Analysis of Odd-Mode Parametric Oscillations in HBT Multi-Stage Power Amplifiers

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***Abstract* — In this paper a technique for predicting odd-mode parametric oscillations from the analysis of exact pole-zero cancellations that take place in the frequency response obtained at some specific nodes of power amplifiers is presented. By using this technique the nature of parametric oscillations can be determined, which allows establishing a suitable strategy for circuit stabilization. The proposed methodology has been applied to the analysis and elimination of parametric odd-mode oscillations in an X-band two-stage MMIC power amplifier. The analysis has been complemented with the harmonic-balance calculation of the odd-mode frequency-divided steady-state solution.**

I. INTRODUCTION

Several oscillation mechanisms can affect multi-stage power amplifiers [1]. In particular, HBT multi-stage power amplifiers have a tendency to exhibit parametric frequency divisions (the start-up of the sub-harmonic frequency component being function of the input power, for instance). In order to detect and avoid the presence of these undesired responses and ensure successful designs, a careful stability analysis is required.

The symmetry in the topology of multi-stage power amplifiers and the presence of power combining blocks introduce the possibility of odd modes of oscillation [1-3]. Small-signal analysis techniques [3] for predicting the existence of odd-mode oscillations are not applicable to parametric oscillations. In addition, time-domain simulations are often impractical due to the considerable presence of elements defined in the frequency domain and the large transients involved.

Stabilization techniques should be based on an in-depth knowledge of the nature and origin of the oscillation mechanism. Ignoring the type of the oscillation mode can lead to the insertion of non-optimal stabilization networks. As an example, usual stabilization strategies for parametric oscillations apply RC networks at the input of the transistors [1], [4], [5]. However, this may not be the most suitable solution when dealing with odd-mode oscillations [3].

In this paper a technique for predicting odd-mode oscillations from the analysis of exact pole-zero cancellations that take place in the frequency response obtained at some specific nodes of the circuit is reported. The stability analysis method proposed in [6] is adapted here to provide a straightforward methodology to conclude the oscillation mode. This stability analysis was based on the calculation of the system poles and zeroes associated to the linearization of the simulated large-signal steady state [6]. The method, low time consuming and easily combinable with any standard CAD package, is particularly well adapted to the rigorous investigation of parametric stability in complex circuits.

The proposed methodology for analysing and eliminating odd-mode parametric oscillations has been applied here to a MMIC power amplifier.

II. LARGE SIGNAL STABILITY ANALYSIS OF AN X-BAND POWER AMPLIFIER

The analysis methodology is applied to a MMIC X-band two-stage power amplifier. The circuit is built in HBT technology based on AsGa/GaInP process. Design goals were 2 Watt output power with maximum power-added efficiency. The layout of the circuit is shown in Fig. 1.

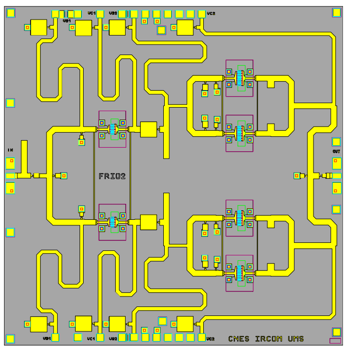

Fig. 1. Layout of the X-band power amplifier

A parametric frequency division has been experimentally found in this amplifier. Fig. 2 shows the output spectrum measured around the fundamental and divided frequencies for f_{in} = 9.65 GHz and P_{in} = 12.34 dBm.

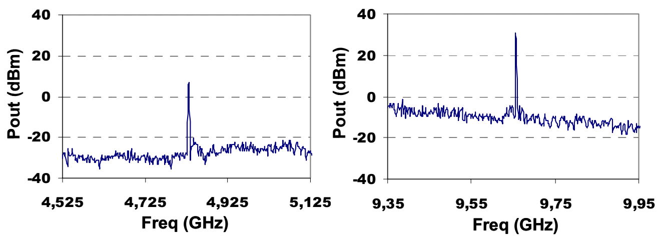

Fig. 2. Spectrum measurements near $f_{in}/2$ and f_{in} of X-band power amplifier (f_{in} = 9.65 GHz, P_{in} = 12.34 dBm)

A. Parametric stability analysis

The stability of this amplifier was carefully analyzed in [7] using two large-signal stability methods [6], [8]. In these analyses, simulations confirmed the presence of the measured parametric frequency division.

Using the method proposed in [6], a parametric stability analysis is carried out. For that, the frequency response of the circuit has been obtained by introducing a current perturbation at the base of a transistor in the second stage of the amplifier, for different input power values. Complex conjugate poles at $f_{in}/2$ have been obtained using frequency domain identification methods [6]. As an example, in Fig. 3 the evolution of $f_{in}/2$ poles with the input power value is represented for f_{in} = 9.65 GHz. These poles become unstable (with positive real part) as input power increases. For f_{in} = 9.65 GHz a frequency division instability was detected for P_{in} higher than 10.45 dBm.

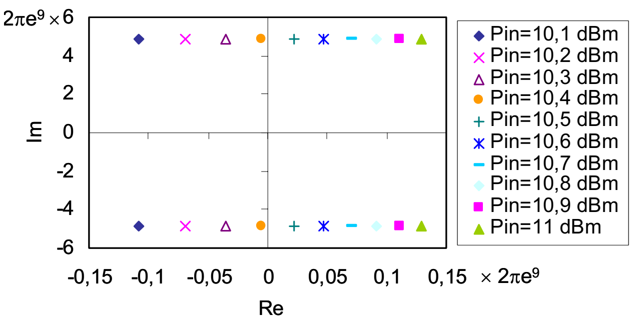

Fig. 3. Evolution of $f_{in}/2$ poles with the input power value (f_{in} = 9.65 GHz)

B. Determination of the oscillation mode

In order to study the origin of the parametric frequency division, let us illustrate the analysis through a simplified circuit (Fig. 4) that qualitatively exhibits the same unstable behaviour as the whole amplifier. This basic cell is only composed of two HBT transistors with a simplified power splitter network at the input and without power combining network at the output.

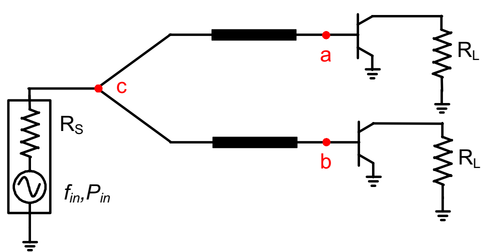

Fig. 4. Basic cell that qualitatively exhibits the same behaviour as the original amplifier circuit

The injection of a current perturbation into the circuit allows the excitation of odd and/or even modes depending on the node of the circuit where the perturbation is introduced:

- Into the base of one transistor, nodes 'a' or 'b', the current perturbation excites both odd and even modes of the circuit. Thus the presence of odd- and even-mode oscillations can be predicted.
- Injecting two current perturbations with identical amplitude and a phase difference of 180º at the bases of both transistors (nodes 'a' and 'b') excites only the odd mode and therefore only odd-mode instabilities will be detected.
- At the combining node of the power splitter, node 'c', (or introducing two identical current perturbations at the bases of both transistors, nodes 'a' and 'b') only the even mode is excited, thus only even-mode instabilities will be detected.

Examples of these procedures, applied to the basic cell of Fig. 4 (f_{in} = 9.65 GHz, P_{in} = 23.3 dBm), are shown in figures 5 to 7. Fig. 5 shows the frequency response and the identification results obtained when only one current perturbation is applied to node 'a'. The presence of an unstable pair of complex conjugate poles at $f_{in}/2$ indicates the start-up of a frequency division. No conclusion about the nature of the oscillation mode can be extracted yet. Fig. 6 shows the results corresponding to the connection of two perturbations with a phase difference of 180º at nodes 'a' and 'b'. The obtained unstable poles suggest an odd-mode oscillation. This is confirmed by the results shown in Fig. 7 in which the current perturbation was connected at the node 'c' (combining node of the power splitter). No unstable poles are detected because an exact pole-zero cancellation occurs in the frequency response obtained at the symmetry line of the power splitter. We can thus confirm that the instability corresponds to an odd-mode frequency division.

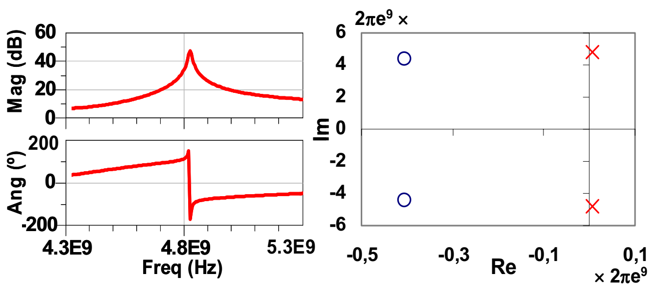

Fig. 5. Frequency response and identification results when exciting odd and even modes. Unstable poles at $f_{in}/2$ are obtained (f_{in} = 9.65 GHz, P_{in} = 23.3 dBm)

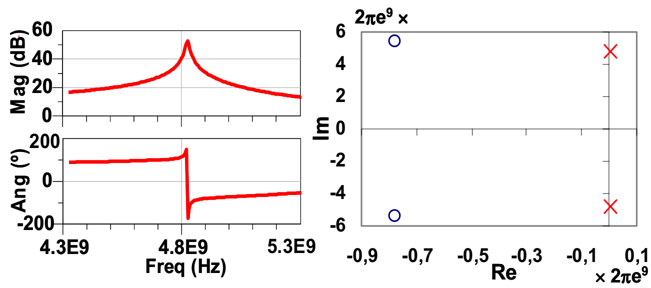

Fig. 6. Frequency response and identification results when exciting only the odd mode. Unstable poles at $f_{in}/2$ are obtained (f_{in} = 9.65 GHz, P_{in} = 23.3 dBm)

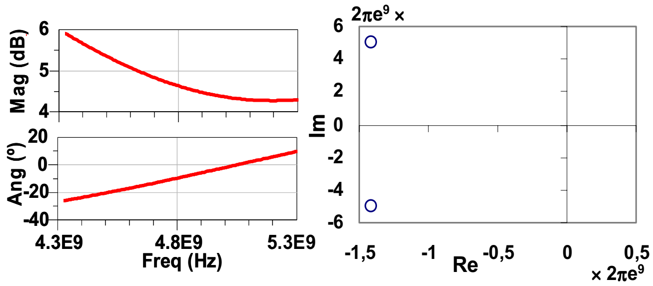

Fig. 7. Frequency response and identification results when exciting only the even mode. No unstable poles are obtained (f_{in} = 9.65 GHz, P_{in} = 23.3 dBm)

In the odd mode, signals in both branches of the basic cell (Fig. 4) are 180º out of phase at the oscillation frequency. Consequently a virtual ground can be assumed at the symmetry line of the power splitter (Fig. 8a). In the even mode, the signals in both branches are in phase, so a virtual open circuit can be assumed between the two halves of the circuit (Fig. 8b).

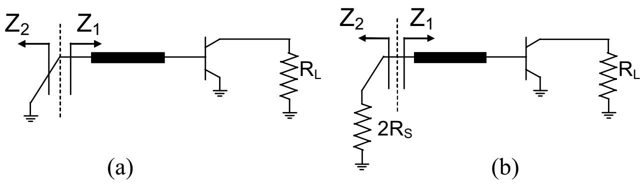

Fig. 8. (a) Odd-mode equivalent circuit. (b) Even-mode equivalent circuit

From odd and even mode equivalent circuits of Fig. 8 the oscillation start-up conditions for each mode can be stated as:

- Odd-mode: Real (Z_1) < 0 and Im (Z_1) = 0
- Even mode: Real (Z_1) < $-2R_S$ and Im (Z_1) = 0

Even-mode oscillation conditions are more restrictive that the odd-mode ones, which are satisfied at the divided frequency for certain input power values.

A stability analysis of the odd-mode equivalent circuit can also be performed to verify that the frequency division is an odd-mode oscillation. In order to do this, the large signal steady state has to be maintained while presenting a virtual ground at the symmetry line. A simple procedure to obtain the odd-mode equivalent circuit around a given large signal steady state is to introduce an ideal stop-band filter at f_{in} and its harmonics between the combining node and the virtual ground (Fig. 9). Thus, the large signal steady state of the circuit is not distorted. This approach is a generalization of the small-signal odd-mode analysis to the large-signal case. The frequency division instability detected in the basic cell (Fig. 4) has also been observed using the odd-mode equivalent circuit of Fig. 9, confirming again the odd nature of the oscillation.

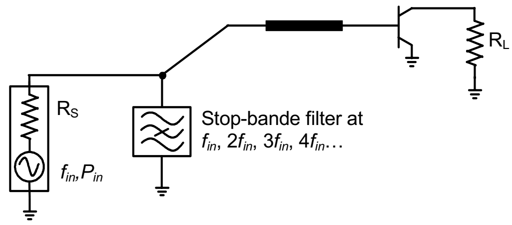

Fig. 9. Odd-mode equivalent circuit used for the large-signal stability analysis

Finally, the stability of the whole circuit has been studied in order to determine the oscillation mode in the whole amplifier. The power amplifier scheme is shown in Fig. 10. In [7], the frequency response was obtained by introducing a current perturbation at the base of one transistor of the second stage (nodes a, a′, a″ or a‴) and unstable poles at $f_{in}/2$ were detected. In doing so, both odd and even modes of the amplifier are excited so the nature of the oscillation can not be determined yet. With the aim of determining the nature of the oscillation, the frequency response of the amplifier has been obtained here using pure odd or even excitations.

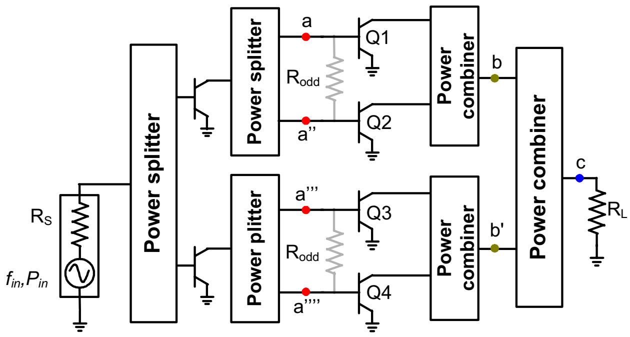

Fig. 10. Power amplifier scheme with stabilization resistances

A pure even excitation can be achieved introducing the current perturbation at the combining nodes of the inter-stage power splitter networks or at the combining nodes of the output power combiner networks. Similarly, only the even-mode is excited by introducing four identical perturbations at the bases of the four transistors of the second stage. By analyzing the frequency responses obtained in this way, no unstable poles at $f_{in}/2$ are detected in this amplifier. In fact, an exact pole-zero cancellation occurs in the frequency response obtained by introducing the current perturbation at the combining nodes of power splitters and combiners. The parametric frequency division of this amplifier is thus an odd-mode oscillation.

As explained in [3], different odd-mode oscillations can be found in a circuit with multiple combined devices. In particular, three odd-mode oscillations [3] can be found in a circuit with 4 combined devices, like the one under analysis. As the instability is not detected at nodes b or b′, we can conclude that Q1 and Q2 operate with a phase difference of 180º at $f_{in}/2$, and Q3 and Q4 operate also with a phase difference of 180º at $f_{in}/2$. If the instability were detected at nodes b or b′ but not at node c, Q1 and

Q2 would operate in phase with each other but 180º out of phase with Q3 and Q4 at $f_{in}/2$.

B. Frequency divided steady-state solution with harmonic balance

Time-domain simulations were not applicable to the power amplifier under study because of its large amount of distributed parameter components. Therefore, a method to obtain the frequency divided steady-state in harmonic balance (HB), originally developed for frequency dividers [9], has been adapted and successfully applied to the analysis of power amplifiers. The voltage time waveforms and spectrum obtained in the bases of transistors Q1 and Q2 for f_{in} = 9.65 GHz and P_{in} = 12 dBm are represented in Fig. 11. Observe that the odd harmonics of the oscillation frequency ($f_{in}/2$, $3f_{in}/2$, $5f_{in}/2$...) have a phase difference of 180º, confirming the odd-mode oscillation.

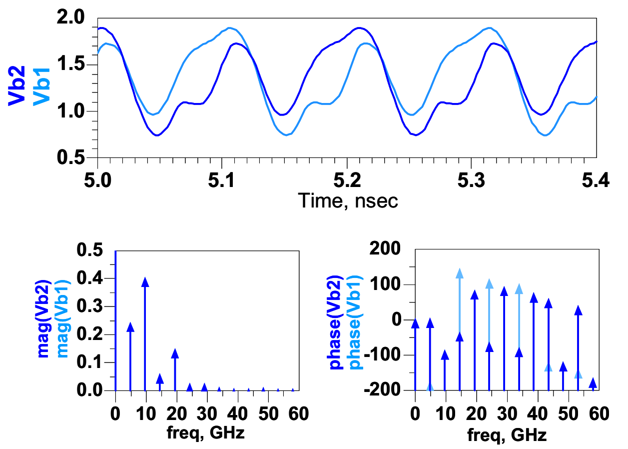

Fig. 11. Voltage time waveforms and spectrum obtained in the bases of Q1 and Q2 through HB simulations (f_{in} = 9.65 GHz, P_{in} = 12 dBm)

III. Circuit Stabilization

The most suitable approach to eliminate odd-mode oscillations relies on the connection of resistances between the stages [1], [3]. In the case of the analyzed power amplifier, Q1 and Q2 operate with a phase difference of 180º at the divided frequency (as Q3 and Q4). Therefore, the most appropriate is to introduce the odd-mode resistances between Q1 and Q2 and between Q3 and Q4. Exhaustive parametric stability analysis showed that the optimum configuration for the circuit under study consisted of two resistances placed between the bases of the second-stage transistors, as shown in Fig. 10. The optimum resistor values have been quantitatively established guarantying the stability of the circuit for any input power and frequency. The introduction of two odd-mode resistances of 30 Ω between the bases of the transistors of the second stage is enough to stabilize the circuit. The normal operation of the amplifier is not affected since no current will flow through these resistances provided that ideally symmetric circuit is considered.

VI. Conclusion

A technique for predicting parametric odd-mode oscillations in power amplifiers has been presented. This technique is based on the analysis of exact pole-zero cancellations that take place in the frequency response obtained at some specific nodes of the circuit. The knowledge of the oscillation mode allows finding a suitable strategy for circuit stabilization. The methodology has been successfully applied to the analysis and elimination of parametric odd-mode oscillations in an X-band two-stage MMIC power amplifier.

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