Wideband 50W Packaged GaN HEMT With Over 60% PAE Through Internal Harmonic Control in S-Band

Jérôme Chéron[1], Michel Campovecchio[1], Denis Barataud[1], Tibault Reveyrand[1], Michel Stanislawiak[2], Philippe Eudeline[2], Didier Floriot[3].

[1] XLIM – UMR 6172, Université de Limoges/CNRS, 123 avenue Albert Thomas, 87060 Limoges, France.

[2] THALES AIR SYSTEM, ZI du Mont Jarret, Ymare, 76520 Boos, France.

[3] UMS, Parc Silic de Villebon-Courtaboeuf, 10 avenue du Québec, 91140 Villebon sur Yvette, France.

***Abstract* — This paper presents an internally-matched packaged GaN HEMT for achieving not only high-efficiency and high-power performances but also wide bandwidth and insensitivity to harmonic terminations in S-band. The internal matching circuits of the optimized package enable to reach a wider bandwidth and to confine the harmonic impedances seen by the internal GaN powerbar into high-efficiency regions whatever the external impedances presented to the package. In a 50Ω environment, the packaged GaN HEMT delivers 45 W output power with more than 55% PAE from 2.9 to 3.7 GHz (24% relative bandwidth). By optimizing source and load impedances at the 1st-harmonic, the packaged GaN HEMT demonstrates 50 W output power with more than 60% PAE over 21% bandwidth.**

***Index Terms* — Power amplifiers, GaN HEMTs, high efficiency, wide bandwidth, harmonic control, packaged powerbars.**

I. Introduction

Emerging radar applications in S-band are more and more confronted with the trade-off between high power-added efficiency (PAE), high output power, and wideband operation of power amplifiers. High efficiency classes are well suited for maximizing PAE [1] and GaN HEMTs have already demonstrated high PAE performances. However, high efficiency operation is usually restricted to narrow bandwidths.

Although MMIC and quasi-MMIC amplifiers have already demonstrated high-PAE and high-power performances up to 20% relative bandwidth [2]-[3], packaging is still a critical issue of hybrid amplifiers for reaching high power and high PAE over wide bandwidths. For example, hybrid power amplifiers are generally optimized by designing the matching networks outside the package so that optimum harmonic impedances cannot generally be reached due to the cut-off frequency of the package. In addition, whatever the external circuits, their wideband matching capabilities can also be limited at the fundamental frequency by the package elements. To overcome these drawbacks of packaged transistors for wideband PAE performances, specific matching networks have to be inserted inside the package as close as possible to the active die. Recent study [4] has demonstrated high-efficiency and high-power performances for more than 10% bandwidth using matching networks inside the package.

Since the matching capability of the external circuit is more and more reduced with increasing frequency due to the cut-off frequency of the package, this work is particularly focused on the internal matching of the GaN HEMT at the 2nd-harmonic frequencies. Our aim is to synthesize an optimized package for providing wideband optimum matching of the active die at the 2nd-harmonic frequencies whatever the impedances presented outside the package. The package is also synthesized to facilitate the external matching at fundamental frequencies so as to reach the best trade-off between bandwidth, PAE, and external matching capabilities. Sections II and III describe the synthesized package and power measurements, respectively.

II. Technology & Package Synthesis.

We use device from the released GaN GH50_10 process provided by UMS. This technology has been qualified up to operating drain voltage of 50V. The GaN HEMT powerbar has a gate periphery of 14.4 mm composed of six unit cells with 2.4 mm gate width. On-wafer pulsed-IV and pulsed-RF measurements were performed on the 2.4 mm GaN die to derive its non linear model. Then, nonlinear simulations and load-pull measurements of the unit cell were performed from 2.9 to 3.7 GHz in order to check the model reliability and define the optimum source and load impedance contours at f_0 and $2f_0$ for maximum PAE. By using these impedance contours, internal matching circuits of the GaN powerbar were designed so that each unit cell can be matched to its optimum source and load impedances at $2f_0$ while easing the external matching at the fundamental frequencies. Our aim was to desensitize the packaged transistor to external harmonic loads while ensuring more than 20% bandwidth, high-PAE and easier external matching at f_0.

Fig. 1 shows a circuit schematic of the packaged GaN HEMT where Z_S and Z_L denote the external loads.

At first, a L_1-C_1 low-pass filter is optimized to confine the 2nd-harmonic load impedances of each unit cell into their high-PAE regions whatever the impedances presented outside the package (i.e. Z_L at $2f_0$ is swept all over the entire Smith chart).

This methodology has recently demonstrated that harmonic loads can be controlled on wide bandwidths [5] but the low-pass filter must be optimized under the constraint that fundamental impedances can still be matched. Then, the L_2-C_2 circuit is inserted and optimized so that it has a negligible impact on the 2nd-harmonic matching, and facilitates the matching at the fundamental frequencies when associated to the L_1-C_1 filter with Z_L fixed at 50Ω.

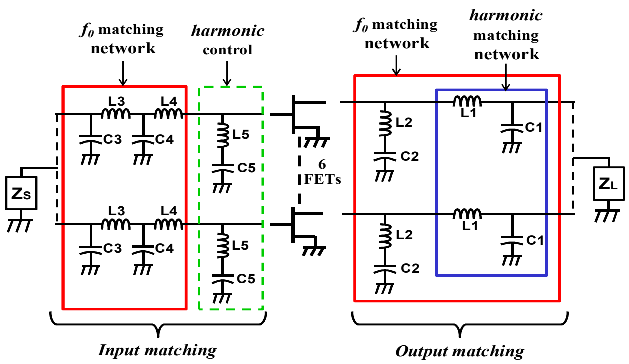

Fig. 1. Equivalent circuit model of the synthesized package.

Secondly, the input matching at fundamental frequencies is performed by a 2nd-order low-pass filter (L_3-C_3 and L_4-C_4) in the case of Z_S fixed at 50Ω. Then, the L_5-C_5 circuit is added in order to present low impedances (with negative reactance) at the 2nd-harmonic frequencies within the gate plane of each unit cell. The 2nd-harmonic source impedances of each GaN die are confined into their high-PAE regions whatever the impedances presented outside the package (i.e. Z_S at $2f_0$ is swept all over the entire Smith chart). At the input, the L_5-C_5 circuit performs the same function as the L_1-C_1 low-pass filter at the output except that it has a negligible impact on the input matching at the fundamental frequencies. Fig. 2 shows a photograph of the fabricated power amplifier and a schematic presenting the implementation of the ideal circuit elements.

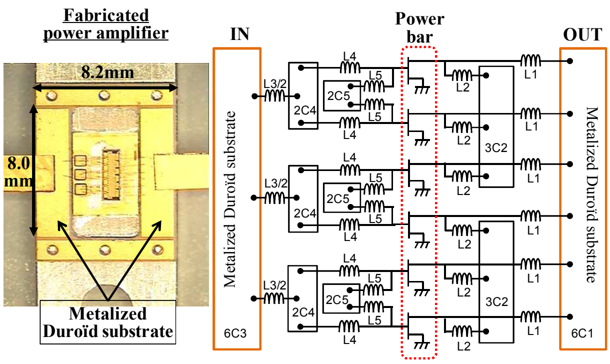

Fig. 2. Photograph and schematic of the fabricated package.

It should be noted that the ideal C_1 and C_3 capacitances were actually synthesized by shaping the widths of the metalized Duroïd substrate at the output and input of the package, respectively. Indeed, the package capacitances are determined by the substrate thickness and the surface area of metal plates. Hence, these parasitic capacitances are absorbed into the matching network. The other matching capacitances (C_2, C_4, C_5) were synthesized by MIM capacitors while all inductances were realized by bond wires for which the length, diameter and shape were optimized to have the required inductance values.

III. Power Measurements

A dedicated 50Ω test fixture was fabricated for power measurements of the packaged GaN HEMT, and measured performances were shifted to the package ports using TRL de-embedding. The RF input power was pulsed using a 10µs pulse width at a 10% duty cycle while biasing voltages were continuous. The gate bias voltage was slightly above pinch-off and the drain bias voltage was set to 50V.

A. Measurements with 50Ω source and load impedances

At first, the packaged GaN HEMT was measured with 50Ω source and load impedances at f_0 and $2f_0$. Fig. 3 shows the measured power performances from 2.9 to 3.7 GHz at 35.4dBm of available RF input power and 1.5dB gain compression. In 50Ω environment, this packaged GaN HEMT already demonstrates promising results from 2.9 to 3.7 GHz with 45W output power, 11dB power gain, and a limited PAE variation between 55 and 60% over such a wide bandwidth.

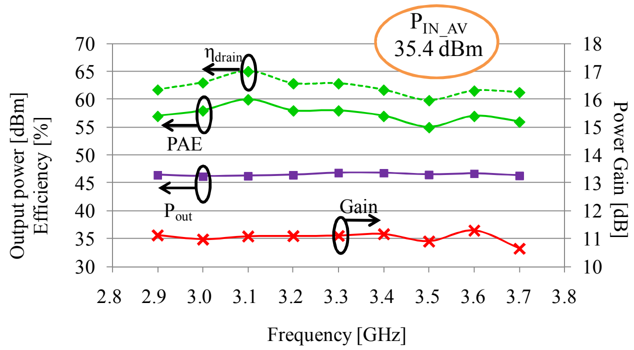

Fig. 3. Measured performances of the packaged GaN HEMT in 50Ω environment from 2.9 to 3.7 GHz at 1.5dB gain compression.

B. Measurements with optimum source and load impedances

In order to evaluate the potentiality of this packaged GaN powerbar over such a large bandwidth, two different characterizations were successively carried out.

The first characterization step consisted of source-pull and load-pull measurements at each fundamental frequency f_0 of the bandwidth while Z_S and Z_L were set to 50Ω at $2f_0$. The optimum impedances ($Z_{L\text{-}OPT}$ and $Z_{S\text{-}OPT}$) of the package were determined at each f_0 for achieving maximum PAE and minimum return loss, respectively. The curves of Fig. 4 shows the measured results of the first characterization step from 2.7 to 3.7 GHz at 34.4dBm of available input power and 2dB gain compression. In a 50Ω environment at $2f_0$ with optimum source and load impedances at f_0, more than 50W output power, 12dB gain, and 60% PAE are achieved from 2.9 to 3.6 GHz (i.e. 21% bandwidth). The PAE varies between 60% and 66% over the bandwidth. Moreover, Fig. 5a shows the loci of optimum load impedances ($Z_{L\text{-}OPT}$) at f_0 from 2.9 to 3.7 GHz demonstrating that the internal matching circuits have moved the optimum load impedances closer to 50Ω.

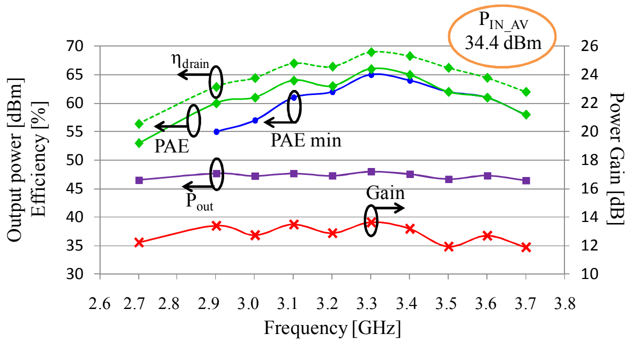

Fig. 4. Power measurements of the packaged GaN HEMT with optimum impedances ($Z_{S\text{-}OPT}$, $Z_{L\text{-}OPT}$) at f_0 and 50Ω at $2f_0$. The blue curve denotes the worst value of measured PAE at each frequency when Z_L is swept all over the entire Smith chart at $2f_0$.

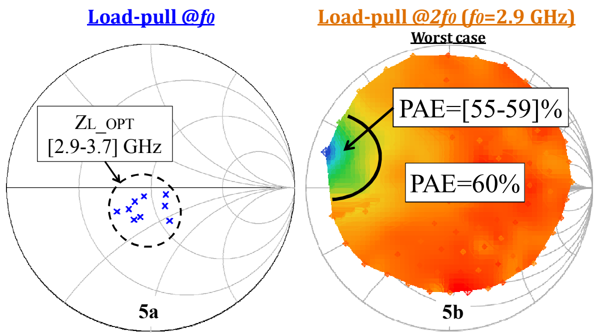

Fig. 5. a) Loci of optimum load impedance ($Z_{L\text{-}OPT}$) at f_0 when Z_L=50Ω at $2f_0$ from 2.9 to 3.7 GHz, b) Worst-case variation of PAE at 2.9 GHz when Z_L is swept all over the entire Smith chart at $2f_0$.

In order to assess the insensitivity of the packaged GaN HEMT to external load variations at $2f_0$, the second characterization step consisted in sweeping Z_L all over the entire Smith chart at $2f_0$ while Z_L was fixed at its optimum value $Z_{L\text{-}OPT}$ at f_0. Under these worst-case conditions, the blue curve of Fig. 4 shows the worst values of measured PAE from 2.9 to 3.7 GHz, demonstrating that the worst-case variation of PAE remains lower than 5 points at 2.9 GHz and lower than 1 point above 3.5 GHz. At the frequency of 2.9 GHz where the maximum variation of PAE is measured, Fig. 5b shows the impedance sweep performed at $2f_0$ on the Smith chart with its corresponding level of measured PAE. It can be observed on Fig. 5b that the worst-case impedances at $2f_0$ are located in a very small area of the Smith Chart. In comparison to the same measurements performed on one unit-cell, on-wafer load-pull measurements at $2f_0$ have exhibited more than 20 points of variation for the measured PAE which demonstrates that the internally-matched packaged GaN HEMT is desensitized to external load variations at $2f_0$.

IV. Conclusion

The reported method of wideband package design dedicated to high-power GaN HEMT powerbar demonstrates the capability to reach high PAE over wide bandwidths in S-band. To our knowledge, this packaged GaN HEMT exhibited the best PAE performances over such wide bandwidths in S-band. In a 50Ω environment, more than 55% PAE and 45W output power are demonstrated over 24% bandwidth in S-band while more than 60% PAE and 50W output power are achieved over 21% bandwidth. Table I summarizes the performances of this internally-matched packaged GaN HEMT. Finally, this work also demonstrates that the load impedances of the internal powerbar at 2nd-harmonic frequencies can be confined into high PAE regions whatever loads presented outside the package. Therefore, the packaged powerbar is desensitized to external load variations at the 2nd-harmonic frequencies.

TABLE I

PERFORMANCES OF THE PACKAGED AMPLIFIER vs. BANDWIDTH

Freq [GHz]	Relative bandwidth	Terminations Z_S / Z_L	PAE min	PAE max	Pout	Gain
[2.9-3.7]	24%	50Ω / 50Ω	55%	60%	45 W	11 dB
[2.9-3.6]	21%	$Z_{S\text{-}OPT}$ / $Z_{L\text{-}OPT}$	60%	66%	50 W	12 dB
[2.7-3.7]	31%	$Z_{S\text{-}OPT}$ / $Z_{L\text{-}OPT}$	53%	66%	45 W	12 dB

Acknowledgement

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