A UHF Class E^2 DC/DC Converter using GaN HEMTs

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***Abstract* — In this paper, the design of a class E^2 resonant DC/DC converter, operating at UHF band, is proposed. Combining the use of GaN HEMT devices, both for the inverter and the synchronous rectifier, with high Q lumped-element multi-harmonic matching networks, a peak efficiency value of 72% has been obtained at 780 MHz with a 10.3 W output power. By means of a Pulse Width Modulation (PWM) over the gate driving envelope, the output voltage may be controlled while keeping low switching losses, with an estimated small-signal bandwidth (BW) and a slew rate of 11 MHz and 630 V/μSeg, respectively.**

***Index Terms* — Class E, DC/DC converter, GaN HEMTs, UHF.**

I. INTRODUCTION

Modern power electronics applications are demanding for converting systems with a very fast transient response, the case for instance of the envelope modulator in highly efficient envelope tracking (ET), envelope elimination and restoration (EER) or hybrid ET/EER transmitters. Together with the interest in miniaturization and cost reduction, to reach the power supply-in-package (PSiP) and power supply-on-chip (PwrSoC) ultimate targets, 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 values.

Achieving competitive efficiency figures in DC/DC converters at VHF, UHF or higher frequency bands, requires keeping frequency dependent switching loss mechanisms under control. Using zero voltage switching resonant solutions [1], those mechanisms may be minimized by 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 converters.

Several solutions at HF and VHF bands have appeared during the last years [2], based on class E^2 [3] or more recently in class Φ_2 topologies [4]. Operation at higher frequencies has been however limited to a few works on small power levels [5], mainly due to the non availability of appropriate power transistors and Schottky diodes. In this paper, a UHF resonant DC/DC power converter, following a class E^2 scheme, is proposed. The use of RF GaN HEMT devices, both for the inverter and the synchronous rectifier, together with high Q lumped-element multi-harmonic matching networks and a sort of on/off output voltage control [2], allow improving the operating bandwidth while also keeping high efficiency.

II. CLASS E^2 DC/DC CONVERTER

A class E^2 resonant converter combines a class E inverter with a class E rectifier. In its original form [3], a simple series LC circuit, interconnecting both devices, simultaneously assures the required impedance conditions for zero voltage and zero voltage derivative switching (ZVS and ZVDS). However, the parasitics in their equivalent circuit models may result in non-optimum terminations at the higher order harmonics when this scheme is extrapolated to high frequency implementations.

A. RF Converter Particularities

The proposed class E^2 converter topology is depicted in Fig. 1. A RF power amplifier (PA), the inverter, is integrated with a synchronous rectifier, designed both over GaN HEMTs. Besides this technology offering a very low value for the on-state resistance output capacitance product ($R_{on}\cdot C_{out}$ = 1.5 Ω·pF for the selected CGH35030F device, from Cree Inc.), its high breakdown voltage (> 120 V) allows alleviating the transistor stress associated to the voltage peaking waveform typical of this mode of operation.

For appropriate current and voltage waveform shaping, multi-harmonic impedance matching networks are needed at drain side. At the selected UHF band, centered at 780 MHz, such networks may be implemented with high Q coils and capacitors [6]. As detailed in Fig. 1, while series LC combinations are used to force short-circuit conditions at the third (L_{3s}-C_{3s}) and second harmonic (L_{2s}-C_{2s}), a parallel resonant tank (L_{3p}-C_{3p}) and a very small inductance (L_{2p}) are here used to produce the desired open-circuit terminations. The device equivalent output capacitance, C_{out} = 2.9 pF, was characterized at V_{DS} = 28 V and V_{GS} = -3.5 V (the value just before observing any increase in the output conductance). Based on this estimation, an initial value for the optimum impedance at the fundamental, $Zd_{opt}(\omega) = 0.28/(\omega\cdot C_{out}).e^{(j\cdot 49^{o})} = 12.92 + j\cdot 14.87\ \Omega$, was synthesized through simulations by means of a simple lumped-element ∏ equivalent of a length of transmission line interconnecting the integrating blocks.

The phase shift between the inverter and rectifier RF excitations, required for appropriate synchronization of the rectifier gate and drain voltage waveforms, was estimated to be close to 90º.

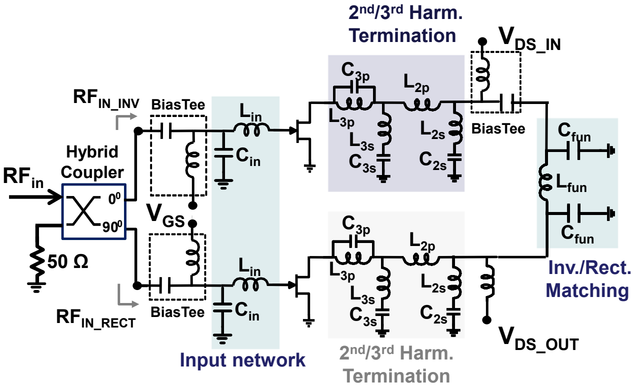


Fig. 1. Simplified schematic of the UHF class E^2 converter.

B. Converter Implementation Details

Following the suggested topology, a lab model for the resonant DC/DC converter was fabricated (see Fig. 2). Individual connectors were used for gate driving both devices, while also auxiliary RF measuring ports were introduced at drain side. In this way, both circuits could be independently adjusted as to operate in soft-switching conditions, while the required phase shifting could be exactly characterized. An ANAREN hybrid coupler was externally added for RF input signal splitting, while Air Core coils from Coilcraft and 100B capacitors from ATC were employed in the passive networks.

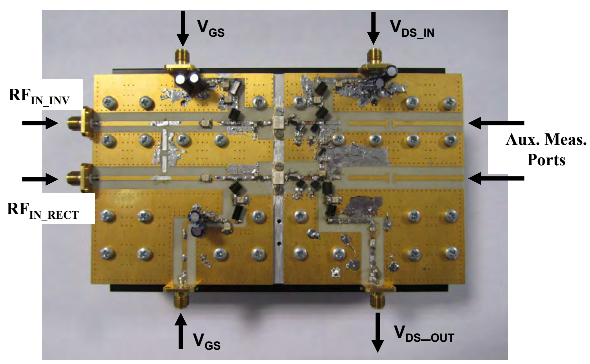
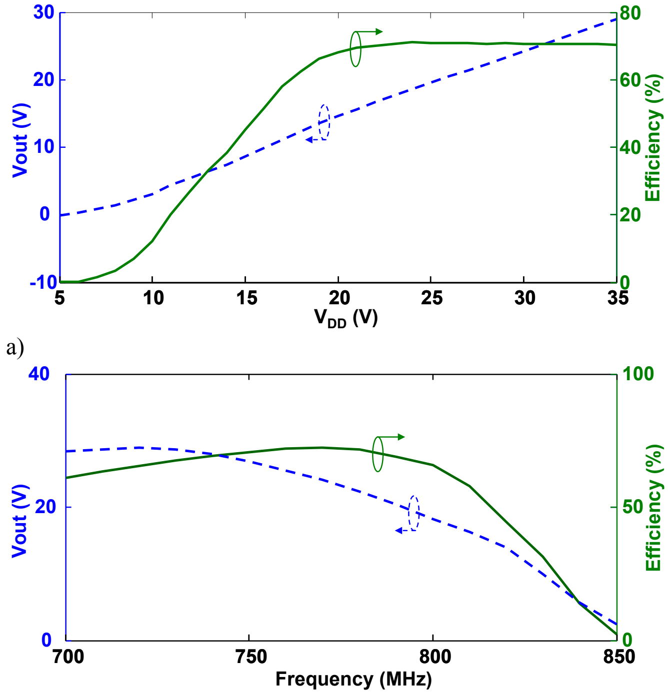


Fig. 2. Photograph and details of the implemented converter.

III. DC/DC Converter Characterization

A. Static and Dynamic Figures of Merit

The designed UHF converter was then characterized, first in terms of the input DC voltage and the switching frequency. For simplicity, a load resistor of 50 Ω, higher than the theoretical optimum value, $R_{DC} = 1/(\pi \cdot \omega \cdot Cout)$, was employed. The results are plotted in Fig. 3a and 3b. As expected [1], the rectified voltage follows the inverter drain biasing in a highly linear mode, while the conversion efficiency keeps high over a broad power range. Defining an overall efficiency figure as $\eta_{ov} = P_{out\_DC}/(P_{in\_DC} + P_{in\_RF})$, with P_{out_DC} and P_{in_DC} representing the output and input DC power, respectively, while P_{in_RF} the required RF gate driving level, a peak value of 72% was measured, in the state-of-the-art for DC/DC converters in this frequency band. The bandwidth, for which the efficiency decreases in only 10%, was estimated to be as high as 90 MHz, 11.5% of the central operating frequency.



a)

b)

Fig. 3. (--) Output voltage and (—) efficiency versus a) input voltage (f = 780 MHz) and b) switching frequency (V_{DD} = 28 V).

The output voltage control was implemented using a PWM over the envelope of the gate driving signal (an on/off type of control strategy [2]). In this way, the switching frequency and its optimum duty cycle, DC = 0.5, are kept fixed, as to assure the desired low switching loss conditions. The efficiency may also stay high across a wide control range, as no loss would exist when the converter is in its off or non-excitation state. In Fig. 4, the evolution of the output DC voltage and overall efficiency are plotted in terms of the envelope duty cycle, for a pulse repetition frequency of 500 kHz and introducing a simple but appropriate reconstruction filter at the output.

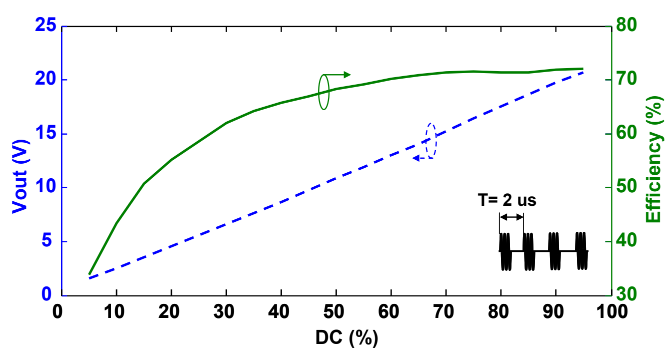


Fig. 4. (--) Measured output voltage and (—) efficiency profiles versus envelope duty cycle at V_{DD} = 28 V and f = 780 MHz.

The dynamic response of the converter, both in small- and large-signal regimes, was also measured. For estimating the small-signal bandwidth, a low-level chirp signal, whose frequency was varied in a logarithmic mode between 20 kHz and 20 MHz, was superimposed to a 0.9 normalized DC input voltage, as to force variations of the duty cycle between 0.85 and 0.95. A reference signal of 100 MHz was used for the PWM, while a matched lowpass reconstruction filter, in this case with a 12 MHz cutoff frequency, was inserted in the output. The estimated 3 dB bandwidth, BW, resulted in 11 MHz (see Fig. 5), as determined by the employed filter.

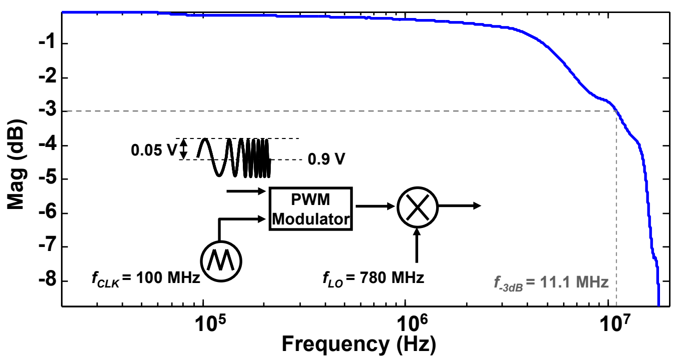


Fig. 5. Measured small-signal versus frequency response. Details of the implemented PWM for this experiment appear in the inset.

Finally, a voltage step was used as modulating signal, as to force a fast duty cycle transition from 0.05 to 0.95. A slew rate value of 630 V/μSeg was estimated from the output voltage excursion captured with a high BW oscilloscope.

B. UHF DC/DC Converter as Envelope Modulator

In order to test the suitability of the implemented converter for very high speed applications, as the reproduction of the strongly time-varying envelopes in ET or hybrid ET/EER transmitters, a WCDMA envelope was clipped and used as PWM modulating signal. The effect of the 12 MHz reconstruction filter and PWM non-idealities over the recovered voltage appears as a compression of the envelope excursion in Fig. 6. Except for this compression, the recovered voltage seems to correctly follow the fast envelope transitions.

The estimated average efficiency was reduced to 42% under these extreme operating conditions, a value not currently competitive with switched-mode assisted linear converter topologies. The impact of the out-of-band filter terminations should be considered to further fit the converter performance to this or similar demanding applications.

A possible improvement could be obtained if also switching (at a much slower rate) the input voltage among a few levels, carefully selected according the envelope probability density function.

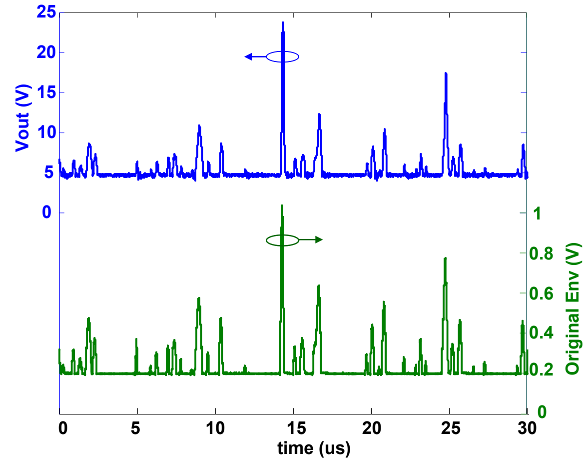


Fig. 6. (-) Original and (-) recovered clipped WCDMA envelope signals, as used in ET or hybrid ET/EET wireless transmitters.

IV. Conclusion

A 780 MHz class E^2 resonant converter, designed over GaN HEMT devices, has been proposed. A peak efficiency value of 72% has been measured for an output power value of 10.3 W at a 28 V DC input voltage. A small signal bandwidth as high as 11 MHz and a slew rate value of up to 630 V/μseg were measured, in presence of a 12 MHz lowpass output filter.

Acknowledgement

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