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

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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 \( f_o \) and \( 2f_o \) 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 \( 2f_o \) 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 \( f_o \).

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 \( 2f_o \) 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 \( L_1-C_2 \) circuit is inserted and optimized so that it has a negligible impact on the 2\textsuperscript{nd}-harmonic matching, and facilitates the matching at the fundamental frequencies when associated to the \( L_1-C_1 \) filter with \( Z_s \) fixed at 50Ω.

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.

#### 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 \( Z_d \) were set to 50Ω at \( 2f_0 \). The optimum impedances (\( Z_{s,OPT} \) and \( Z_{d,OPT} \)) 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,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.

![Power measurements of the packaged GaN HEMT with optimum load impedances (Z_{L,opt} at f_0, 2.9 3.7 GHz)](image)

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,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**

<table>
<thead>
<tr>
<th>Freq [GHz]</th>
<th>Relative bandwidth</th>
<th>Termination Z_L/Z_0</th>
<th>PAE min</th>
<th>PAE max</th>
<th>Pout</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>[2.9-3.7]</td>
<td>24%</td>
<td>Z_0/50Ω</td>
<td>55%</td>
<td>60%</td>
<td>45W</td>
<td>11dB</td>
</tr>
<tr>
<td>[2.9-3.6]</td>
<td>21%</td>
<td>Z_{L,opt} / Z_{L,opt}</td>
<td>60%</td>
<td>65%</td>
<td>50W</td>
<td>12dB</td>
</tr>
<tr>
<td>[2.7-3.7]</td>
<td>31%</td>
<td>Z_{L,opt} / Z_{L,opt}</td>
<td>53%</td>
<td>66%</td>
<td>45W</td>
<td>12dB</td>
</tr>
</tbody>
</table>

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### REFERENCES


