Device Characterization and Modeling for the Design of UHF Class-E Inverters and Synchronous Rectifiers

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***Abstract*— In this paper, the advantages derived from an appropriate characterization and modeling of active and passive devices, leading to the optimized design of Ultra-High Frequency (UHF) Class-E inverters and synchronous rectifiers, are highlighted. While the combination of a couple of low-frequency and RF measurement techniques is shown to be valid for the extraction of a simplified model as a switch, a more complex approach may be required if also addressing the design of the continuous wave (CW) driving network or if interested in taking fully advantage of other transistor characteristics. Design examples, based on GaN HEMTs and a GaAs E-pHEMT, are presented, in which the parasitics of the employed coils and capacitors are also taken into consideration. Wireless transmitting and powering applications have been addressed.**

Keywords*— Class E, DC-DC converter, E-pHEMT, frequency modulation, GaN HEMT, inverter, outphasing, synchronous rectifier, UHF.

I. INTRODUCTION

During the last years, the Radiofrequency (RF) and Microwave engineering community has shown an increased interest in the design of class-E power amplifiers. The critical requirement for transmitting modern wireless communication standards (LTE, WiMAX, etc.) in a highly linear and efficient way [1] has motivated a lot of research activities on GaN HEMT-based zero voltage switching (ZVS) and zero voltage derivative switching (ZVDS) inverting topologies, optimized for operation under bias or load modulating conditions. In parallel, the need for minimizing losses in the receiving end of far-field wireless power transmission links [2] has led to an increased work 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 [3], [4] is, at the same time, under strong consideration by Power Electronics (PE) specialists, motivated by the implementation of high performance (fast response and small footprint) DC/DC converters [5].

In a growing imbrication scenario of PE and RF areas, this paper addresses the relevance of device characterization and modeling techniques in the RF implementation of well-known PE topologies. The design of an outphasing GaN-based inverter, operating at 770 MHz, a 900 MHz self-synchronous E-pHEMT rectifier and a frequency-controlled 1 GHz class E^2 resonant converter will be under consideration.

II. ACTIVE DEVICE CHARACTERIZATION AND MODELING

When extracting a simplified switch model (R_{on}, C_{out} and R_{off}) for a III-V compound transistor (the case of GaAs or GaN HEMT technologies), low-frequency dispersion effects should be taken into account. Being not only related to self-heating, but also to trap states, they could lead to errors in the estimation of the ON-state resistance if derived from the slope of the DC curves. Launching narrow pulses (hundreds of ns or a few µs) from the selected OFF-state biasing point (V_{GS} = -3.4 V and V_{DS} = 28 V for the case of the CGH60030D die from Cree Inc. in Fig. 1a), with a duty cycle below 1%, the dynamic R_{on} may be properly estimated.

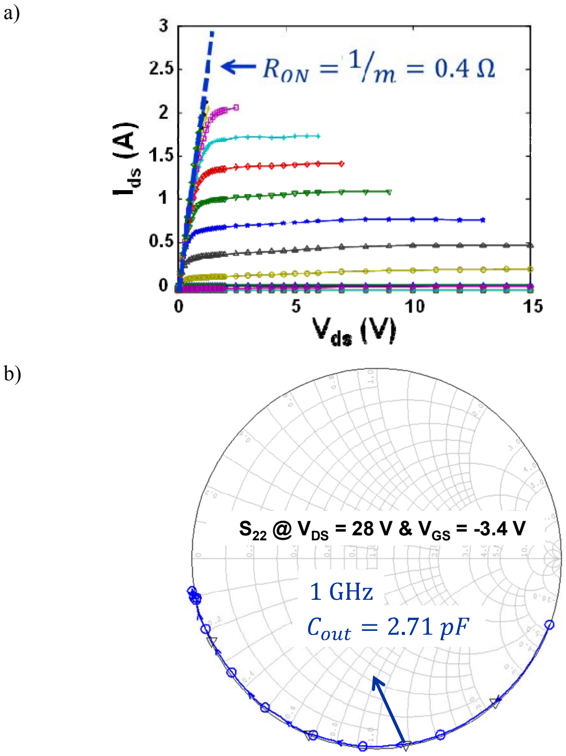


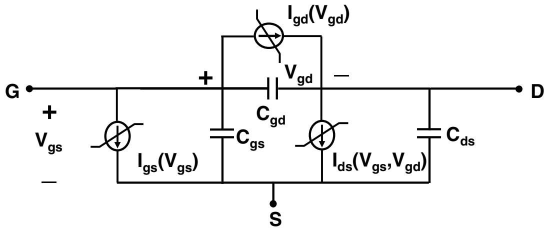
Fig. 1 Extraction of a) R_{on}, from pulsed I/V measurements, as well as of b) C_{out} and R_{off}, from [S] parameters. The results correspond to a CGH60030D GaN HEMT die from Cree Inc.

The output equivalent capacitance and OFF-state resistance may be obtained, instead, from the device S_{22} parameter, measured at the same biasing point with the aid of a vector network analyzer (see Fig. 1b).

While this simple switch representation may be good enough for synthesizing a class E drain terminating network [6], the design of the CW gate driving circuit or the operation of the device in a self-synchronous rectifying mode would require from additional parameters or elements (the case of those describing the gate-to-channel Schottky junction). In Fig. 2a, a more elaborated nonlinear model of this kind is presented, in this case for a VMMK-1218 GaAs E-pHEMT from Avago Technologies. Aimed for its use in the design of a synchronous rectifier for far-field wireless powering applications, attention should be paid to the reproduction of the third quadrant of the device I/V characteristics, not a common feature in most available models for RF and microwave transistors, usually conceived to provide a good fit of the device saturated region, where current source mode amplifying classes (A, AB, B and C) usually operate.

In the proposed equation for the $I_{ds}(V_{gs}, V_{gd})$ main nonlinearity [7], continuous and continuously derivable functions have been included for accurately describing the exponential nature of the sub-threshold device behavior. A comparison of measured and predicted current values is presented in Fig. 2b [7].

a)



$$Ids(V_{gs},V_{gd}) =$$
$$= \beta[1+\lambda(V_{gs}-V_{gd})]\left\{\left[\alpha(V_{gs}-V_{th})+\ln\left(2\cosh\left(\alpha(V_{gs}-V_{th})\right)\right)\right](1+\mu V_{gs}) - \left[\alpha(V_{gd}-V_{th})+\ln\left(2\cosh\left(\alpha(V_{gd}-V_{th})\right)\right)\right](1+\mu V_{gd})\right\}$$

b)

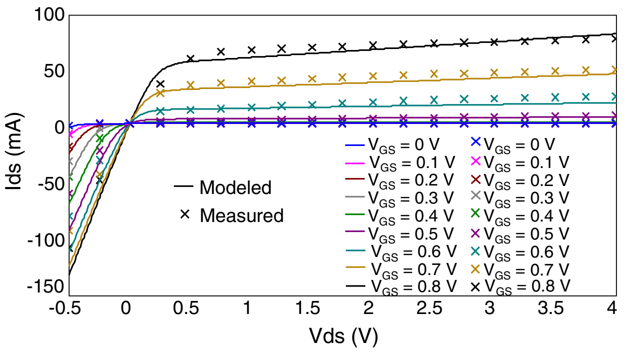
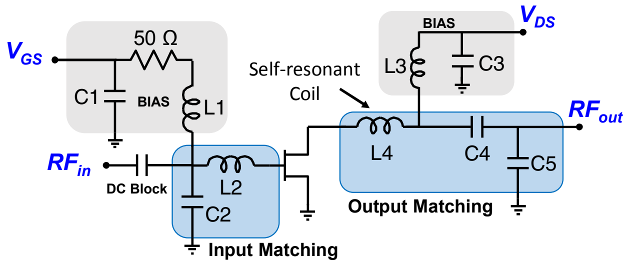


Fig. 2 a) Nonlinear equivalent circuit model together with its b) I/V prediction capability for the VMMK-1218 E-pHEMT from Avago Tech.

Widely accepted models in the industry for RF/microwave GaN HEMT devices, usually based in the equation proposed by Fager [8], may be also conveniently modified for improved reproduction of the linear region and the inverse operation. Taking advantage of the equations in [9], [10], addressing by that time the nonlinear distortion prediction of FET devices operated as resistive switches, attenuators or mixers, the gate to source and gate to drain voltages may be used for describing the real device symmetry.

III. UHF CLASS-E TOPOLOGIES

At UHF frequencies, high Q coils and capacitors represent the best choice for the design of the passive networks. While in the classical topology [6], a simple series LC circuit may force a sinusoidal current through the load while also providing the desired inductive termination at the fundamental, coil parasitics may have a detrimental influence at these frequency bands. Considering the tremendous impact of the second and third harmonics over the efficiency figure [11], two topologies may be preferred among others: a multi-resonant or poly-harmonic terminating network [12] and an LC network based on an appropriate high Q coil, self-resonating between those two frequency components [13]. The latter, represented in Fig. 3, may be a good selection for approximating the desired class E conditions with a compact and low footprint implementation.



C_1, C_3	68 pF	L_1, L_3	150 nH
C_2	8.2 pF	L_2	3.85 nH
C_4	3.3 pF	L_4	12.5 nH
C_5	2 pF	DC block	82 pF

Fig. 3 Class-E lumped-element topology based on a self-resonant high Q coil.

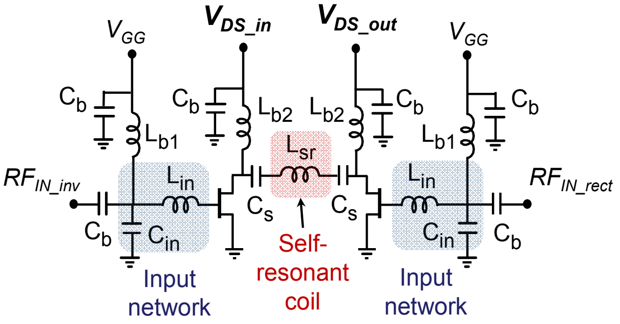
The values in the included table are for a 770 MHz design, using the packaged CGH35030F GaN HEMT device from Cree Inc. (the package contains the CGH60030D die, whose characterization results were presented in Fig. 1).

The capacitor in series, C_4, would allow a fine adjustment of the desired inductive reactance at the switching frequency, $0.2116/(\omega C_{out})$, while the capacitor to ground, C_5, would help transforming the reference impedance at RF/microwave bands (50 Ω) to the optimum or nominal drain resistive load $0.1836/(\omega C_{out})$ [6].

Although representing an inverter, the lumped element topology in Fig. 3 could also work in its time-reversed mode: a class E rectifier [14]. Depending on the application, the required gate driving signal may be independent of (although properly synchronized) or derived from the AC signal, in the UHF band, to be rectified. A precise control could be obtained in the first case, while a simpler implementation from the latter.

If finally cascading two of these topologies, a double class E resonant DC/DC converter would result [15]. Its schematic and values, in this case corresponding to a 1 GHz design using the CGH60030D die device, are included in Fig. 4.

Two capacitors, C_s, are employed in the interconnecting network as to provide a fine tuning of the series resonant circuit below the fundamental, while also avoiding undesired asymmetries in the device terminations due to the impedance transformation effects of the required lengths of transmission lines between them.



C_{in}	6.8 pF	L_{sr}	8 nH
C_s	8.2 pF	L_{b1}	120 nH
C_b	47 pF	L_{b2}	18.5 nH
		Tx. Line (L_{in})	30.2º

Fig. 4 Double class E or class E^2 resonant converter: schematic and values for a 1 GHz design.

IV. UHF IMPLEMENTATION EXAMPLES AND RESULTS

Implementation examples of class E topologies at UHF frequencies will be presented in this section, based on the above considered GaN HEMT and GaAs E-pHEMT devices. They include an inverter, a self-synchronous rectifier, and a resonant DC/DC converter, conceived for their use in wireless communication or powering applications.

A. Outphasing Inverter

In Fig. 5a, a photograph with details of an outphasing amplifier [16] (a phase-controlled resonant inverter), operating at 770 MHz, is presented. Both constituting class-E switching branches follow the topology suggested in Fig. 3. As proposed in [17], appropriate lengths of transmission lines were adjusted between the output of the amplifiers and the inputs of the reactive or Chireix combiner, in order to produce the desired mutual load modulation loci [18].

Measured results for the efficiency evolution versus power back-off (output power relative to the peak, 35 W) are also included in Fig. 5b, where it is shown that the efficiency may be kept over 70% for a significant dynamic range (a power value nearly 10 times below the peak). Aimed for the efficient and linear transmission of modern wireless communication signals, the case of 4G Long Term Evolution (LTE), with very high values for the peak-to-average power ratio, class-E based outphasing transmitters currently stand as a promising technique [19].

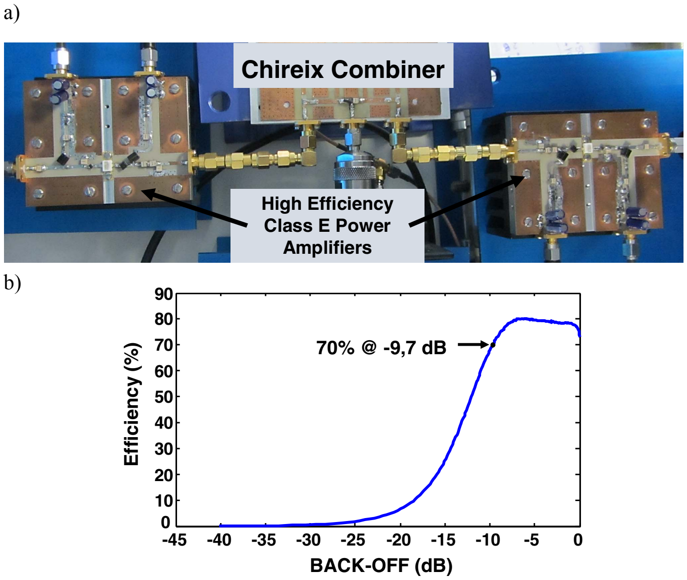
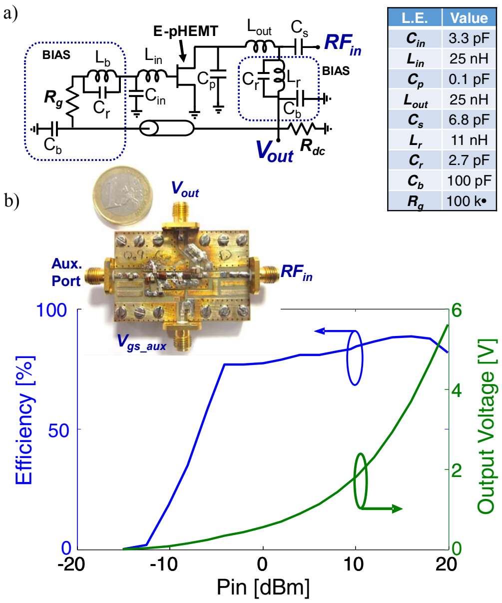


Fig. 5 a) Implementation details of the phase-controlled class-E inverter together with b) its efficiency vs. output voltage profile.

B. Self-syncrhonous and self-biased rectifier

A self-synchronous and self-biased E-pHEMT rectifier, also based on a self-resonant drain terminating coil, is shown in Fig. 6. Designed over the VMMK-1218 (model details were presented in Fig. 2), this solution is aimed for its use in far-field 900 MHz wireless powering links. As no additional source would be available for forcing the device operation as a switch, advantage has been taken from the Miller capacitance, C_{gd} [20]. The synthesized impedance at gate terminal was carefully adjusted through simulations to force the required amplitude and phase of the gate driving voltage [7].



L.E.	Value
C_{in}	3.3 pF
L_{in}	25 nH
C_p	0.1 pF
L_{out}	25 nH
C_s	6.8 pF
L_r	11 nH
C_r	2.7 pF
C_b	100 pF
R_g	100 k•

Fig. 6 a) Class-E self-synchronous rectifier based on the VMMK-1218 E-pHEMT. b) Evolution of output voltage and efficiency [7].

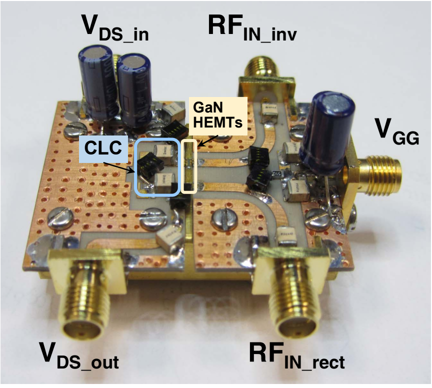
The measured variation of efficiency with the input power level is depicted in Fig. 5b. The gate to source biasing value was also adjusted with the input power level, deriving it from the rectified voltage through the use of a properly calculated resistor, R_g. Using this adaptive biasing technique, an 88% efficiency peak was measured at 16 dBm, staying over 76% for power levels above -4 dBm.

C. *FM-controlled Resonant Conveter*

Finally, a photograph of the resonant converter, following the circuit schematic in Fig. 4, is presented in Fig. 7a. Requiring low valued and sized components, the implementation is relatively compact. In Fig. 7b, the measured output voltage and efficiency profiles are presented in terms of the switching frequency [21]. In the 11 V – 28 V range, the voltage follows the frequency in a relatively linear law. Peak drain and overall efficiency values of 80% and 77%, respectively, have been measured, staying above 70% for an output voltage 5 dB below the peak. The power of the driving signals is accounted for in the overall efficiency calculation.

Besides being close to the state-of-the-art for reported high frequency resonant converters, the measured performance may fit the probability density function of modern communication signal envelopes. Taking this feature into account, together with the dynamic response capabilities to be expected from a 1 GHz frequency of operation, this converter is being evaluated for its use as envelope modulator in envelope tracking or polar transmitters [21].

a)



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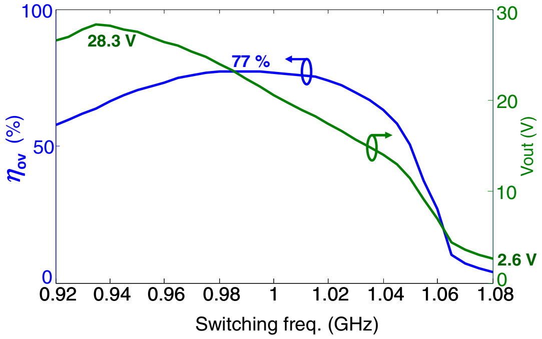


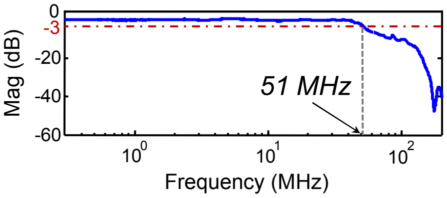
Fig. 7 a) Photograph with details of the 1 GHz class E^2 resonant converter. b) Evolution of output voltage and efficiency with the switching frequency.

Using a frequency-modulation, FM, output voltage control as in [15], the converter dynamic performance was characterized. Values for the large signal bandwidth and slew rate of 51 MHz and 1.37 V/nS, respectively, have been estimated. Along the measured large-signal bandwidth the efficiency kept around 71%. This converter has been also tested with success, handling the envelope of 2c- and 4c-WCDMA signals, as in [21].

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, an E-pHEMT class-E synchronous rectifier and a double class E resonant DC/DC converter. Measured results, close to the state-of-the-art for switching frequencies in the UHF band, show the feasibility of these topologies with currently available RF/microwave device technologies. A lot of work would need to be done in the future for further improving their performance.

a)



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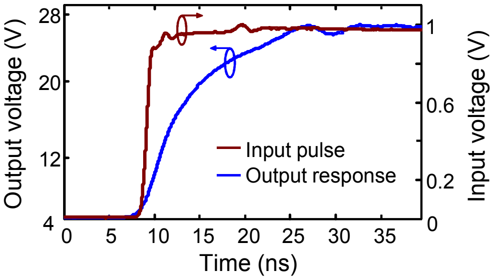

Fig. 8 Characterization of the converter large-signal response: a) bandwidth and b) slew rate.

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