Investigation of Class-B/J Continuous Modes in Broadband GaN Power Amplifiers

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Abstract — The class-B/J mode continuum in power amplifiers (PAs) defined at the current source plane is discussed considering different parasitic elements including C_{DS} as well as the package. Based on this realistic device description the change of the continuous load impedances depending on the reference plane is demonstrated. It is shown that the design flexibility predicted by the continuous mode theory decreases if the transistor package is taken into account. The presented investigations provide the basis for the design of a broadband GaN PA. In the frequency range of 0.9 GHz to 1.8 GHz, this PA achieves a saturated output power of more than 70 W with an efficiency η of 56-63 %. In the extended frequency band up to 2.3 GHz an output power of still 60 W with 53 % drain efficiency is available.

Index Terms — Broadband amplifiers, Gallium nitride, HEMTs, Impedance matching, Microwave amplifiers, Power amplifiers.

I. INTRODUCTION

The wide variety of modern wireless applications requires communication systems that are able to cover multiple standards such as GSM, UMTS and LTE. In order to reduce the operational costs of multi-standard transmitters, highly efficient broadband PAs are preferred. A well-known approach to boost the efficiency is the implementation of harmonic tuning strategies. However, the required harmonic terminations at the current source plane of e.g. class-F amplifiers can practically not be realized over larg bandwidths. More precisely, the device and package parasitic elements together with high quality factor matching networks limit the broadband capability of such classical concepts.

In this context, continuous modes of operation have been recently investigated for class-B/J [1], [2], class-F [3] and class-F[-1] [4] amplifiers. The presented theoretical formulations state the existence of continua of amplifier modes with the same high efficiency over a continuous range of fundamental and harmonic terminations. With respect to the design of harmonically tuned PAs, this approach offers a more flexible methodology to achieve high efficiency over increased bandwidths.

In this work we investigate the practical behavior of continuous class-B/J modes for high power ranges. The impact of the device parasitic elements as well as the effect of the package is analyzed. The results of these considerations provide the basis for the design of a broadband 70-Watt GaN-HEMT PA with more than one octave bandwidth.

The organization of this paper is as follows. In Section II the optimum load impedances of continuous class-B/J operation and the impact of the device parasitic elements on these impedances are investigated. The design and characterization of a broadband 70-Watt GaN-HEMT PA are presented in Section III.

II. OPTIMUM LOAD IMPEDANCES

The origin of class-J mode of operation is the classical tuned load class-B amplifier with 78.5 % of maximum efficiency assuming short circuited harmonics. In contrast to class-B operation, the class-J amplifier uses a complex fundamental impedance together with a purely reactive 2nd harmonic termination as defined in (1) and (2) with α equals 1. The corresponding waveforms consist of a truncated sinusoidal current and a voltage with 2nd harmonic content resulting in the same efficiency and power performance as class-B operation. However, class-J is not the only possible solution. The phase shift between voltage and current waveforms can be set by the parameter α keeping the total overlap over one period constant. In other words, a continuum ranging from class-J ($\alpha = 1$) over class-B ($\alpha = 0$) to class-J[-1] ($\alpha = -1$) with constant power and efficiency has been recently presented in [1]. Fig. 1 illustrates the continuous $f_0/2f_0$-impedance pairs defined in (1) and (2). Using this range of possible impedances, a more flexible design methodology is available.

$$Z_{f0} = R_{opt} + j \cdot \alpha \cdot R_{opt} \quad (-1 < \alpha < 1) \qquad (1)$$

$$Z_{2f0} = 0 - j \cdot \alpha \frac{3\pi}{8} R_{opt} \quad (-1 < \alpha < 1) \qquad (2)$$

With regard to the design of a practical PA, it is important to mention that the impedances in (1) and (2) correspond to the current source reference plane of the transistor. The device parasitic elements as well as the package introduce frequency-dependent impedances at the accessible reference planes of the device. In order to analyze these effects, the element values of the simplified equivalent circuit in Fig. 2 were derived for the high power GaN-HEMT of choice (Cree CGH40045).
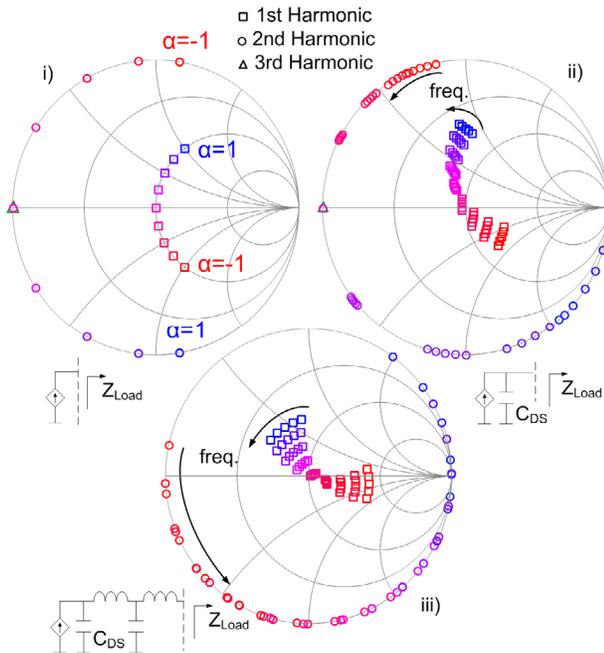
Fig. 1. Load impedances of the class-B/J continuum ($-1 < \alpha < 1$, step 0.25), current source plane (i), C_{DS} included (ii), lead plane (iii), normalized to $R_{opt}=12\,\Omega$ of the GaN-HEMT device of choice, fundamental frequency range from 1.0 to 1.8 GHz.
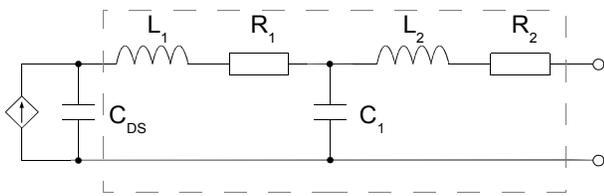

Fig. 2. Simplified equivalent circuit of the transistor output including C_{DS} and parasitic elements [5].

To determine the values of the equivalent circuit elements the large-signal model of the packaged transistor and a bare-die transistor with the equivalent circuit were compared in simulation. Using this knowledge their effect on the continuous optimum load impedances was analyzed. Fig. 1 (ii) shows the impact of the drain-source capacitance ($C_{DS}=4$ pF) on the continuous optimum load reflection coefficient for a fundamental frequency range of 1.0-1.8 GHz. The load line impedance of the selected device ($R_{opt}=12\,\Omega$) has been used to normalize the reflection coefficient. It can be seen that C_{DS} introduces frequency-dependent optimum load impedances with increased expansion at higher $|\alpha|$ values. However, the basic characteristic of the continuum remains similar for the considered device and frequency range. The major concern regarding the PA design is which load impedances can be practically implemented using a real matching network. In this context, it must be ensured that the selected $f_0/2f_0$-impedance pairs will lead to a continuous clockwise curve in the Smith chart across the frequency band. Such load impedance is exemplarily illustrated in Fig. 3 (i) and (ii).
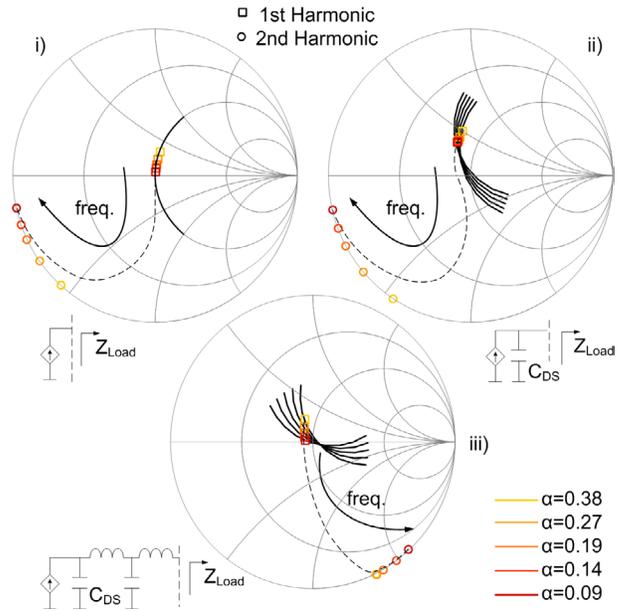

Fig. 3. Matching example: Load impedance trace of the class-B/J continuum, current source plane (i), C_{DS} included (ii), lead plane (iii), normalized to $R_{opt}=12\,\Omega$ of the GaN-HEMT device of choice, fundamental frequency range from 1.0 to 1.8 GHz.

In this case α ranges from +0.38 at 1 GHz to +0.09 at 1.8 GHz. The situation becomes more difficult in the case of packaged transistors. Taking into account the package parasitics the optimum load impedance continuum shown in Fig. 1 (iii) is the consequence. It can be seen that the array of fundamental curves is further expanded and the 2nd harmonic regions for different α are overlapping. Accordingly, it becomes more difficult to construct a continuous clockwise load impedance curve over the frequency band out of the available $f_0/2f_0$-pairs.

For instance, if the load impedance shown in Fig. 3 (i) should again be realized at the current source plane, the anti-clockwise load impedance curve in Fig. 3 (iii) is required at the lead reference plane of the device. The reason is that for different α the 2nd harmonic impedance range is affected differently by the parasitic elements. This example demonstrates that the implementation of a continuous mode PA is challenging and the degree of freedom is more and more lost if large packaged devices with increased parasitic element values are taken into account. Nevertheless, the design methodology can still lead to a satisfactory broadband performance if certain compromises are accepted for the load impedance as will be shown in the following section.
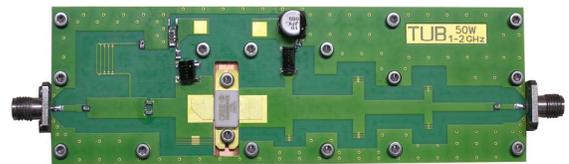

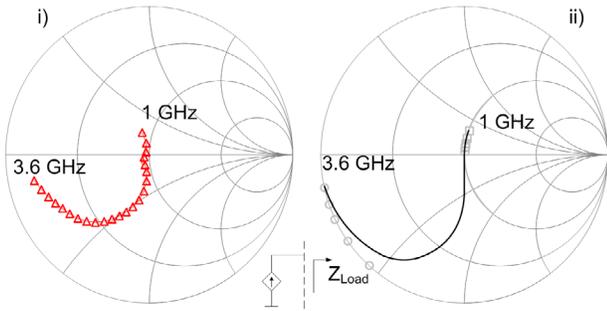Fig. 4. Fabricated broadband PA using a CGH40045 GaN HEMT.

Fig. 5. Realized impedances of the OMN at the current source plane (i), theoretical optimum of the continuous load impedances (ii), normalized to R_{opt}=12 Ω.

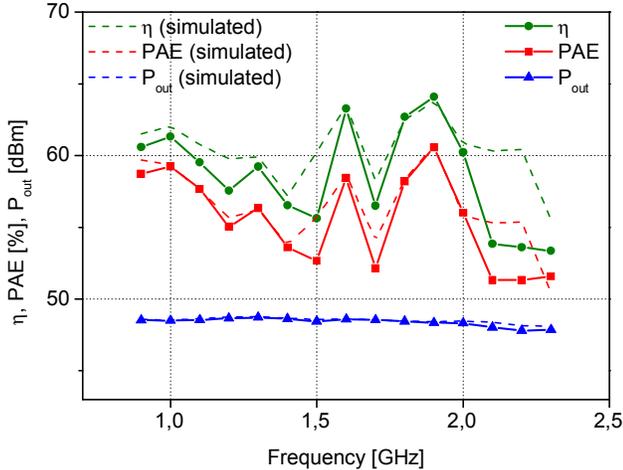Fig. 6. Measured (solid) vs. simulated (dashed) saturated output power and efficiency of the broadband PA, V_{dd}=36 V, I_{dq}= 0.5 A.

III. POWER AMPLIFIER DESIGN

According to the results of the previous section a broadband PA was designed. The optimum load impedances have been verified and have been slightly adopted, by means of source/load-pull simulations in order to get an optimum power efficiency trade-off at around 3-dB power compression.

This provides the basis for the design of a multi-section microstrip output matching network consisting of three open stubs. At the input a microstrip matching network using a short-stub provides the optimum source impedances found in the source pull characterization. Fig. 4 shows a photograph of the manufactured broadband PA on a Rogers substrate (ε_r = 3.55) with a total board area of 12 x 4 cm².

Considering again the simplified equivalent circuit in Fig. 2, the load impedances in Fig. 5 (i) are realized at the current source plane of the device. It can be seen that the realized impedances show a shape very similar to the optimum case in Fig. 5 (ii). This is especially valid for the impedances of the fundamental frequency ranging from 1.0 GHz to 1.8 GHz. For the 2nd harmonic terminations a compromise had to be implemented resulting in load reflection coefficients with decreased magnitudes. This compromise enables an increased

bandwidth exceeding one octave with minor performance degradation. The measurement results versus simulated performance are shown in Fig. 6. In the frequency range of 0.9-1.8 GHz an output power of more than 48.4 dBm with η of 56-63 % was measured. The overall power gain was 12 dB. In the extended bandwidth 1.8-2.3 GHz, the output power was reduced to 47.8 dBm with η of around 53 %.

VI. CONCLUSION

This contribution shows the behavior of the optimum load impedances considering the output capacitance as well as the package parasitic elements of a transistor. The behavior of continuous PA modes in the case of a non-accessible current source was analyzed. For the targeted transistor it was demonstrated that the effect of the C_{DS} in the considered frequency range kept a high degree of freedom to choose $f_0/2f_0$-impedance pairs. This freedom is strongly limited if package parasitic elements are considered. Using the design space provided by the class-B/J continuum a highly efficient amplifier with a frequency range of 0.9-1.8 GHz was manufactured. A saturated output power of at least 48.4 dBm with a η of 56-63 % was measured. Due to compromising between fundamental and 2nd harmonic frequency the bandwidth was extended up to 2.3 GHz with an output power of more than 47.8 dBm and η of 53 %.

ACKNOWLEDGMENT

REFERENCES

[1] P. Wright, J. Lees, J. Benedikt, P. J. Tasker, and S. Cripps, "A Methodology for Realizing High Efficiency Class-J in a Linear and Broadband PA," *IEEE Transactions on Microwave Theory and Techniques.,* vol. 57, no. 12, pp. 3196–3204, Dec. 2009.
[2] S. C. Cripps, P. J. Tasker, A. L. Clarke, J. Lees, and J. Benedikt, "On the Continuity of High Efficiency Modes in Linear RF Power Amplifiers," *IEEE Microwave. Wireless Component Letters,* vol. 19, no. 10, pp. 665–667, Oct. 2009.
[3] V. Carrubba , A. L. Clarke, M. Akmal, J. Lees, and J. Benedikt, P. J. Tasker, S. C. Cripps, "On the Extension of the Continuous Class-F Mode Power Amplifier," *IEEE Transactions on Microwave Theory and Techniques,* vol. 59, no. 5, pp.1294–1303, May 2011.
[4] V. Carrubba , A. L. Clarke, M. Akmal, Z. Yusoff, J. Lees, and J. Benedikt, S. C. Cripps, P. J. Tasker, "Exploring the design space for broadband PAs using the novel "Continuous Inverse Class-F mode," *Microwave Conference (EuMC), 2011 European*, pp. 433–436, Oct. 2011.
[5] J. Chéron, M. Campovecchio, D. Barataud, T. Reveyrand, S. Mons, M. Stanislawiak, P. Eudeline, D. Floriot, W. Demenitroux, "Design and modeling method of package for power GaN HEMTs to limit the input matching sensitivity," *Workshop on Integrated Nonlinear Microwave and Millimeter-Wave Circuits 2011*, pp. 1–4, Apr. 2011.