GaN HEMT Class E\(^2\) Resonant Topologies for UHF DC/DC Power Conversion

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Abstract—In this paper, the design and performance of class E\(^2\) resonant topologies for DC/DC power conversion at Ultra High Frequencies (UHF) are considered. Combining the use of RF GaN HEMT devices, both for the inverter and the synchronous rectifier, with high Q lumped-element terminating networks, peak efficiency values over 70\% may be obtained. Control strategies based on carrier bursting, switching frequency modulation, or outphasing are also shown to be feasible. Taking advantage of their improved dynamic response, when compared to low frequency more traditional switched-mode converters, a class E\(^3\) polar transmitter for the EDGE standard has been designed and tested at 770 MHz, offering an average global efficiency over 46\% at 4.3 W of output power, through RF-based amplitude and phase constituting branches. Finally, the potential of such a high frequency of operation in terms of power density is explored, absorbing undesired coil parasitics for the original LC series interconnecting network in a 1 GHz design methodology.

Index Terms—Class E, DC-DC power converters, FETs, gallium nitride, high power amplifiers, phase control, predistortion, pulse width modulation, radio transmitters, rectifiers, resonant inverters, switching converters, UHF circuits, zero voltage switching.

I. INTRODUCTION

M odern power electronics applications are continuously demanding power efficient converting systems with a very fast transient response and improved control bandwidth. That has been recently the case, for instance, of the envelope modulator in envelope tracking (ET), envelope elimination and restoration (EER) or hybrid ET/EER wireless transmitters [1], where the amplitude component of a high data rate digitally-modulated signal (multicarrier WCDMA, OFDM or similar), with tenths of MHz of spectral content, has to be linearly reproduced at the output. Together with the interest in miniaturization, associated to the reduction in the required energy storage and the use of smaller valued and sized passive components, as to reach the power supply-in-package (PSiP) and power supply-on-chip (PwrSoC) ultimate targets [2], a great motivation has appeared on the operation of power converters at switching frequencies quite over the 0.1-10 MHz range of today’s figures.

Achieving competitive efficiency values in DC/DC converters at VHF, UHF or higher frequency bands, requires keeping frequency dependent switching loss mechanisms under control. Using zero voltage switching (ZVS) [3], they may be alleviated by mitigating the voltage/current overlap while also forcing a low voltage across the semiconductor terminals during the ON/OFF transitions, resulting also in a reduction of the electromagnetic interference (EMI) associated to hard-switched more traditional converters [4]. Several solutions at HF and VHF bands have appeared during the last years [5], based on class E\(^2\) [6] or more recently in class \(\Phi_e\) topologies [7]. Operation at higher frequencies was also explored in the past [8], but restricted to small power levels, mainly due to the non availability of appropriately fast power transistors and Schottky diodes by that time.

In this paper, the implementation of UHF resonant DC/DC power converters, following class E\(^2\) topologies, is considered. The use of RF depletion-mode GaN HEMT devices, both for the inverter and the synchronous (active) rectifier, together with high Q lumped-element terminating networks allow improving the operating bandwidth while also preserving a high efficiency. The output voltage is shown to be perfectly controlled through different techniques, each with its advantages and limitations, finding the improvement of the dynamic response application in a wireless high efficiency transmitter. A solution is also considered in the miniaturization direction.

In section II, the selected topology is introduced, described and adapted according to UHF particular implementation restrictions with Gallium Nitride transistors. Characterization results are then presented in section III under different output voltage control strategies. Special attention is put in the design of an alternative outphasing scheme, introducing recent advances on class E load modulation techniques. The use of a carrier bursting converter as envelope modulator for an EDGE standard wireless polar transmitter is considered in section IV, while a small sized topology is finally proposed in section V.

Manuscript received July 10, 2012. This paper is an expanded paper from the IEEE MTT-S Int. Microwave Symposium held on June 17-22, 2012 in Montreal, Canada.

This work was supported by the Spanish Ministries MICINN and MINECO through the FEDER co-funded project TEC2011-29126-C03-01 and CSD2008-00068. J. A. García and R. Marante acknowledge the funding received by means of a Mode A Professorship Mobility Grant (ref. PR2010-0202) and a MAEC-AECID Doctorate Grant Program (ref. 0000524566), respectively.

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II. CLASS E² DC/DC CONVERTER

With the aim of operating at hundreds of kHz or even MHz frequencies, alternative transistor-based topologies to hard-switched converters were proposed by power supply specialists in the 80’s [9]. As turn-on and turn-off losses were associated to the employed rectangular waveforms, the introduction of a resonant circuit helped shaping either a sinusoidal voltage or a sinusoidal current. Combining a DC/AC resonant inverter and a high-frequency rectifier, a resonant converter first transforms the DC input power into a controlled AC power, to then turn it back into the desired DC output [3, 4].

A. Original Topology

Conceived as a class E RF power amplifier (RF PA) in [10], the idea of using zero voltage and zero voltage derivative switching (ZVDS) for the inverter in resonant power conversion is due to Gutmann [11], while a deeper insight into its operation was later provided in [12]. Forcing soft-switching conditions not only for the inverter, but also for the rectifier, the double class E or class E² converter was later proposed by Kazimierczuk in [13, 14]. One of its many possible topologies [13] is presented in Fig. 1, where the rectification is of active or synchronous type. At high operating frequencies, UHF and beyond, fast enough Schottky diodes able of handling high current and voltage levels are rarely available, reason why a transistor-based rectifier may be the only choice.

![Fig. 1. a) The class E inverter or PA, b) its time reversal dual, a class E synchronous rectifier, together with c) a basic class E² DC/DC converter obtained when cascading a) and b.](image)

The class E inverter of Fig. 1a) was analyzed in detail in [15], assuming an infinite choke inductance, $L_b$, in order to consider the device biasing branch as a DC current source, and a high enough loaded quality factor for the resonant circuit as to assure the current through it is a sinusoid at the driving signal frequency. Tuning the LC series resonant circuit slightly below the switching frequency, the optimum conditions, defined as those resulting in the ideal 100% efficiency operation with maximum output power (according to the voltage and current restrictions imposed by the device characteristics), were found by Raab [15] to be:

\[
D = 0.5 \quad R_{ac} = \frac{0.1836}{\omega \cdot C_{out}} \quad X = \frac{0.2116}{\omega \cdot C_{out}}
\]

(1a) (1b) (1c)

with $D$ the switching duty cycle, while $R_{ac}$ and $X$ the real and imaginary components of the impedance to be seen by the device (including the capacitance) at the fundamental frequency. Under these conditions, the inverter was proved to be seen by its DC supply as a load with value,

\[
R_{dc} = \frac{1}{\pi \cdot \omega \cdot C_{out}}
\]

(2)

From the inverter circuit, applying the time reversal (TR) duality principle as described in [16], the class E rectifier of Fig. 1b) may be easily derived. In this case, optimum operation is obtained for $D$, $X$ and $R_{ac}$ values as in eq. (1a), (1c) and (2), respectively, while the required phase shift, $\Delta \phi$, between the gate-to-source and the drain-to-source voltage waveforms should be set to 180º as to obtain the desired synchronization. The class E rectifier, as inverter TR dual, would then appear to its AC excitation as a perfectly resistive load $R_{dc}$, following eq. (1b).

The class E² DC/DC converter of Fig. 1c) results from cascading the above described circuits. The rectifier provides by itself the load resistance $R_{ac}$ required by the inverter, so both of them may operate under the desired soft-switching conditions without adding any further element for the interconnection. Combining in series the two resonant circuits, the overall reactance to be presented by the resulting LC combination [16] should then be:

\[
2 \cdot X = \frac{0.4232}{\omega \cdot C_{out}}
\]

(3)

For an ideal lossless operation, the output DC voltage would be equal to the input biasing value, while the DC load offered by the converter to its power supply would be exactly its load resistance $R_{dc}$.

B. Device Model and Simulations

Following this basic topology and concept, a packaged GaN HEMT from Cree Inc., the CGH35030, was selected to be employed as the switching element. Besides this technology offering a very low value for the on-state resistance output capacitance product, $R_{on} \cdot C_{out}$, its high breakdown voltage (> 120 V) allows alleviating the transistor stress associated to the voltage peaking waveform ($V_{peak} = 3.562 \cdot V_{DD}$) typical of a class E mode of operation.

In order to construct a very simple model of the device as a switch, the ON state resistance was estimated from the low drain voltage slope of the measured I/V curves at high $V_{GS}$ values, as represented in Fig. 2a). For the equivalent frequency-dependent output capacitance, the $S_{22}$ parameter was measured in Fig. 2 b) at $V_{DS} = 28$ V (the voltage value initially selected for operation) and for a $V_{GS}$ slightly below pinch-off, just before observing any significant increase in the output conductance.

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The efficiency figure was simply computed as in eq. (4), with \( P_{\text{out, DC}} \) and \( P_{\text{in, DC}} \) representing the output and input DC power, respectively.

\[
\eta_d = \frac{P_{\text{out, DC}}}{P_{\text{in, DC}}}
\]  

As expected, the efficiency figure reduces with frequency, staying above 80\% up to 1 GHz. Considering the simplicity of the model as well as the perfectly ideal terminating conditions implemented in the simulations, the real performance would be probably below these predicted curves. The design frequency was then selected to be 780 MHz, since the maximum frequency for optimum class E operation [17, 18] was estimated from the extracted \( C_{\text{out}} \) to be around this value.

The drain voltage and current waveforms, obtained from HB simulations at 780 MHz, are represented in Fig. 4. The voltage waveforms at the rectifying device in Fig. 4b, as theoretically described [13, 16], are time-reversed versions of those for the inverter in Fig. 4a. When one transistor is in its conduction state, the other is not. The ZVS and ZVDS conditions may be also appreciated, in the device transitions from OFF to ON (inverter) or from ON to OFF (rectifier).

When turned-on, the rectifying GaN HEMT operates in the third quadrant of its \( I/V \) characteristic s, as it should provide power to the DC load. Most available non-linear models, using a hyperbolic tangent function over \( V_{\text{DS}} \) as part of the \( I_{\text{ds}}(V_{\text{gs}}, V_{\text{ds}}) \) equation, fail in accurately reproducing this “inverse” operating region.

Fig. 2. Estimated values for \( R_{\text{on}} \) and \( C_{\text{out}} \): a) \( R_{\text{on}} \) extracted from the measured \( I/V \) curves and b) \( C_{\text{out}} \) from the \( S_{22} \) parameter.

With this model, and forcing the required conditions for both the inverting and the rectifying devices, the class E² topology was evaluated in terms of the switching frequency through harmonic balance (HB) simulations. The converter DC load and the interconnecting reactance were carefully adjusted according to eq. (2) and eq. (3), respectively, while open circuit conditions were implemented at both drain terminals to the second and third order harmonics. The precise phase shifting angle between the gate driving signals, required for assuring the desired coherent or synchronous operation of the rectifier, was also set at each frequency point. In Fig. 3, the obtained evolution for the output DC voltage and drain efficiency are plotted.

Fig. 3. Evolution of (→) output voltage and (←) drain efficiency with the switching frequency as obtained from HB simulations.

Fig. 4. Drain voltage and current waveforms for a) the inverting and b) the rectifying device, as obtained from HB simulations. The observed ringing may be ameliorated with the number of harmonics.
C. UHF Converter Design

As the simple LC series network of Fig. 1 may turn inappropriate for RF operation, due to the undesired reactive parasitics generally associated to the coil and the capacitor, a multi-harmonic terminating network was proposed in [19], as a lumped-element version of the widely used microwave transmission line topology suggested in [20]. Based on this technique, the topology selected for the UHF converter and already introduced in [21] is reproduced in Fig. 5. Using Air Core “Spring” series inductors from Coilcraft and 100B multilayer capacitors from ATC (values included in Table I), the desired drain termination at the fundamental, second and third harmonics were forced. A commercial hybrid coupler from Anaren allowed distributing the gate excitations with the required phase shift. A photograph with implementation details may be also found in the IMS paper [21].

![Fig. 5. Simplified schematic of the UHF converter from [21].](image)

**TABLE I.
Lumped Element Values in the Converter Schematic**

<table>
<thead>
<tr>
<th>Inductor</th>
<th>(L_{2p})</th>
<th>(L_{3s})</th>
<th>(L_{2s})</th>
<th>(L_{2p})</th>
<th>(L_{2p})</th>
<th>(L_{2p})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>3.85 nH</td>
<td>5.6 nH</td>
<td>2.5 nH</td>
<td>8 nH</td>
<td>5.6 nH</td>
<td>43 nH</td>
</tr>
<tr>
<td>Capacitor</td>
<td>(C_{in})</td>
<td>(C_{3p})</td>
<td>(C_{3p})</td>
<td>(C_{3p})</td>
<td>(C_{3p})</td>
<td>(C_{3p})</td>
</tr>
<tr>
<td>Value</td>
<td>8.2 pF</td>
<td>0.5 pF</td>
<td>0.8 pF</td>
<td>0.6 pF</td>
<td>3 pF</td>
<td>82 pF</td>
</tr>
</tbody>
</table>

\(L_{2p}\) was implemented with a small length of transmission line.

III. DC/DC CONVERTER PERFORMANCE

Considering the overall efficiency, \(\eta_{ov}\), as the figure of merit, where the required RF gate driving power, \(P_{in\_RF}\), is accounted for as in eq. (5), a peak value of 72% was reported in [21], in the state-of-the-art for DC/DC converters in this frequency band.

\[
\eta_{ov} = \frac{P_{out\_DC}}{P_{in\_DC} + P_{in\_RF}}
\]  

(5)

A. Output Voltage Control through Carrier Bursting

In [21], a pulse width modulation, PWM, over the envelope of the gate driving signal (an ON/OFF type of output voltage control strategy [5]) was proposed. This mode of operation, with bursts of the carrier exciting the device gate terminals, has been also suggested for high efficiency transmitters [22]. The switching frequency and its optimum duty cycle, \(D = 0.5\), were kept fixed as to have switching losses under control.

According to the reported evolution of output voltage and overall efficiency versus the envelope duty cycle, for a pulse repetition frequency of 500 kHz, a 3.7:1 control range could be perfectly covered with \(\eta_{ov} \geq 60\%\) [21]. Being the duty cycle to reconstructed voltage characteristic nearly linear, such coding results appropriate for reproducing dynamic variations with high fidelity. However, as the efficiency figure started degrading when increasing the pulse repetition frequency over a few tenths of MHz, mainly due to the highly demanding requirements for terminating the rectifying circuit at the carrier frequency as an open, while at the PWM frequency components as a short, excess losses could appear in the reproduction of wideband communication signal envelopes, as exemplified with a WCDMA format in [21].

B. Output Voltage Control through Frequency Modulation

Other control techniques may offer alternative performance to PWM, as described in detail along this and the following sub-section. Attending to the measured evolution of efficiency and DC voltage, reproduced from [21] in Fig. 6, the switching frequency may be used as control variable instead of the envelope duty cycle. Proposed with the original topology in [13, 14], advantage may be taken from the reduction in the output voltage with frequency, typical of class E operation, as to code the desired voltage variations using frequency modulation, FM, of the gate driving signals.

![Fig. 6. (--) Output voltage and (--) efficiency versus the switching frequency for a continuous wave excitation (\(V_{DD} = 28\) V).](image)

A maximum value of 72% could be obtained for a voltage 0.83 times the peak value, while the efficiency could be kept over 50% for a 1.9:1 voltage relation (corresponding to a peak-to-average power ratio, PAPR, of 5.6 dB, if thinking on its possible use as envelope modulator). Although for such specific application, the efficiency would be preferred to peak at a lower voltage value, this strategy would avoid the impact of a reconstruction filter in terms of the dynamic response.

C. Output Voltage Control through Outphasing

A third possible alternative for output voltage control, also employed for low frequency DC/DC converters using class D or class DE topologies, is based on phase coding. Following the outphasing principle [23], two amplifiers are combined in a phase controlled inverting topology, followed by a rectifier.
Advantage is usually taken from class D relative independence on the appearance of reactive components in the load.

At the frequencies of our interest, where single-switch inverters are preferred, the impact of a non purely resistive termination at the inputs of a Chireix combiner may seriously degrade the performance of class A, AB, B, C, F or inverse F based outphasing transmitters [24]. However, as it has been recently proved in [25], that is not necessarily the case for the class E topology. If properly transforming the load modulation paths, imposed by the combiner, into impedance loci at the drain terminals as close as possible to the optimum, where the ZVS condition may still be kept, through the addition of a carefully selected length of transmission line, the output power may be controlled while also conserving a high efficiency. Impressive results, following this strategy, have been reported for a wireless transmitter in [26].

Based on these works and using the simplified switch model of section II.B, a load-pull simulation at the fundamental was performed over the basic class E inverting topology of Fig. 1a) at 780 MHz. Open circuit terminations were forced at the second and third harmonics. The efficiency and output power circles are represented in Fig. 7, together with the trajectories to be obtained after properly transforming the impedance at both inputs of a simple reactive combiner with $X = 35 \, \Omega$ (see Fig. 8 for details). From this very simple simulation, an efficiency value over 80% could be expected for such outphasing class E inverter along a power range greater than 8 dB.

Based on these results, an alternative class E$^2$ DC/DC converter to the one in [21] has been designed, following the schematic represented in Fig. 8. Two class E UHF PAs are asymmetrically combined through a reactive lumped-element topology and lengths of transmission line, constituting an outphasing inverter, followed by a class E rectifier. As when controlling the inverter output power, the resulting phase component of the RF (our AC) signal also varies with the outphasing angle, the phase of the rectifier gate driving excitation would need to be consequently adjusted. A possible solution to this problem comes from taking a sample of the RF signal at the rectifier input to excite its device gate terminal.

This sample should be correctly dimensioned as to force a switched-mode operation of the rectifier over a range as wide as possible. To avoid device damage at high power values, the resistance in its gate DC path may be correctly dimensioned in such a way that the gate-to-source voltage is reduced with respect to the applied biasing value when a small rectifying current appears at this terminal. In the proposed design, a small valued capacitor, $C_s$, was used to take the sample, followed by the introduction of a $T$ $L_{ph}$-$C_{ph}$-$L_{ph}$ network in the drain-to-gate interconnecting branch as to assure the appropriate phasing between the drain-to-source and gate-to-source voltages. Since the selected GaN HEMT is able to provide a very high gain at this frequency band, close to 20 dB, the impact on overall efficiency when taking such a small sample of the inverter AC output (the rectifier AC excitation) may be neglected.

In Fig. 9, a photograph with details of this alternative double class E UHF converter, implementing the outphasing control voltage technique, is presented. No special attention was paid to produce a compact design, only to validate the topology.

After characterizing the converter in terms of the outphasing angle, the output DC voltage and the overall efficiency have been represented in Fig. 10.
A peak overall efficiency also of 72% has been obtained, but in this case for an output voltage 1.52 times below the maximum (corresponding to a 3.66 dB PAPR signal if thinking again on an envelope modulating application). The overall efficiency was kept over 50% for a 2.1 voltage control range. Although this range is reduced with respect to the results using the carrier bursting control technique, no reconstruction filter is here required. This makes this topology highly attractive in terms of the dynamic response. Through a careful selection of the reactance value and the use of an alternative solution for the rectifier gate driving signal, the voltage range might be extended as to reproduce signals with a higher PAPR.

IV. CLASS E³ POLAR TRANSMITTER

In order to test the potential of the carrier bursting class E² converter of [21] in a real fast response application, as the above mentioned bias adaptation wireless transmitters, a polar architecture has been selected. Since in a pure EER technique, the load impedance presented by the RF PA stays constant, there would be no need for regulating the converter output voltage despite its finite output impedance. Such regulation would be instead required in ET or hybrid ET/EER schemes.

Taking also into account its bandwidth limitations, in terms of efficiency, related to the minimum required ratio to be conserved between the desired converter frequency response and the pulse repetition frequency (for PWM coding such voltage variations), as well as between this frequency and the carrier, an EDGE standard signal was selected. Having a moderate 200 kHz bandwidth, a 3.8 dB PAPR and a hole in its constellation, to avoid the feedthrough effect, this format is certainly amenable for polar transmission.

A. UHF Polar Transmitting Scheme

In Fig. 11, a simplified diagram of the proposed class E³ polar transmitter is represented. The class E² resonant power converter is used to high level amplitude modulate a class E RF PA, in an analogous way to [27], excited with a constant-envelope phase modulated (PM) signal. The same carrier frequency is used, both for the PM and the AM branches, resulting in a fully RF-based implementation. One of the advantages of handling the envelope with a RF switching frequency is the reduced size of the implemented transmitter.

In Fig. 12, a photograph with details of the RF part of the scheme may be appreciated. Three similar GaN HEMT devices, the CGH35030 from Cree Inc., are employed, two for the converter plus the one for the RF PA. The CLC reconstruction filter, with a 1 MHz bandwidth and a maximally flat response may be also distinguished. A 5 MHz pulse repetition frequency was employed for PWM coding the envelope variations. Since this frequency is quite below the carrier value, optimum rectifier terminations are possible.

A second advantage of using this type of converter has to do with the correction of the differential delay between the AM and PM paths, one of the main nonlinear distortion sources in this type of architectures [28, 29]. Being the AM component processed also at the frequency used for the PM modulation, the differential delay was not significant at all.

B. RF PA Stage

For the RF PA, a stage similar to those integrating the converter has been selected. In Fig. 13, the measured static (with CW RF excitation) $V_{dr}$-to-AM and $V_{dr}$-to-PM profiles are plotted, together with the probability density function, pdf, for the EDGE AM component and the PAE evolution. A peak drain voltage value of 28 V was assumed. As typical from class E operation [30], the most significant part of the envelope variation coincides with a nearly linear amplitude characteristic and a minor undesired phase modulation. Although the voltage and current waveforms have not been measured, these profiles may show that the device is operating close to the desired ZVS and ZVDS conditions.
Taking also into account the nearly linear Duty Cycle-to-AM characteristic measured for the class E\(^2\) converter in [21], a low predistortion effort could be required for transmitter linearization. Most part of the envelope also fits in the region where the power added efficiency, PAE, is over 75%, reason why a high average figure could be expected.

![Graph](image)

Fig. 13. \(V_{\text{dur}}\) to-AM, \(V_{\text{dur}}\) to-PM and PAE static profiles for the class E\(^2\) RF PA. The EDGE envelope pdf function has been also plotted.

C. DPD and Characterization Results

After implementing the transmitter, a static characterization of output amplitude, \(a_n\), and phase variations, \(\phi\), with the envelope voltage, \(V_{\text{DS}}\), was made (see Fig. 11 for notation). The input DC biasing voltage was fixed to 35 V, as to obtain a peak voltage at the converter output close to 28 V. A simple memoryless digital predistortion, DPD, based on [31], was then implemented as a look-up table, LUT, in order to reproduce the desired signal. As described in Fig. 14, the digitally generated amplitude component, \(a_d(n)\), should include corrections to the AM-to-AM profile, including PWM modulation, DC/DC converter and RF PA \(V_{\text{dur}}\) to-AM nonlinearities. After that, the parasitic phase variations, \(\Delta\phi\), to be introduced by the AM modulating signal, from the characteristic in Fig. 13, were digitally subtracted from the desired PM component, \(\phi_y(n)\).

![Diagram](image)

Fig. 14. Diagram representation of the implemented DPD.

Once this simple predistortion strategy was applied, the spectrum of the output EDGE modulated signal was compared to the spectrum of the original version in Fig. 15. As it may be appreciated, the recovered signal nearly fits the original. Out-of-band emission components were also measured at \(\pm 5\) MHz from the carrier and 55 dBc below its level. They are due to the PWM spectral components and the attenuation offered by the implemented reconstruction filter.

A summary of the measured output power, linearity and efficiency figures is also included in Table II. The linearity specifications, -58 dBc at 400 kHz and -60 dBc at 600 kHz, are satisfied with an average transmitter efficiency figure over 46% (including envelope modulator and RF PA). In these specific operating conditions, the average efficiency of the DC/DC converter was estimated to be over 60%.

![Graph](image)

Fig. 15. Spectrum of the output signal, as compared to the original.

Attending to these results, approximately dimensioning a class E\(^2\) power converting topology, a linear reproduction of a time-varying voltage envelope may be assured with low losses. If interested in efficiently handling signals with a wider frequency of at least 100 MHz would be required. If using a particular PWM resonant converter, a pulse repetition frequency of at least 100 MHz would be required. If using a higher carrier switching frequency, such as the 2.14 GHz required for base stations, the desired filter terminations would be feasible at the expense of a reduction in the achievable peak efficiency value (at least for the here employed devices).

V. UHF POWER CONVERSION FOR MINIATURIZATION

Having described the benefits of a UHF power converter in terms of frequency response enhancement, attention may be paid to the second benefit of a high frequency conversion for power density improvement (size and weight reduction). The above proposed implementations are not exactly compact, mainly due to the selection of a multi-harmonic network to properly terminate the inverting and the rectifying devices, as well as the use of packaged versions for the transistors.

A. LC Series Class E\(^2\) Converter using Coil Self-Resonance

To reduce the footprint and volume, the original LC series topology in [13, 14] is a very attractive candidate. If taking advantage of the lumped-element parasitics, selecting a high Q coil with a self-resonant frequency between the second and third harmonic, while carefully tuning the capacitance value as to provide the desired 2\(X\) reactance of eq. (3), the converter size could be significantly reduced.
After characterizing, as in section II.B, a die GaN HEMT with similar power capability, the CGH60030, also from Cree Inc., a simple network with an 8 nH Air Core “Spring” inductor from Coilcraft and two 8.2 pF 100B ATC capacitors was adjusted. In Fig. 16, the evolution with frequency of the impedance as seen in one of its port, when loading the other with the desired AC resistive component is shown. As it can be appreciated, the impedance at the fundamental frequency nearly fits the desired $R_{ac} + j·2·X$ value, while the second and third order harmonic terminations are relatively close to the open circuit condition thanks to the coil parasitic capacitance.

In Fig. 17, a photograph of the suggested 1 GHz implementation is shown. The input and output DC networks have been included, as well as gate matching capacitors. The gate driving signal was externally split using a commercial in-phase power divider, also from Anaren. The desired phasing between the inverter and rectifier excitations was set by adding a few SMA transitions. The gate biasing voltage was also applied to both die devices through an external bias tee.

B. Measured Performance

The characterization results in terms of frequency are finally represented in Fig. 18. A good performance has been obtained, with a peak overall efficiency over 70%, through a much more compact and simple implementation. The voltage and efficiency profiles measured versus the duty cycle approximately followed those reported for the converter in [21]. Frequency or carrier bursting modulation for output voltage control would be also feasible.

![Fig. 16. Measured evolution with frequency of one port impedance, when loading the other with the optimum resistance value, $R_{ac}$.](image16.png)

![Fig. 17. Photograph with magnified details of the miniaturized implementation at 1 GHz.](image17.png)

![Fig. 18. (--) Measured output voltage and (--) efficiency versus the switching frequency at $V_{DD} = 28$ V for the converter in Fig. 17.](image18.png)

VI. CONCLUSION

Class $E^2$ resonant topologies for DC/DC power conversion at Ultra High Frequencies (UHF) have been designed and characterized in this paper, considering their benefits for improving the response speed and power density over current lower frequency solutions. In the first case, a class $E^2$ polar transmitting application for the EDGE standard has been proposed and tested at 770 MHz, offering an average global efficiency of 46% for more than 4 W of output power, with amplitude and phase branches fully implemented at the carrier frequency. Further considerations for obtaining a higher bandwidth have been also suggested, such as the use of an outphasing output voltage control strategy. In the miniaturization direction, a compact implementation, taking advantage of passive element parasitics and die device versions has been also proposed. A peak value for the overall conversion efficiency over 70% has been measured, at 12.4 W of output power and 1 GHz. Comparing this work with previously published converters (see Table III) the obtained efficiency results are in the state-of-the-art according to the switching frequency and power level.

Although the employed GaN HEMTs have not been conceived for this mode of operation and the efficiency figures are not currently competitive with more traditional kHz converters, the great potential of RF conversion using this technology has been proved.

<table>
<thead>
<tr>
<th>Switching Frequency (GHz)</th>
<th>Output Voltage (V)</th>
<th>Output Power (W)</th>
<th>Overall Efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>7</td>
<td>6</td>
<td>84</td>
<td>[32]</td>
</tr>
<tr>
<td>0.03</td>
<td>65</td>
<td>472</td>
<td>83</td>
<td>[33]</td>
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<td>220</td>
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<td>[7]</td>
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<td>35</td>
<td>90</td>
<td>[34]</td>
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TABLE III

STATE-OF-THE-ART HIGH FREQUENCY DC/DC CONVERTERS
ACKNOWLEDGMENT

J. A. Garcia wants to acknowledge all the advice and suggestions on the treated topics received from Prof. Z. Popovic and Prof. D. Maksimovic, Univ. Colorado at Boulder, Prof. J. Sebastian, Univ. Oviedo, Prof. D. Perreault, Massachusetts Institute of Technology, Prof. J. C. Pedro, Univ. Aveiro, and Dr. F. Raab, Green Mountain Radio Research Co. The contributions to this research line from previous members of the group, Dr. L. Cabria and Ms. L. Rizo, are also appreciated, as well as the support received from Mrs. Sandra Pana, Univ. Cantabria, with die mounting and bonding, and from Mr. Ryan Baker, Cree Inc., related to the GaN HEMT devices. Finally, the authors want to thank the editor and the reviewers by their kind comments and detailed suggestions to improve this manuscript.

REFERENCES

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