High Efficiency GaN Switching Converter IC with Bootstrap Driver for Envelope Tracking Applications

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***Abstract* — In this paper, we report a DC/DC converter based on GaN HEMT's with a switching frequency of 200 MHz that can be used to generate envelope-modulated power supply voltages for use in envelope tracking power amplifiers. The converter consists of switching circuits using 0.25-um GaN HEMTs, inductor, and low pass filter, and can provide output voltages above 28V. An integrated bootstrap driver of the switching circuits is employed in order to reduce DC power consumption of the driver stage. Generation of envelope power supply voltages for 20 MHz LTE signals was demonstrated using 200 MHz switching rates with efficiency of 73%(including dissipation in final and driver stages). The chip size is 1075×990 um².**

***Index Terms* — Bootstrap, DC/DC converter, envelope tracking power amplifiers, GaN, pulse width modulation.**

I. Introduction

The envelope tracking (ET) technique, in which an envelope amplifier provides dynamic supply voltage to the RF amplifier, has demonstrated high efficiency for signals with high peak-to-average power ratio such as WCDMA. As modern communication systems such as 3GPP LTE and WiMAX are introduced, it is challenging to maintain high ET efficiency, because of the increasing demands of wider modulation bandwidths and higher data rates. One of the key components for the development of high efficiency ET PAs is an efficient broadband envelope amplifier to provide the dynamically varying power supply voltages. This circuit is often a combination of a linear stage and a switcher stage (as used, for example, in [1], a high efficiency GaN envelope tracking power amplifier operated at 780 MHz using 5 MHz WCDMA and 10 MHz LTE signals). Conventionally, the switcher stage is controlled by a hysteretic comparator or a PWM controller. For improved efficiency, a supplementary linear regulator, a two-phase PWM control, or a dual switch have been used in [2]-[4]. These techniques enable more accurate tracking of the switching amplifier without increase of the switching frequency. However, the higher frequency components of the envelope signal are still provided with a relatively inefficient wideband linear stage. Recently, single high-frequency dc/dc converters (with 100 and 200 MHz switching frequencies) in order to replace(or at least to minimize the operation of) the linear stage in hybrid switching supply modulators for WCDMA applications have been reported [5]. Recently, Shinjo *et al.* [6] have reported a high voltage buck converter using resistor pull-up type driver stages with 0.7-μm GaN HEMT process which achieves a high final stage efficiency. However, the GaN driver circuits consume a relatively large amount of power, especially when the duty cycle is low.

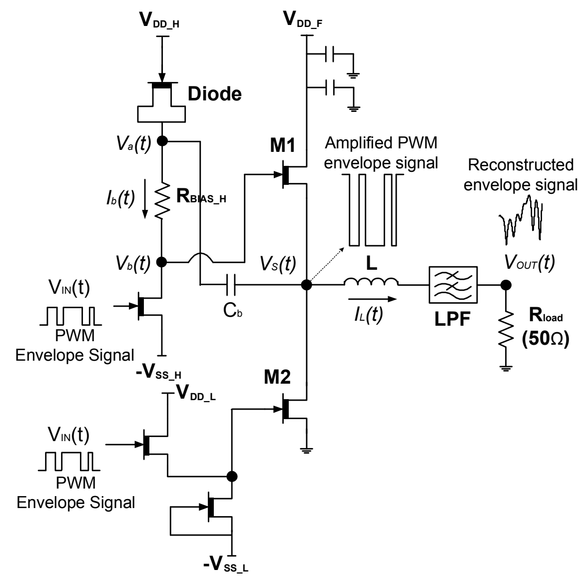

Fig 1. Proposed GaN switching converter IC.

In this paper, we report a high speed switching converter using GaN HEMTs to realize the envelope amplifier. Compared to the dc/dc converter in [6], the switcher stage takes advantage of bootstrap-based driver design for higher efficiency, and uses shorter gate-length(0.25-μm) GaN HEMTs. As a result, its efficiency is higher, up to 73% for waveforms corresponding to 20 MHz LTE. The output voltage is as high as 28 V, which is appropriate to drive GaN or LDMOS RF power amplifiers.

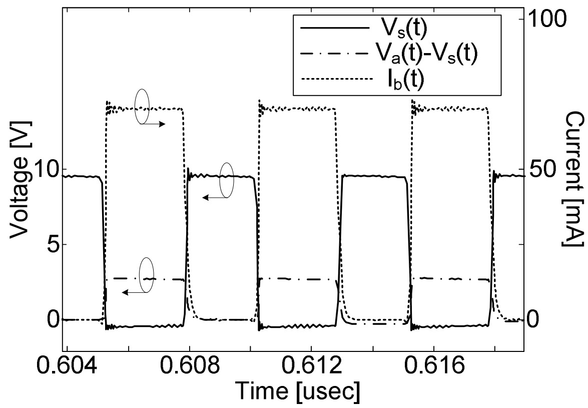

Fig 2. Simulated voltage and current waveforms with V_{DD_F}=10V.

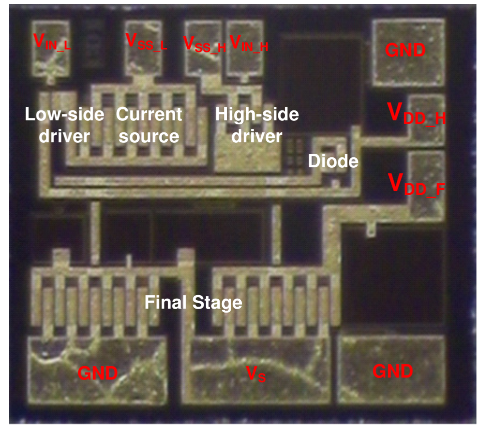

Fig 3. GaN MMIC chip.

II. Switching Converter Design

Figure 1 shows a schematic of the proposed GaN switching converter IC. The switching converter comprises a switching circuit, an inductor, and low pass filter to provide DC and envelope (baseband) current after suppressing spurs in the high frequency range around harmonics of the switching frequency. The switching circuit consists of 1) an inverter-type final stage, 2) a low-side driver stage based on a source follower employing a current source type pull-down; and 3) a bootstrap diode/capacitor type high-side driver stage.

The circuit was designed to operate at 200 MHz and above using a 0.25-µm GaN HEMT process, with devices whose gate periphery is 1 mm. The transistors are n-channel depletion-mode devices (Vt=-2.5V) and show a saturation current I_{DSS}=0.6 A/mm, transit frequency f_T of 30 GHz, and high breakdown voltage(>40V). As differential pulse signals are used as inputs to the final stage, the circuit operates as a voltage mode class-D amplifier.

As shown in Fig. 1, due to the absence of the P-channel transistors in GaN technology, the high-side driver design is more complicated than for the low-side driver because the gate voltage for the top device must have a very large swing, from below ground to approximately the full power supply voltage. This is accomplished with the bootstrap driver without a significant increase in dc power dissipation. The bootstrap operating procedure is as follows: when M2 is turned on, the capacitor C_b charges to the auxiliary supply voltage(V_{DD_H}). In the following phase, when M2 is turned off, V_S rises and as a result V_a rises, as shown in Fig. 2. This provides an appropriately high drive voltage for the gate of M1.

The fabricated GaN MMIC chip is pictured in Fig.3. The diode was implemented using a GaN HEMT device with source and drains shorted. MIM capacitors and resistor were also implemented on-chip. Overall dimensions including bond pads were 1.075 mm x 0.99 mm.

III. Switching Converter Measurement Results

Fig. 4 shows a block diagram of the test setup for the GaN switching converter IC. Modulation of the duty cycle of the input pulses is numerically generated using Matlab, and read out using a programmable pulse generator with maximum clocking frequency of 13.5 GHz. Dual in-phase output pulses from the generator are first amplified by a buffer, followed by bias tees to provide proper input voltage swing level for the switching circuits. The output signal is measured by means of a 50-Ω high-speed oscilloscope in time domain, connecting the output through a off-chip air-coil inductor (470 nH) and low pass filter(Mini-circuit's SLP-150).

The converter ICs designed in 0.25-µm GaN technology are measured on PCB [see Fig. 4]. The pads of the chips are connected to the tracks of the PCB through bond wires without any package. In Fig. 5, measured efficiency and output power at the frequency of 200 MHz with pulse width modulated signals at 50% duty cycle is plotted versus drain voltage (V_{DD_F}) with 50-Ω load impedance. The drain efficiency (DE) considers the final switching stage power consumption only. The overall efficiency quoted here considers the total dc power consumed by both the driver and final stage. As expected, it is shown that the overall efficiency is improved with increasing drain voltage since the output power increases significantly, while the power dissipated in the driver stage increases less rapidly.

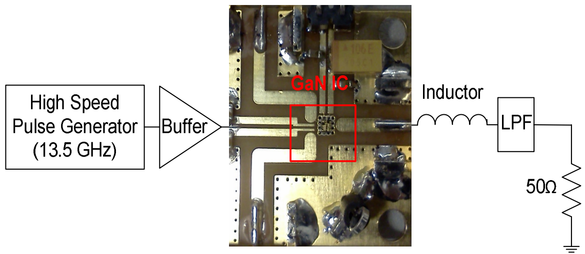

Fig 4. Test setup, showing details of the PCB used.

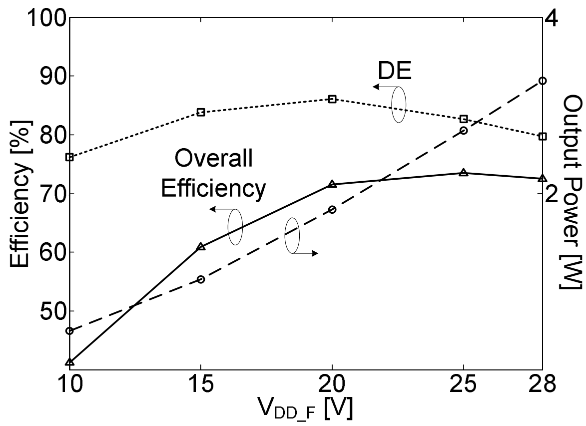

Fig 5. Measured efficiency and output power with pulse width modulated signals in continuous time as a function of supply voltage(V_{DD_F}) .

The switching converter was also tested with pulse width modulated signals in continuous time. In order to encode the envelope waveform required for a 20 MHz PAPR=7.7dB LTE-style signal, Matlab was used to generate a corresponding pulse-width modulated signal stream. Since the digital pulse generator used to produce the driving pulses has a fixed clock rate, a delta-sigma algorithm was used to reduce the clock jitter resulting from the finite selection of pulse widths. The envelope signal was "detroughed", that is, the minimum voltage was increased from zero to a finite value to avoid driving the RF PA in envelope tracking with too low a voltage. In this work, we used the relation below [4] with b=0.3

$$V_{DD} = |x_{RF}| + b \cdot e^{-|x_{RF}|/b} \tag{1}$$

To avoid clipping during the peak of envelope signal in continuous time, maximum duty cycle of envelop signal is limited to 0.85, which results in excellent NRMSE while maintaining high efficiency. Assuming there is no voltage drop through the LPF in Fig. 1, $V_s(t)$ can be expressed as:

$$V_s(t) = V_{out}(t) + \frac{L}{R}\frac{dV_{out}(t)}{dt} \tag{2}$$

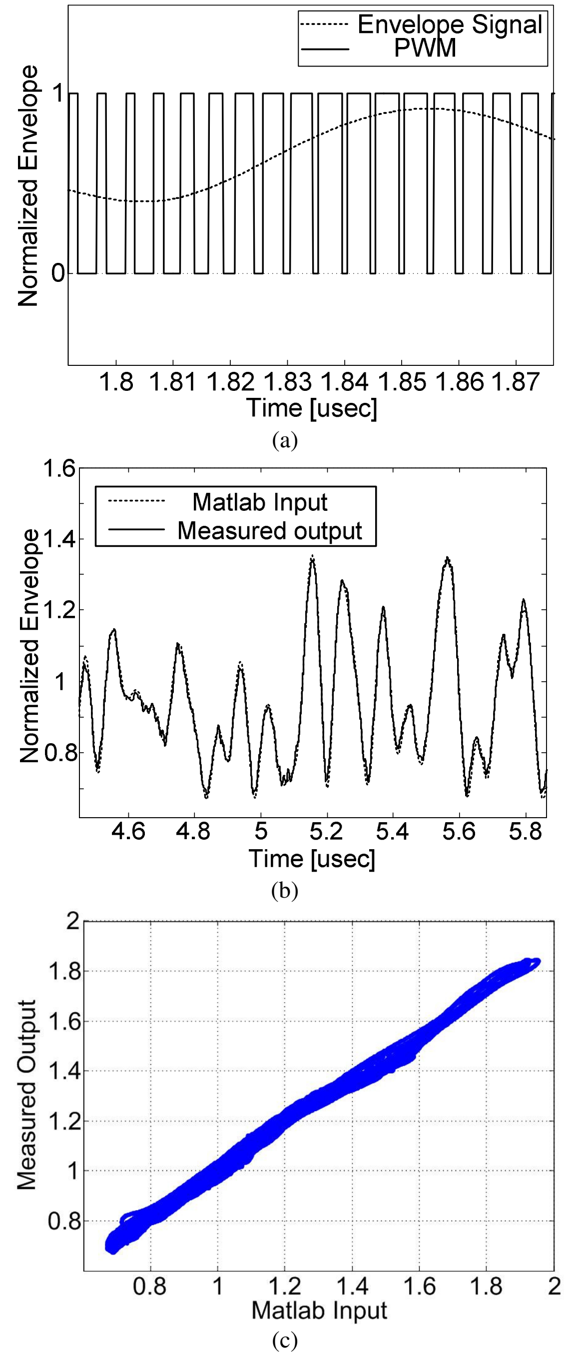

Fig 6. Input and output signals with 200 MHz switching frequency and 20 MHz bandwidth (a) envelope signal and PWM encoded input signal (b) input and output envelope signal (c) AM-AM.

To achieve the proper value of $V_{out}(t)$, the target $V_s(t)$ was appropriately chosen taking into account the derivative term. Signal generation techniques will be reported separately in more detail.

TABLE I
PERFORMANCE COMPARISON TO PREVIOUS ETPA

	Signal BW [MHz]	η* [%]	Vmax [V]	Pout# [W]
Ref. [1]	5	84	32	27
Ref. [4]	10	70	28	26
Ref. [5]	15	79	2.4	0.9
Ref. [6]	20	64	20	1.9
This Work	**20**	**73**	**28**	**3.3**

*: average efficiency, #: average output power

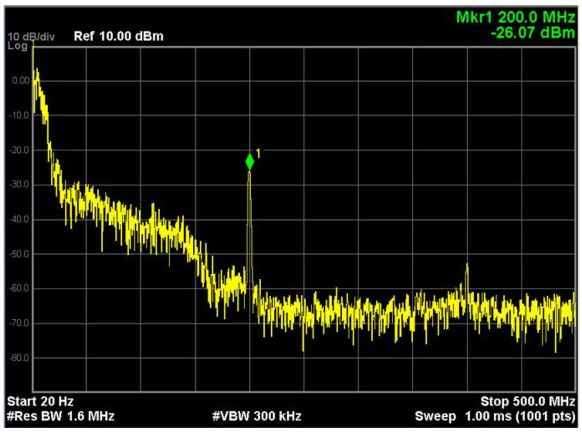

Fig 7. Spectrum of output envelope signal.

In Fig. 6(a), representative waveforms of both the envelope signal and PWM encoded signal are presented. Fig. 6(b) shows measured output voltage waveform with 20-MHz signal and 200 MHz switching frequency, showing that the output signal properly tracks the input signal. Fig. 6(c) shows the measured output amplitude vs the desired output (Matlab input), corresponding to AM-AM distortion; the amount of scatter can be related to memory effects. The proposed high speed switching converter achieved overall efficiency of 73% at 200 MHz switching frequency. Normalized root mean square error (NRMSE) between envelope input and envelope output signal is 0.028. The spectrum of output envelope signal is shown in Fig. 7. With the LPF, the fundamental and the second harmonic of the switching frequency (200 MHz) are reduced to -36 dBc and -64 dBc, respectively. There is room for improvement of the harmonic suppression by improved design of the LPF with higher out-of-band rejection while maintaining good in-band insertion loss. Also, switching frequency above 200 MHz may be useful for wider bandwidth signals or to simplify the LPF requirements. Table I provides the performance summary of the envelope amplifier reported here and a comparison to other published results. To the authors' knowledge, the combination of signal bandwidth, efficiency, and output voltage is the best reported to date for envelope amplifiers.

IV. CONCLUSION

In this paper, we have demonstrated high efficiency GaN-based high speed switching converters that can be used as the supply modulator in ET power amplifier applications. The use of GaN provides for a significant increase in switching frequency(to 200 MHz and above) while providing high output voltages. This compares very favorably with the switching frequency of several MHz used in conventional high voltage switcher stages in envelope amplifiers based on silicon devices.

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