Design of UHF Class-E Inverters and Synchronous Rectifiers for Efficient Transmission Topologies

M. Nieves Ruiz, Susana Pérez and José Ángel García.
ruizmn@unican.es, joseangel.garcia@unican.es
(1) Dept. Communications Engineering. University of Cantabria. Edificio "Prof. José Luis García",
Plaza de la Ciencia s/n, Santander, 39005, Spain.

Abstract*- In this paper, the design of efficient transmitting architectures is addressed. Taking advantage of the modeling and characterization of novel active devices as GaN HEMT and E-pHEMT, several topologies have been approached. An outphasing transmitter at 770 MHz have been implemented from two class-E RFPA designed over package GaN HEMTs. In addition, for multiband applications, a dual band outphasing transmitter (able of operating either at 770 MHz or 960 MHz) has been also realized. A Chireix reactive combiner allows positioning the drain impedance loci to produce high efficiency and good dynamic range profiles, for both designs. Average drain efficiency figure over 61% has been measured for a 8.4 dB PAPR WCDMA signal, in the dual-band implementation. Besides, in the first approach, an efficient value of 57.5% was estimated when reproducing a LTE with a PAPR of 9.6 dB. On the other hand, wireless powering applications have been into account in the design of self-biased and self-synchronous class-E rectifier, based on an E-pHEMT. Two implementations at 900 MHz and 2.45 GHz, with efficient values of 76% and 64% at power levels of -4 dBm and -1 dBm, respectively, and peak figures of 88% and 77%, have been measured.

I. INTRODUCTION

In modern wireless systems, the critical requirement for transmitting communication standards (LTE, WiMAX, etc.) in a highly linear and efficient way [1] has motivated a lot of research activities on GaN HEMT-based class-E inverting topologies, optimized for operation under bias or load modulating conditions. In this sense, architectures such as Envelope Tracking (ET) [2], Doherty [3] or outphasing [4], are being under serious investigation these days also with power saving purposes to reduce the operational costs in the base stations and to extend battery lifetime in the handsets. Besides, the design of systems with multi-band capabilities is taking into account for reducing the number of components and cost of the RF front-end.

In parallel, the need for minimizing losses in the receiving end of far-field wireless power transmission links [5] has led to an increased activity in the design of its time reversal dual, the class-E rectifier, using not only Schottky diodes, but also high performance transistor technologies. The integration of both parts in resonant converters [6] is motivated by the implementation of high performance (fast response and small footprint) DC/DC converters also available to employ as an envelope modulator in ET transmitters.

II. ACTIVE DEVICE CHARACTERIZATION AND MODELING

In order to extract a simplified switch model (R_{on}, C_{out} and R_{off}), the ON-state resistance was estimated from the low drain voltage slope of the measured I/V curves at high V_{GS} values, as it is described by authors in [7]. For the selected CGH35030 device, a $R_{on} = 0.5\ \Omega$ has been measured.

With the aid of a vector network analyzer, the output equivalent capacitance and OFF-state resistance may be obtained, from the S_{22} parameter (see in Fig. 1), measured at $V_{DS} = 28$ V and for a V_{GS} slightly below pinch-off, just before observing any significant increase in the output conductance.

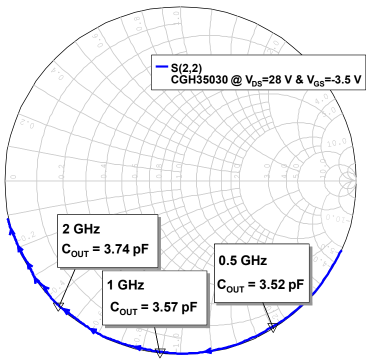

Fig. 1 Extraction of C_{out} and R_{off}, from [S] parameters.

In the case of the E-pHEMT model, additional parameters would be required to design the CW gate driving circuit for the operation of the device in a self-synchronous rectifying mode. A simple non-linear model, whose equivalent circuit, together with the equation which describes the main nonlinearity $I_{ds}(V_{gs}, V_{gd})$, appears in [8], has been extracted for the selected device, the VMMK-1218, a 0.25 µm gate E-pHEMT from Avago Technologies.

Most available models for RF and microwave transistors, usually are conceived for their operation in linear amplifying classes. However, in this case, the reproduction of the third quadrant of the device I/V characteristics, for the use of this model in the design of a synchronous rectifier, has been also taken into account.

As it may be appreciated from Fig. 2, a good agreement exists between the measured and modeled characteristics.

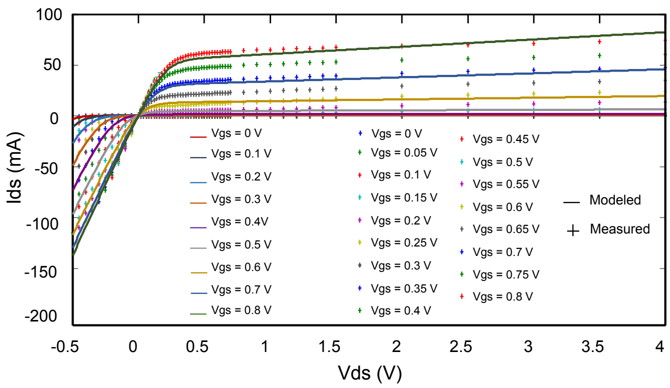

Fig. 2 I/V prediction capability of the proposed E-pHEMT model.

III. Class E Topologies

A. Class-E inverter

At UHF frequencies, the passive networks could be designed over high Q coils and capacitors. Since in the classical topology [9], a simple series LC circuit may force a sinusoidal current through the load while also providing the desired termination at the fundamental, coil parasitics may have a detrimental influence at these frequency bands. A self-resonating coil, L_{1s}, between the second and third harmonic may be a good selection for approximating ZVS and ZVDS operation, as it is represented in Fig. 3a. The series capacitance C_{1s}, would allow a fine adjustment of the inductive reactance at the switching frequency, 0.2116/(ω.Cout), while the capacitor to ground, C_{1p}, would help matching the reference impedance at RF/microwave bands to the optimum or nominal drain resistive load [10].

B. Broadband Class-E inverter

Following the original topology, the drain impedance at the fundamental gets apart from the nominal or optimum value, when varying the operating frequency [10]. This leads to a narrowband characteristic in terms of efficiency, besides an output power profile decreasing with frequency, which limits the use of these topologies for broadband PAs.

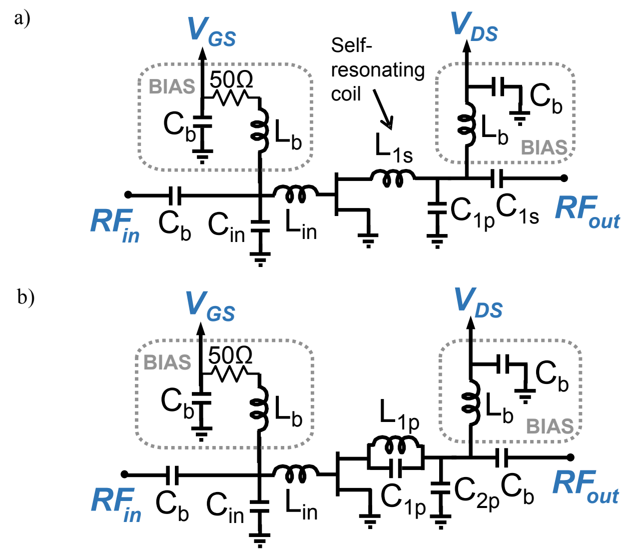

Fig. 3. Simplified schematics of the proposed a) single frequency and b) broadband high efficiency PAs.

Therefore, to improve the bandwidth of class E amplifiers, a broadband design, proposed in [11], is shown in Fig. 3b. A parallel $L_{1p}C_{1p}$ circuit was tuned between the bands of the second and third harmonics. Its quality factor, Q_{1p}, was selected as a trade-off between the desired termination at the harmonics by one side and the desired termination at the fundamental by the other. This inductance and the capacitance to ground, C_{2p}, allowed transforming from 50 Ω to a fundamental impedance locus near the nominal values.

C. Class-E synchronous rectifier

The class-E synchronous rectifier has been aimed by means of the previously designed class-E inverter. Attending to the Time-Reversal Duality Principle [12], if exciting the signal port with a power value in the order of the inverse of the amplifier gain, while loading the drain DC path with $R_{DC} = V_{DD}/I_{DD} \approx 1/(\pi \cdot \omega \cdot C_{out})$, it would be expected to properly operate as class-E synchronous rectifier.

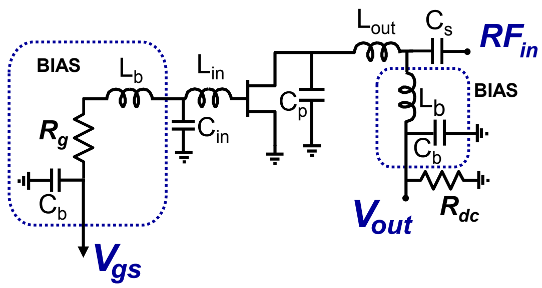

Fig. 4. Proposed Class-E rectifier schematic.

In the Fig 4, the schematic of the proposed class-E rectifier is presented. As it can be appreciated, the output matching network follows basically the suggested for the inverter. A self-biased strategy, implemented to improve the efficiency profile versus input power, is described in Section IV.B.

IV. Implementation Examples And Results

A. Outphasing transmitters

A 770 MHz and a dual-band (able of operating either at 770 MHz or 960 MHz) outphasing transmitters have been implemented following the topology proposed by Beltran in [13] (also presented in Fig. 5). The length of the lines together with the value for the compensating or Chireix reactances [14] was adjusted to produce near optimal load modulation paths at the selected frequency bands.

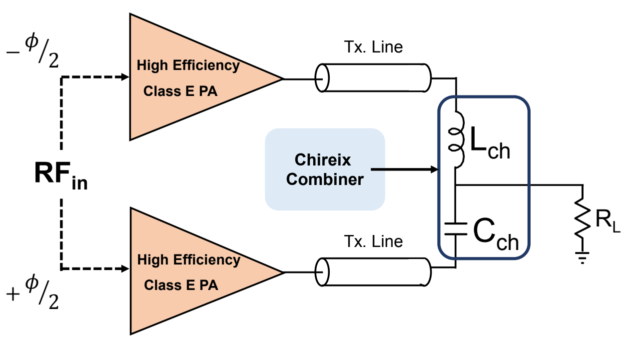

Fig. 5. Outphasing transmitting topology.

1. *Phased-controlled inverter at 770 MHz*

By using two class-E PAs over GaN HEMTs devices at 770 MHz (with a peak of efficiency measured over 85%), which employ the drain termination network previously described, a high efficient profile for a significant power range, has been obtained. The drain efficiency keeps over 70% for a power back-off of 9.7 dB, as it may be appreciated in [15]. This performance would allow the efficient handling of high PAPR signals.

In order to estimate the capability of this transmitter when reproducing complex modulated signals, a LTE with a value of 9.6 dB of PAPR was selected. An average efficiency of 57.5% was measured. Only the ACPR requirements for the alternate channel have been satisfied probably due to the impossibility to reproduce the envelope values close to zero in a pure outphasing mode. An enhanced DPD technique could also improve the linearity (a simple memory-less DPD was used).

2. *Dual-band outphasing transmitter implementation*

In the same way, a dual-band version has been realized. Although a broadband combiner could have been designed instead, not a trivial task, it was decided to take full advantage of the rotation of the drain impedance loci over the Smith Chart with frequency, due to the variation of the electrical lengths of the constituting transmission lines.

To accomplish this topology, two PAs were implemented in the 750 MHz to 960 MHz frequency band, from the design of the broadband class-E inverter proposed. In Fig. 6, the output power and efficiency profiles with frequency, measured for one of them, are plotted. Drain efficiency values of 83.8% and 82.5% have been estimated at 770 MHz and 960 MHz, respectively.

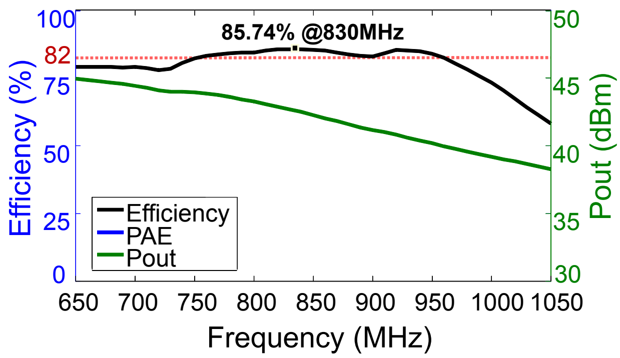

Fig. 6. Measured output power and efficiency characteristics with frequency.

A photograph with details of the implementation is shown in Fig. 7. A set of SMA connectors was employed, in addition to the microstrip lines at the output of the PAs and the combiner inputs, to approximately fit the required transmission line length.

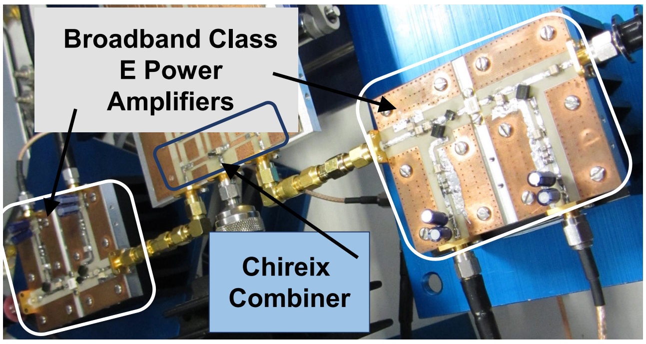

Fig. 7. Photograph with details of the amplifiers and the reactive or Chireix combiner.

Average drain efficiency figures over 68% and nearly 40% have been measured for two WCDMA signals with a peak-to-average power ratio of 5.1 dB and 8.4 dB, respectively.

B. *Self-biased and self-synchronous rectifier*

A self-synchronous E-pHEMT rectifier implementation is also presented [8]. The proposed self-biased topology is based on the connection of the output DC voltage port (drain side) to the gate biasing path. In this way, when increasing the input power, the rectified voltage allows increasing V_{GS} up to close the threshold value.

As observed from Fig. 8, the efficiency suddenly grows thanks to this self-biased effect, for both (900 MHz and 2.45 GHz) implementations. A properly dimensioned resistor, R_g, introduced in the gate biasing path, allows reducing the gate-to-source DC voltage, following $V_{GS} = V_{out} - R_g \cdot I_{GS}$.

As it may be appreciated, a peak value of 88% was obtained at 16 dBm , while the efficiency was as high as 76% at a power value of -4 dBm, for the 900 MHz circuit. In the case of the 2.45 GHz rectifier, a peak of 77% at 13 dBm and a 64% value at -1 dBm have been measured.

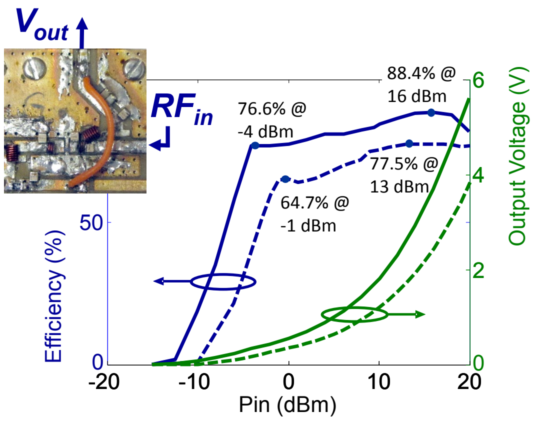

Fig. 8. Evolution of output voltage and efficiency versus input power for (-) 900 MHz and (--) 2.45 GHz implementations, and a photograph with a detail of one of the circuits.

These results, at a higher frequency band, support the validity of the proposed design methodology, the accuracy of the extracted device nonlinear model for rectifier simulation, as well as the potential of the employed E-pHEMT technology. Employing a transistor instead of a diode, besides the flexibility associated to the auxiliary control provided by the gate voltage, the circuit may be reconfigured for operation in an inverse rectenna mode (class-E oscillator) [16].

V. Conclusion

The combination of appropriate device characterization and modeling techniques is employed in this paper for the optimized design of a GaN HEMT class-E inverter, a broadband class-E inverter and an E-pHEMT class-E synchronous rectifier. In this last case, the efficiency may be kept high for a significant power range by using a self-biasing strategy. In the implemented outphasing transmitters, high efficiency profiles over a wide dynamic range have been obtained. Future actions include the use of an hybrid mode, allowing envelope variations in the RF excitation signals, together with an enhanced DPD for reducing the remaining distortion. In addition, the inverter and synchronous rectifier proposed could be also applied to the conception of a class-E^2 resonant converter to be employed in envelope tracking transmitters.

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