Harmonically-Tuned Octave Bandwidth 200 W GaN Power Amplifier

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Abstract—**In this paper, the design, implementation, and experimental results of a 200 W high efficiency broadband GaN HEMT power amplifier (PA) are presented. Power combining was used to combine the outputs of two individual octave bandwidth 100 W power amplifiers. Optimum fundamental and harmonic load impedances were obtained using load-pull simulations for the active device across the design band. A systematic approach was applied for the design of wideband output and input matching networks. From continuous wave large-signal measurements a maximum output power of greater than 200 W was obtained over an octave bandwidth. The corresponding drain efficiency (power-added efficiency) ranged between 45–56% (40–52 %).**

Keywords *- broadband power amplifier; Gallium Nitride HEMT; harmonic analysis; 200 W*

I. INTRODUCTION

Power amplifiers (PAs) are among the most important blocks of modern wireless telecommunication and radar transmitters. Besides the generation of an adequate transmit power, efficiency enhancement techniques and broadband amplifier concepts became more and more important topics over the last years. The drivers behind these developments are mainly costs, which could be significantly reduced with multi-standard transmitters covering several standards with only one highly efficient PA. Potential areas of application are mobile communications like DCS1800, PCS1900 and LTE, radar as well as broadcasting systems.

A well-known approach to boost the efficiency is the implementation of switch-mode amplifier concepts. However, the required harmonic terminations at the current source plane of e.g. classical class-F amplifiers can practically not be realized over larger bandwidths. More precisely, the device and package parasitic elements together with high quality factor matching networks limit the broadband ability of such classical concepts. Nevertheless, high power with likewise high efficiency over increased bandwidths can be achieved by employing harmonic tuning strategies. The reason is that there exists a continuous range of fundamental and harmonic terminations offering the same high efficiency and output power. With respect to the design of harmonically tuned power amplifiers, this approach offers a more flexible methodology to achieve high performance over increased bandwidths [1].

In this contribution we investigate the design and practical implementation of an efficient harmonically-tuned 200 W PA with a bandwidth of one octave. In order to achieve the targeted output power performance, two Cree CGH40120F GaN HEMT based PAs were combined with 90° power combiners. Table I shows the state-of-the-art performances of published broadband GaN PAs, proving the superior performance of the designed PA in this work.

TABLE I. STATE-OF-THE-ART BROADBAND GAN POWER AMPLIFIERS

Reference	*BW[GHz]*	*P_{out} [W]*	*Gain [dB]*	*PAE [%]*	*Notes*
2000 [2]	2.7-3.0	250	22	25	Multi-stage
2007 [3]	DC-3.4	5	15	24	Single stage
2009 [4]	2.7-3.0	120	7.5	65	Bare die
2011 [5]	1.0-2.0	90	11	50	Single stage
2011 [6]	1.55-2.25	100	12	60	Single stage
2011 [7]	0.2-0.8	200	14.5	45	4-stage
2012[8]	1.1-2.0	110	11	50	Single stage
This Work	1.0-2.0	200	13	40	90°Power combining

The organization of this paper is as follows. The power combining approach and an analysis of the harmonic tuning considerations will be discussed in Section II. The design procedure for the broadband 200 W PA will be presented in Section III. In Section IV, the experimental results are illustrated and discussed. Finally, the conclusions of this contribution are summarized in Section V.

II. POWER COMBINER AND HARMONIC TUNING

The high power density attained by its large bandgap and high breakdown voltage in combination with high operational frequencies and a very good efficiency makes the GaN HEMT the device of choice. The output capacitance C_{DS} of the high power transistor limits the bandwidth and the efficiency of the PA. The large C_{DS} causes a reduction of the output impedance at higher frequencies which results in higher current losses [5]. Careful design of the output matching network can compensate the capacitive reactance over a specific bandwidth.

In this paper, a broadband PA was targeted to operate in the frequency band of 1.0-2.0 GHz, delivering a saturated output power of 200 W, associated with high gain and efficiency. As mentioned before, the use of power combiners is necessary to achieve this power-level over an octave bandwidth. However, using the power combiner will introduce additional losses to the output signal, so the chosen combiner must have a low insertion loss to obtain the required output power. The resulting combining efficiency η_{comb} can be appraised from a given topology and the average insertion loss L of the combiners. Regarding the power combining architecture, combiners with only two input ports were considered (M=2). The total loss of the deployed combiner topology is given by

$$\eta_{comb} = \frac{P_{out,Comb}}{P_{out,Tran}} = M \cdot 10^{\frac{-L}{10}} \qquad (1)$$

Where:

- $P_{out,\,Comb}$: Output power of the combiner
- $P_{out,Tran}$: Output power of a single PA
- η_{comb}: Combiner efficiency

In this contribution, 90° hybrid couplers from Innovative Power Products Inc. (IPP-7013) were used. These combiners are expected to have an insertion loss of not more than 0.5 dB. The measured insertion loss and amplitude imbalance of the combiner used are shown in Fig. 1. To achieve an output power of at least 200 W, the required output power from each PA stage should be at least 112 W according to (1). The design was started by extracting the optimum source and load impedances over the design band including 2^{nd} harmonic load impedances. In this context, source/load-pull simulations using the large-signal transistor model had been performed. The effect of the harmonic load impedances on output power and efficiency were analyzed and considered in the design to increase the efficiency over the design band. The third order harmonics were not considered in the design of the output matching network because of the high C_{DS} of the power transistor.

Fig. 2 illustrates the optimum efficiency performance of the device versus the phase variation of the second harmonic reflection coefficient performed at unity reflection coefficient magnitude. It is noticed that the ideal performance is rather independent of the phase except when it approaches almost a short circuit (180°-220°). In this range, the efficiency performance of the active device is corrupted. The magnitude influence of the second harmonic reflection coefficient is heeded in Fig. 3 for the center frequency of 1.5 GHz. It can be observed from the Figure that the magnitude of the second harmonic load reflection coefficient has less influence on the performance of the PA than the phase of the reflection coefficient. Avoiding operation at critical phase zones near short-circuit termination for the second harmonic will result in high efficiency over the desired band of operation. Therefore, the predicted optimum load impedances must consider the fundamental and second harmonic frequencies.

III. BROADBAND 200 W PA DESIGN APPROACH

The first step to realize the load impedances extracted from the load-pull simulation is to find out the optimum topology using ideal lumped components, then transforming the resulting topology into distributed network with strip lines.

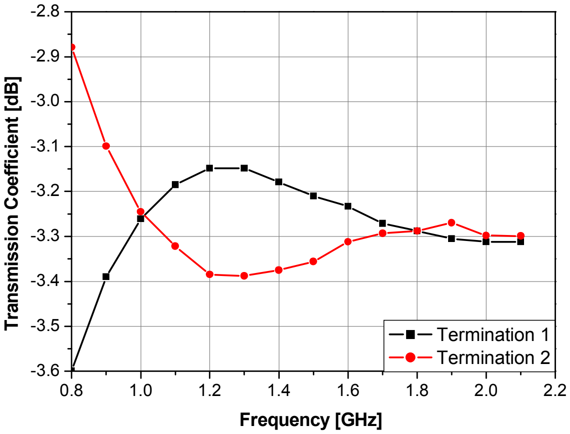

Figure 1. Measured transmission coefficients of the 90° combiner.

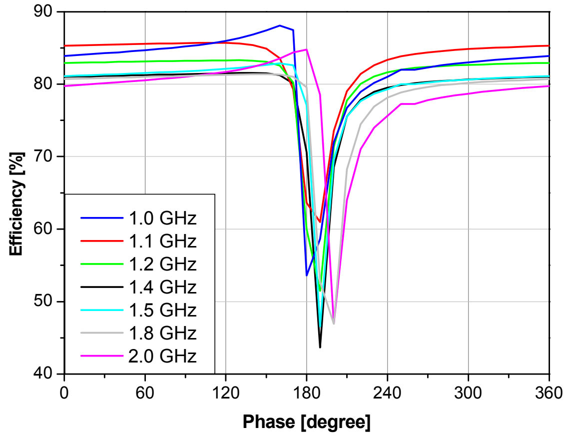

Figure 2. Influence of the 2^{nd} harmonic reflection coefficient phase on PA efficiency, performed with the active device at V_{DD}=36 V, I_{DQ}=900 mA at f= 1.0, 1.1, 1.2, 1.4, 1.5, 1.8 and 2.0 GHz.

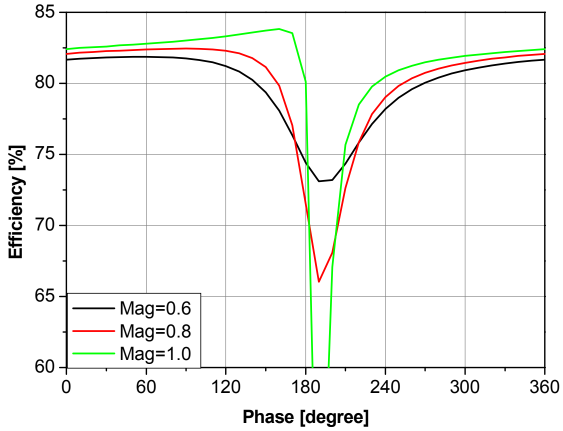

Figure 3. Influence of the 2^{nd} harmonic reflection coefficient magnitude on PA efficiency, performed with the active device at V_{DD}=36 V, I_{DQ}=900 mA at the center frequency of f=1.5 GHz.

The output matching network design considered the fundamental and second harmonic frequencies to obtain high efficiency performance. The input/output matching networks consist of stepped series transmission lines and multiple open stubs. Identical matching networks were designed for both 100 W PAs, where separate fine tuning of the individual PA stages was performed to take into account any amplitude/phase imbalances caused by the combiners. The designed PA structures were completed using broadband bias tees and stability networks and the 200 W PA was finally optimized for high power and efficiency. The output matching network of one of the two PA stages was realized and measured up to the maximum second harmonic frequency of 4 GHz as shown in Fig. 4. From the previously mentioned considerations in Section II, it is mandatory to say that the performance of the PA could be corrupted if the design band from 1 to 2 GHz is exceeded. For higher or lower frequencies critical phase zones near 180° are traversed by the second harmonic. As can be observed from Fig. 4, the second harmonic load reflection coefficient has a minimum magnitude of 0.71 in the simulation (0.69 in the measurement). Both of them result in high efficiency performance as illustrated in Fig. 3. Especially the critical second harmonic phase zone shown in Fig. 2 was avoided in the design. A final diagram of the 200 W PA is shown in Fig. 5. The simulated large-signal performance of the PA is shown in Fig. 6. An output power of higher than 53 dBm was simulated over the whole design band (1.0-2.0 GHz). The corresponding efficiency ranged from 52 % to 71 %, and the PAE from 47 % to 65 %. The broadband PA structure was realized on a Rogers substrate (ε_r=3.55, h=0.51 mm). The size of the amplifier prototype is 80 × 160 mm^2 as shown in Fig. 7.

IV. EXPERIMENTAL RESULTS

The implemented broadband PA was characterized by small and large-signal measurements to evaluate its performance. Preliminary experimental results showed a good agreement with simulated data over the design band.

A. Small-Signal Measurement

Fig. 8 heeds the comparison between the simulated and measured small-signal gain. The measured gain of the designed PA was subsequent to the simulated gain with a minimum value of 13 dB over the 1.0-2.0 GHz band.

B. Large-Signal Measurments

A continuous wave (CW) input signal generated by microwave generator boosted by a microwave driver amplifier was used to perform the large-signal measurements.

First, the sensitivity of PA performance against the gate bias V_{GS} was evaluated by applying different gate-bias voltages, and the output power and efficiency were measured for each gate voltage at different frequencies. It was observed that the PA performance could not be further optimized by post tuning of the gate biases. Therefore, similar gate biases were used for both 100 W PAs. Measurements were performed at a drain bias voltage of 36 V in order to obtain. Lower drain voltages can result in high output power together with high efficiency behavior higher efficiency but at lower output power and vice versa

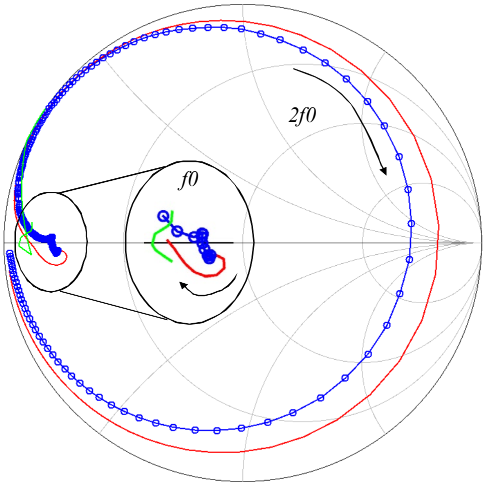

Figure 4. Optimum fundamental and harmonic load reflection coefficients of the output matching network over 1-4 GHz (green), realized coefficients in simulations (red) and measurements (circles-blue).

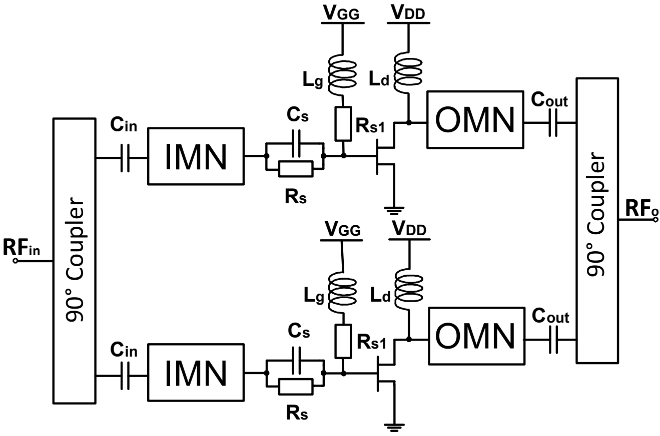

Figure 5. Final schematic of the designed 200 W broadband PA.

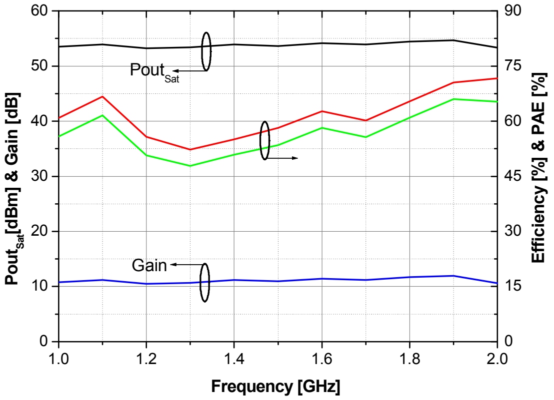

Figure 6. Simulated large-signal performance of the designed PA, with V_{DD}= 36 V, I_{DQ} = 900 mA for both PA stages.

Fig. 9 reports the measured saturated output power, drain efficiency, PAE, and gain as functions of the frequency. As can be observed from the Figure, a saturated output power ranging from 51.3 dBm to 53.5 dBm over 1.0-2.0 GHz (53-53.5 dBm over 1.1-2.0 GHz), with a minimum drain efficiency of 45 % (40% PAE) over the octave bandwidth have been achieved.

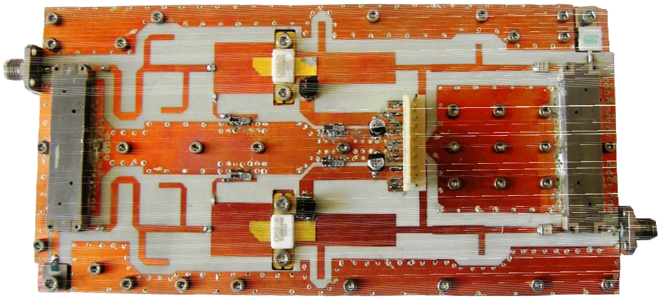

Figure 7. Photo of the fabricated broadband 200 W PA.

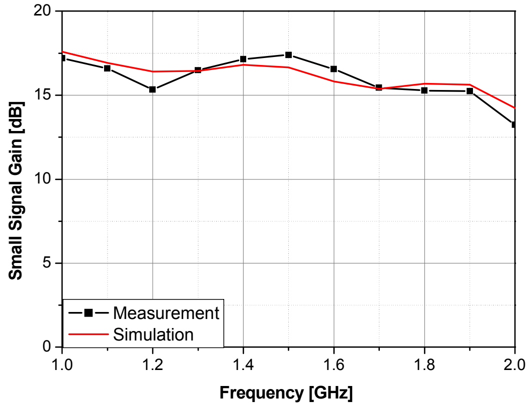

Figure 8. Small-signal gain of the realized PA simulated (solid lines) and measured (symbols) at V_{DD}=36 V, I_{DQ}=900 mA for both PA stages.

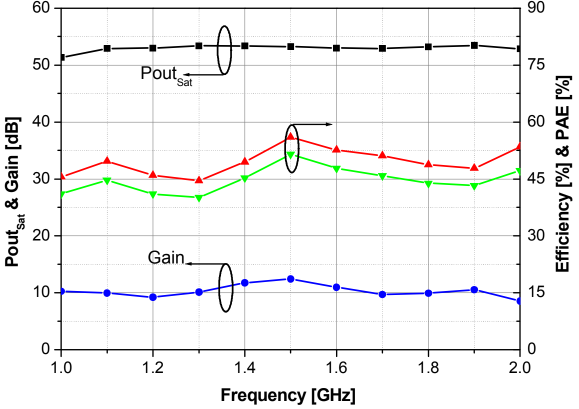

Figure 9. Large-signal performance of the realized PA measured at V_{DD}= 36 V, I_{DQ}=900 mA for both PA stages.

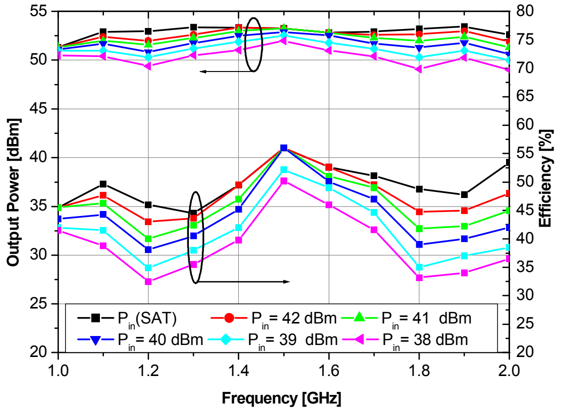

Figure. 10 Measured CW output power and efficiency over the design band at different input power levels, with VDD=36 V, IDQ=900 mA.

In Fig. 10, the measured output power is shown as a function of the frequency for different available input power levels (38-43 dBm in 1 dB step). A flat broadband output power together with acceptable efficiency behavior can be observed from the Figure over the design band for backed off input power.

V. CONCLUSION

In this contribution, the design and characterization of an octave-bandwidth 200 W PA have been presented. Influence of the second-order harmonic load was considered in the design to increase the efficiency across the design band. The designed PA was based on two individual 100 W PA stages with 90^o power combiners. Measurement results showed an output power of at least 53 dBm over 1.1-2.0 GHz (58 % bandwidth), with a minimum drain efficiency of 45 %.

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