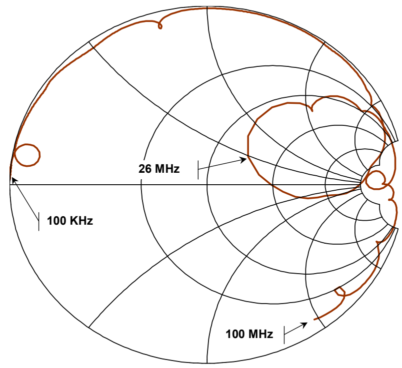


Fig. 8 : S_{11} Measurement of a typical bias source

In fact the real impact on amplifier behavior is from the impedance seen by the transistor in its output plan ($\Gamma out(f_2-f_1)$) which is the result of the DC bias source seen through the internal biasing network. Fig.9 shows the impedance $\Gamma out(f_2-f_1)$ presented to transistors on a typical C-band HFET Amplifier with and without the DC bias source.

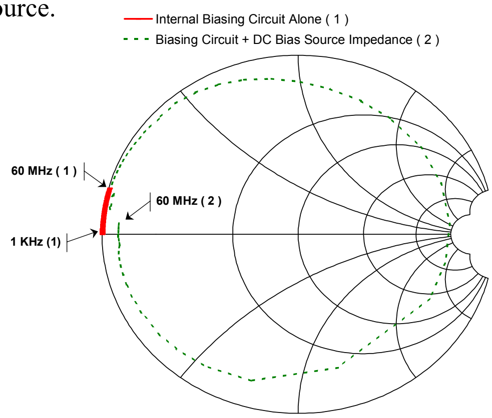


Fig. 9 : $\Gamma out(f_2-f_1)$ to transistor : internal amplifier biasing network (1) , biasing network + bias source (2)

Thus, the combination of the internal biasing circuit and external elements introduces nonlinear low frequency memory in the amplifier response. Indeed, depending on the frequency distance between tones, an optimum as well as bad envelope impedance could be presented to the transistor resulting to a significant variation of IM3 as shown in Fig. 10. The experimental case of Fig. 10, shows in the same time, the thermal influence for high output levels, when tones are very close to each other.

V. Conclusion

Thermal and electrical low frequency memory effects have been exposed. It has been shown how frequency modulation of thermal as well as electrical state of transistor is degrading IM3. If optimization of thermal behavior of transistor is not possible at circuit level, it may be possible to work for limiting electrical memory effects by optimizing biasing circuits to prevent amplifiers from an external bias source major influence.

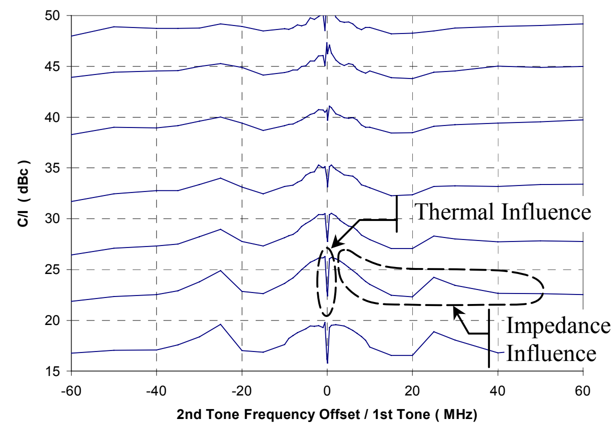


Fig. 10 : Measurement of IM3 for constant output power of an amplifier exhibiting nonlinear memory effects

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