Design of a 55 W Packaged GaN HEMT with 60% PAE by Internal Matching in S-Band

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***Abstract* — This paper reports a package synthesis method in order to ensure good performances in PAE, output power and bandwidth. The internal matching circuits of the optimized package enable to reach the best impedance pre-matching at fundamental frequencies and also to confine the harmonic impedances seen by the internal GaN power bar into safe-efficiency regions whatever the external impedances presented to the package at second harmonic frequencies. In a 50Ω environment, the packaged GaN HEMT delivers 55 W output power associated with 60% PAE and 13.3 dB power gain at 2.7 GHz. By optimizing source and load impedances at the fundamental frequencies, the packaged GaN HEMT demonstrates more than 58% PAE from 2.6 GHz to 3.0 GHz.**

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

I. Introduction

Modern radar applications in S-band require more and more trade-off between power added efficiency (PAE) and output power over wider frequency bandwidths. High-efficiency classes [1-2] are defined by specific shapes of voltage and current waveforms across the transistor which are synthesized by controlling harmonic load impedances. However, packaging of GaN HEMTs presents many inconveniences that lead to a critical harmonic impedance matching on wide bandwidth. For example, hybrid power amplifiers are generally optimized by designing the matching networks outside the package so that optimum harmonic impedances can not generally be reached due to the cut-off frequency of the package.

Recently hybrid power amplifier [3] has associated high efficiency and high output power in S-band. Moreover, quasi MMIC power amplifiers [4-6] have presented very interesting global performances in terms of PAE, output power and bandwidth. Such performances can be reached by an appropriate matching or pre-matching inside the package of fundamental and harmonic impedances. For example, a previous study [7] has demonstrated that second harmonic load impedances can be matched inside the package on more than 30% relative bandwidth. This harmonic matching was designed by optimizing the bond wires and the size of metalized ceramics within the package.

In this paper, our aim is to synthesize a package to provide the best trade-off between impedance matching at second harmonic frequencies and the pre-matching at the fundamental frequencies. Thus, the designed package ensures that the second harmonic impedances seen by the internal active die are controlled, whatever 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 the power measurements, respectively.

II. Technology & Package Synthesis.

The active die is a HEMT device from the released GaN GH50_10 process provided by UMS. This technology has been qualified up to operating drain voltages of 50V. The GaN HEMT powerbar has a gate periphery of 14.4 mm composed of six unit cells of 2.4 mm gate width.

This package synthesis is performed by using measured and simulated impedance contours of the unit cells at the fundamental and second harmonic frequencies. All elements of the package are also optimized to ensure a good trade-off between the control of source and load impedances at second harmonic frequencies and the best pre-matching at the fundamental frequencies from 2.6 GHz to 3.0 GHz.

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

First, the output matching of the internal active die is performed by a 2nd-order low-pass filter (L_0-C_0; L_1-C_1) and a resonant filter L_2-C_2 which are successively optimized so that the internal second harmonic load impedances seen by the active die are confined in safe PAE regions. The synthesis of second harmonic load impedances is first ensured by the 2nd-order low-pass filter when Z_L is swept over the entire Smith chart at $2f_0$. Then, the output pre-matching at f_0 is performed by the optimization of the L_2-C_2 circuit when Z_L is fixed to 50Ω.

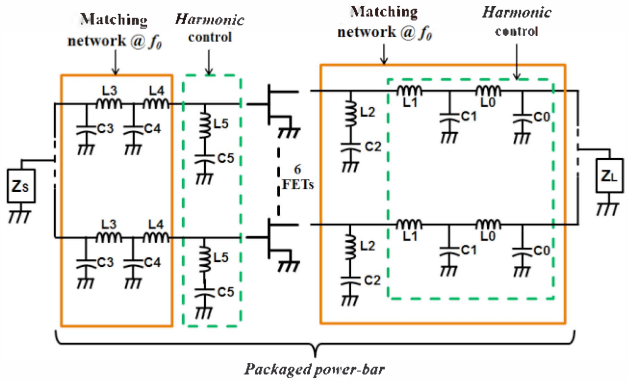

Fig. 1. Equivalent circuit model of the synthesized package.

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. Finally, the L_5-C_5 circuit is added in order to control the second harmonic source impedances. Optimal controls of second harmonic source impedances have already demonstrated PAE improvements [8]. In this study, the L_5-C_5 circuit is optimized only to ensure a control of second harmonic source impedances in safe efficiency regions from [2.6-3.0] GHz. Without the implementation of this filter, second harmonic source impedances would have been controlled in low efficiency regions. Moreover, the filter properties allow second harmonic source impedances of each GaN die to be confined to safe PAE regions, whatever the impedances presented outside the package (i.e. Z_S at $2f_0$ is swept over the entire Smith chart). However, this method of second harmonic source control has already demonstrated significant PAE improvements on wide bandwidth in S-Band while optimal efficiency areas were reached [9].

In order to illustrate the fabricated packaged power bar, Fig. 2 shows the circuit schematic presenting the actual implementation of ideal circuit elements.

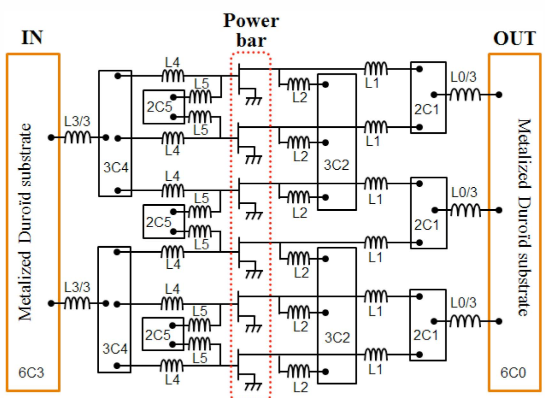

Fig. 2. Schematic of the fabricated package.

The ideal C_3 and C_0 capacitances are synthesized by shaping the metalized input and output ceramics of the power package, respectively. The other capacitances are synthesized by MIM capacitors. Each inductance represents one bond wire. Note that mutual inductances are considered in simulations.

This design method, using different package architecture, was recently applied on the same GaN device in order to reach performances from 2.9 GHz to 3.7 GHz [10]. In a 50Ω environment, more than 55% of PAE associated to 45W output power has been measured over the entire bandwidth.

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.

At first, the packaged GaN HEMT was measured with 50Ω source and load impedances at f_0 and $2f_0$. Dot line curves on Fig. 3 show the measured power performances from 2.6 GHz to 3.0 GHz at 34 dBm of available RF input power. In a 50Ω environment, the packaged GaN HEMT already demonstrates promising results from 2.6 GHz to 2.9 GHz with 40 W output power, 12 dB power gain, and a minimum PAE of 50%. Note that 60% PAE are measured, associated with 55 W output power and 13.3 dB power gain.

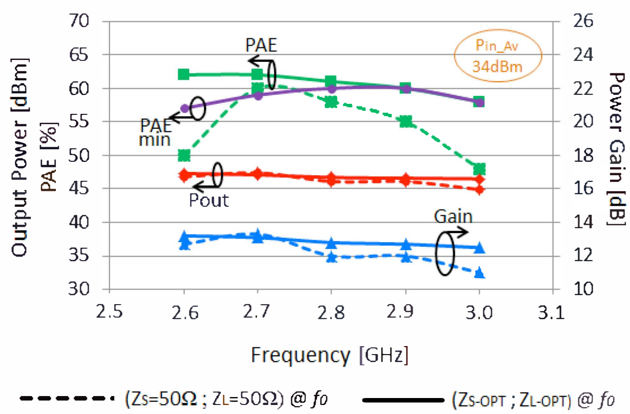

Fig. 3. Power measurements of the packaged GaN HEMT using 50Ω (dotted lines) or optimum impedances [$Z_{S\text{-}OPT}$&$Z_{L\text{-}OPT}$] (full lines) at f_0 (in both cases, 50Ω terminations at $2f_0$). The purple curve (with circle) denotes the worst value of measured PAE at each frequency when Z_L is swept over the entire Smith chart at $2f_0$.

Secondly, in the case of Z_S and Z_L set to 50Ω at second harmonic frequencies, source-pull and load-pull measurements were performed at each fundamental frequency to determine the minimum return losses and the maximum PAE, respectively. The full line curves of Fig. 3 show the measured results from 2.6 GHz to 3.0 GHz at 34 dBm of available input power. This packaged power bar demonstrated more than 45 W output power, 12.5 dB gain, and 58% PAE on 14% relative bandwidth.

In order to assess the insensitivity of the packaged GaN HEMT to external load variations at second harmonic frequencies, Z_L is swept over the entire Smith chart at $2f_0$ while Z_L was fixed at its optimum value $Z_{L\text{-}OPT}$ at f_0. The purple curve on Fig. 3 presents the worst measured PAE from 2.6 GHz to 3.0 GHz. At 2.6 GHz, the PAE variation is only 5 points and becomes insignificant from 2.8 GHz to 3.0 GHz. In comparison to the same measurements performed on a single unit-cell, on-wafer load-pull measurements at $2f_0$ have exhibited more than 20 points variation of the measured PAE. This demonstrates that the internally-matched packaged GaN HEMT is desensitized to external load variations at $2f_0$.

Fig. 4 shows the optimum loci of external source and load impedances measured at the input and the output of the packaged power-bar at fundamental frequencies. On the measurement bandwidth [2.6-3.0] GHz, the magnitude variation of the optimum source reflection coefficients range from 0.2 to 0.45, and the magnitude variation of the optimum load reflection coefficients range from 0.11 to 0.25 from 2.6 GHz to 2.9 GHz.

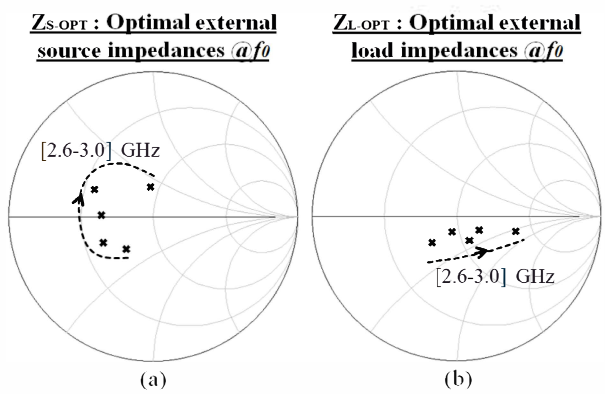

Fig. 4. Loci of optimum source (a) and load (b) impedances @ f_0 of the packaged power-bar when Z_L=50Ω @ $2f_0$.

IV. Conclusion

This packaged power-bar was primarily designed to ensure the insensitivity of the active device to external load variations at second harmonic frequencies, and also to facilitate the external matching at fundamental frequencies. The reported method of package synthesis has led to very good performances in terms of PAE, output power, and bandwidth. This Packaged power bar can provide more than 58% PAE and 45W output power over 14% bandwidth. Moreover, the measured PAE variations are lower than 2 points from 2.7 GHz to 3.0 GHz when a load pull is performed at the second harmonic frequencies outside the package. Table I summarizes the performances of this internally-matched packaged GaN HEMT.

TABLE I

PERFORMANCES OF THE PACKAGED AMPLIFIER VS. BANDWIDTH

Freq [GHz]	Relative bandwidth	Terminations ZS / ZL	PAE min	PAE max	Pout min	Gain min
2.7	-	50Ω / 50Ω	60%		55W	13.3 dB
[2.6-2.9]	11%	50Ω / 50Ω	50%	60%	40W	12 dB
[2.6-3.0]	14%	$Z_{S\text{-}OPT}$ / $Z_{L\text{-}OPT}$	58%	62%	45W	12.5 dB

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