Constant-gain Envelope Tracking in a UHF Outphasing Transmitter based on Continuous-mode Class-E GaN HEMT PAs

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Abstract — A UHF outphasing transmitter, based on continuous-mode class-E power amplifiers (PAs) and implementing a constant-gain envelope tracking (ET) strategy, is presented in this paper. Drain terminating and biasing networks are designed to provide near optima impedance values at the fundamental and higher order harmonics to the selected GaN HEMT device. A high-efficiency wideband performance, 80% for a 630-890 MHz range, is obtained, besides being amenable for load-modulation through a compact outphasing scheme, incorporating a series Chireix combiner and an impedance transformer. Once characterized in a pure output power phase-coding regime, the observed limitation in dynamic range is overcome by operating the amplifiers in a sort of continuous class-J mode, while forcing the load impedance to follow a constant-gain trajectory. A 1c-WCDMA signal, with peak-to-average power ratio (PAPR) of 8.4 dB is shown to be reproduced, satisfying the linearity requirements, with an average efficiency of 58%.

Index Terms — Chireix, Class-E, efficiency, GaN HEMT, outphasing, power amplifiers, UHF.

I. INTRODUCTION

High efficiency is a key issue for modern and future communication systems, reason why wireless transmitter architectures have been evolving to the use of techniques which may adjust the PA power consumption to the envelope of the signal. Dynamic biasing, typical of envelope tracking (ET) and envelope elimination and restoration (EER) topologies, together with load modulation, implemented in the Doherty and outphasing schemes, have found a relevant place among the preferred techniques when handling signals with large peak-to-average power ratio (PAPR) values. The outphasing concept, originally proposed by Chireix [1], has been showing its high potential to become a competitive alternative to the rest, supported by impressive results obtained when implemented with Class-E PAs [2, 3].

This paper presents the design of a UHF outphasing transmitter on GaN HEMT technology, based on the high-efficiency wideband coverage and load-dependent power control offered by the continuum of the class-E mode. Properly modifying the device operation to a continuous class-J mode, while introducing a constant-gain envelope tracking strategy through the mutual load modulation, the linearity requirements may be satisfied with a high average efficiency.

II. CONTINUOUS-MODE CLASS-E AMPLIFIER

The potential for designing class-E PAs using variations in the output network topology was first addressed in the seminar paper by Raab [4]. The continuous-mode operation, proposed later in [5], stablished that the desired zero voltage (ZVS) and zero voltage derivative switching (ZVDS) conditions could be simultaneously satisfied, for any value of the dc-feed inductance L_P, as long as the real and imaginary parts of the impedance seen at the fundamental were conveniently selected as a function of q, defined for a transistor with an output capacitance C_{out} as follows:

$$q = \frac{1}{\omega \cdot \sqrt{L_p \cdot C_{out}}} \quad (1)$$

This simple additional degree of freedom, associated to the value of the biasing coil, may result in different power profiles with frequencies, with a maximum of the output power coinciding with the efficiency peak for $q = 1.412$ (the parallel-circuit class-E PA). An optimum value of $q = 1.3$ was also found in [3], able of guaranteeing a high efficiency profile versus a varying resistive impedance, as the one to be approximately provided by a Chireix combiner [1].

A. Output network design for wideband operation

In order to address the use of the continuum of the class-E mode in [5] for wideband operation, a packaged GaN HEMT transistor from Cree (CGH35030F) was selected. A very simple switch model of the transistor was constructed using the measured values for the output capacitance, 3.6 pF, together with the off- and on-state resistances. The theoretical dc-feed inductor was calculated using (1) at $f_0 = 705\,MHz$ with $q = 1.412$, leading to the selection of a real 8 nH high-Q Air Core part from Coilcraft. Simulated 85% drain efficiency load-pull contours at the fundamental frequency, with ideal terminations (open circuit) at higher order harmonics, are shown in Fig. 1 for different q values and their corresponding frequencies (dashed lines). The q-dependent impedances providing peak efficiency (magenta circle markers) are also included.

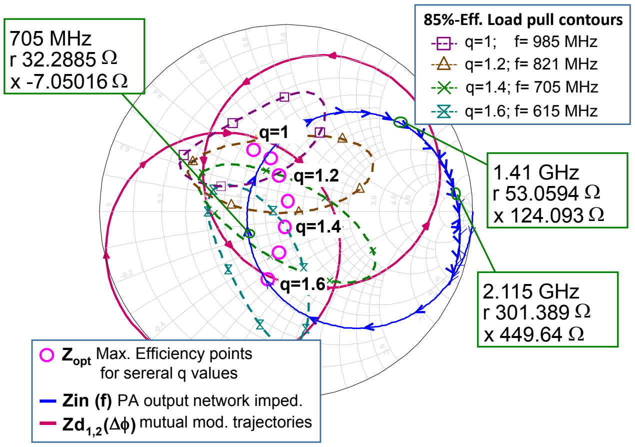

Fig. 1. Simulated efficiency contours for different ‘q’ values, intercepted by the $Z_{in}(f)$ locus. The Chireix mutual modulation trajectories are also shown.

Once the finite biasing inductor has been fixed in the design, there exists an inversely proportional relationship between the frequency and q, as shown in Fig. 1. A simple series LC network was used at drain side, based on a coil self-resonating between the second and third harmonics (12.5 nH in the schematic of Fig. 2) and a 2.7-pF capacitor adjusted to nearly resonate it at the center frequency, 705 MHz. Including the beneficial impedance transforming effect of the small length of 50 Ω microstrip line between them (not represented in the schematic for simplicity), this network allows synthesizing an input impedance locus rotating clockwise with frequency, $Z_{in}(f)$ in Fig. 1, leading to the interception of the 85% efficiency load-pull contours over the desired bandwidth.

B. Implemented power amplifier. Characterization.

The schematic and component values of the implemented PA are shown in Fig. 2. Results obtained from its characterization are included in Fig. 3. The measured efficiency stays above 80% between 630 and 890 MHz, a range in which the output power variation was lower than 2.3 dB. These figures are compared with some state-of-the-art broadband class-E PAs in Table I.

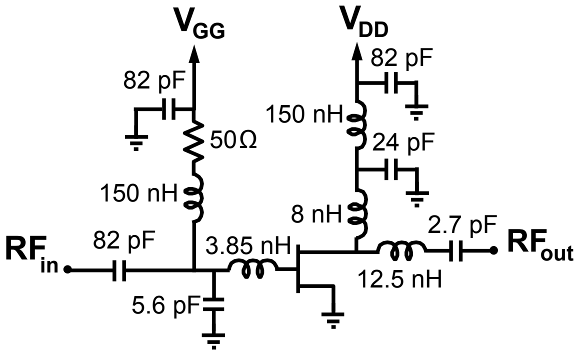

Fig. 2. Schematic of the designed PA. Coils and capacitors are from Coilcraft Air Core and ATC 100B series, respectively.

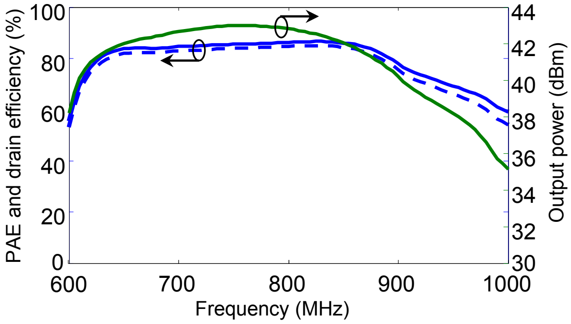

Fig. 3. Measured evolution of drain efficiency (solid line), PAE (dashed line) and output power with frequency.

TABLE I
COMPARISON WITH STATE-OF-THE-ART BROADBAND CLASS E PAS

f (GHz)	Technology	BW η> 80% (MHz)	η_{max} (%)	PAE (%)	P_{out} (dBm)	Reference
0.136-0.174	LDMOS	-	74	-	39	[6]
0.47-0.86	GaN HEMT	90	82	78	40	[7]
0.6-1	GaN HEMT	200	87.8	80.6	46.9	[8]
0.6-1	GaN HEMT	260	86.57	85	42.5	This work
1.73-2.16	GaAs HEMT	-	-	82.1	22.8	[9]

III. CONSTANT-GAIN ET IN AN OUTPHASING TRANSMITTER

A. Topology

An outphasing transmitter, inspired on [3], was then implemented over the previously described wideband PAs (see Fig. 4 for details). A simple combiner was adjusted, with series compensating reactances (3-pF capacitor and 12.5-nH inductor) determining the range of load impedances to be covered. Complemented with a small ratio transformer (1.2-pF shunt capacitor and 12.5-nH series inductor), such range may be also shifted in the desired power control direction. The adjusted modulation trajectories have been added to Fig. 1.

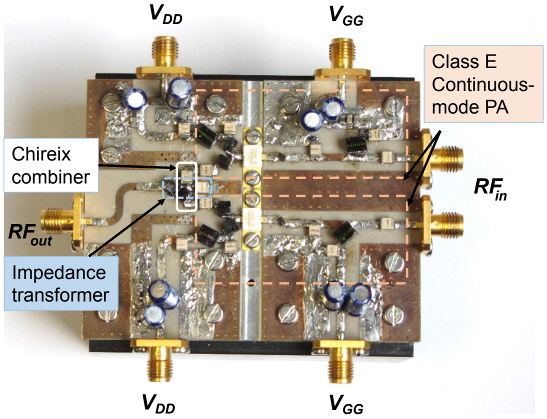

Fig. 4. Implemented outphasing transmitter.

B. Characterization

The transmitter was first characterized in function of the outphasing angle between the CW driving signals. From the results in Fig. 5, a profile with 80% and 70% efficiency values at 7.8 dB and 9.5 dB power back-offs, respectively, was obtained at 700 MHz. The performance degraded when moving apart from the design frequency. Unfortunately, it is also evident that it would be impossible to reproduce envelope values 16 dB below the peak with a pure outphasing operation, one of the reasons why the use of hybrid or mixed modes has been previously proposed [10] (the other responds to the unavoidable reduction in the average PAE when reproducing the envelope's lowest part).

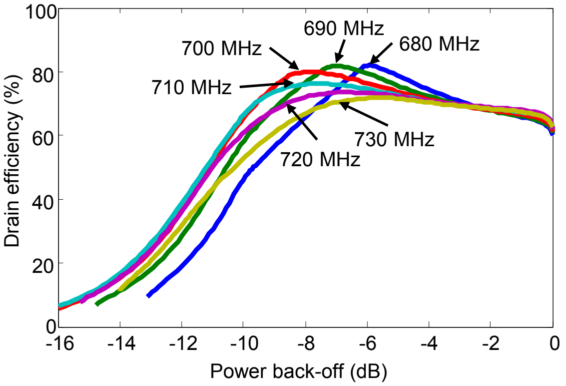

Fig. 5. Measured efficiency profiles vs. output power back-off.

C. Constant-gain Envelope Tracking strategy

The linearization of the mixed modes could turn critical, especially if the gate voltage of the transistors were kept below pinch-off (typical for class-E operation). The gain expansion followed by compression in the AM/AM profile would introduce additional difficulties for its correction through digital predistortion (DPD) techniques. On this basis, it is a common practice to raise the gate voltage slightly above pinch-off [10], which would turn in this case the proposed continuous-mode class-E, excited with a varying envelope signal, into a sort of continuous-mode class-J PA [11].

Considering the above, it was decided to characterize the outphasing scheme against both the power and phase difference between the CW input signals, with the PAs working at V_{GS} = -2.3 V and the same V_{DS} = *28 V*. As it may be appreciated from Fig. 6, it would be possible not distorting the envelope or AM component of the original signal, if the phase difference were coded from the envelope, such that a constant-gain trajectory could be followed. A 20 dB gain with good efficiency profile would involve maintaining a 140º phase difference up to a P_{in} of 11 dBm, while varying the outphasing angle according to the signal envelope for its upper 16 dB range (11 – 27 dBm).

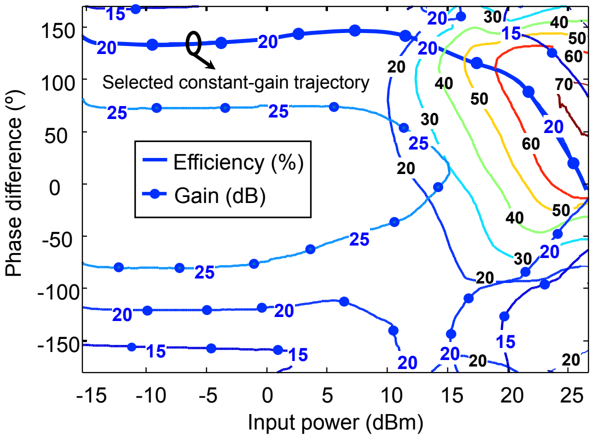

Fig. 6. Constant gain and efficiency contours versus the input power and the phase difference between the two branches.

This strategy, based on the mixed modes in [10], would be analogous to the widely accepted IsoGain ET of [12], but in this case with the Chireix mutual load-modulation substituting the dynamic biasing. In the same way as in [12], it would result in a simpler DPD, conceived only for the correction of undesired deviations in the phase component of the signal along the selected path. As an additional advantage, the input drives to the branches, which would carry not only the phase component of the signal to be reproduced, but also its amplitude (plus a common-mode predistorting phase term and an envelope-dependent phase difference determined by the selected constant-gain trajectory), would also have a lower bandwidth [10] compared to the typical PM signals of a pure outphasing mode.

In order to validate this proposed mode of operation, the envelopes of two 1c-WCDMA signals with very different PAPR (5.1 and 8.4 dB) were encoded according to the results of a dynamic characterization derived from the static results in Fig. 6. Introducing the appropriate phase difference, as to accurately follow a constant-gain path, and aided by a very simple memoryless DPD over the phase components, it was possible to reproduce the original signals satisfying the linearity requirements and with average efficiency values above 55% (measured results are included in Table II).

TABLE II

POUT, EFFICIENCY AND ACPR RESULTS WITH 1C-WCDMA SIGNALS

Signal	Pout (W)	η_{av} (%)	ACPR (dBc)	
			Adj. 5MHz	Alt. 10 MHz
WCDMA 5.1 dB	14.4	66.2	Low -41.1 Up -41.4	Low -48 Up -47.3
WCDMA 8.4 dB	7.8	58.1	Low -37.4 Up -34.9	Low -46.4 Up -43.7

IV. CONCLUSION

The design of a compact outphasing scheme at UHF band, based on the integration of continuous-mode class-E GaN HEMT PAs (with a higher than 80% efficiency for a 34.2% relative bandwidth) using a simple series Chireix combiner complemented by an impedance transformer, has been presented. A 70% efficiency figure for a 9.5 dB back-off was measured at the center frequency. The modification of the PA operation to the continuous class-J mode, together with the selection of a constant-gain envelope tracking strategy (derived from the mixed modes and implemented through a mutual load-modulation), allowed the efficient reproduction of high PAPR communication signals.

ACKNOWLEDGEMENT

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