Decade Bandwidth High-Efficiency GaN VHF/UHF Power Amplifier

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***Abstract*—This work discusses the design of a GaN power amplifier demonstrating high efficiency over more than a decade bandwidth using coaxial baluns and transformer matching networks to achieve over a 50 MHz-500 MHz bandwidth. The power amplifier demonstrates a power added efficiency of 83%-64% over full bandwidth with 15 dB compressed gain at peak PAE.**

***Index Terms*—Power amplifier, GaN, coaxial balun, efficiency, push-pull, VHF, UHF.**

I. Introduction

Mobile multi-channel radio communications, television broadcasting, air traffic control, marine communications and weather forecasting systems require efficient and broadband transmitters operating at VHF/UHF frequencies. A large part of the spectrum allocated by the FCC for land mobile radio (LMR) technologies entails VHF/UHF bands (VHF low, mid and high bands, 220 MHz and UHF 380-512 MHz). Broadband RF power amplifiers (PAs) have the ability to reduce the cost in multi-band communication systems as long as high efficiency is maintained over the operating frequency range. This is challenging as constant compressed gain and output power are required for the application. Circuit implementation of broadband PAs working in the VHF/UHF frequency band has been widely reported [1], [2], [3] using Silicon-based technologies (MOSFET, LDMOS) and more recently GaN transistors with higher f_T [4], [5].

Switching mode power amplifiers (SMPAs) achieve better efficiency than conventional linear mode amplifiers; since there is no overlap in time between current and voltage at the current source, 100% efficiency can ideally be obtained. The theoretical maximum efficiency of a switching amplifier with square-wave current and voltage waveforms is 81% due to power lost in harmonics. By using infinite harmonic shaping, class-F and F^{-1} can theoretically achieve 100% efficiency. An ideal class-E PA with no on-resistance also reaches 100% theoretical efficiency [3]. These are narrowband PA architectures which have demonstrated over 80% PAE at microwave frequencies [6].

In this paper, we present a GaN HEMT PA module operating from 50 to 500 MHz. Using GaN HEMTs at VHF/UHF is not trivial because devices in this technology exhibit high gain at low frequencies and care needs to be taken in the design to ensure stability. Table I summarizes previously published work with achieved performance of power amplifiers operating in the VHF and UHF frequency bands. The work presented in this paper, to the best of our knowledge, has the largest PAE-bandwidth and power combination with flat gain.

TABLE I
SUMMARIZED RECENT WORKS AT UHF-VHF FREQUENCIES

–	**This work**	[7]	[4]	[8]	[5]
Power W	30	0.158	100	1	20
Gain dB	15	12	13-16.5	–	14.5
Drain Eff %	–	–	–	23-37	63-72
PAE %	83-64	59	58-74	–	–
BW MHz	50-500	300-400	100-1000	100-650	50-500

II. Circuit design description

Fig. 1 shows the amplifier configuration. It consists of two Cree HEMTs CGH40025 GaN HEMT mounted on 62 mil FR4 substrate. The input RF signal is injected at the single-ended port of a 50-Ω coaxial balun B1 and is divided into two 180° out-of-phase signals, while broadband Amidon BN-61-2402 ferrite cores provide high impedance to common mode currents. CT1 and CT2 are 4:1 transformers built with 25-Ω UT-047C-25 coaxial cables and provide input impedances to the HEMT transistors according to source pull simulations using the model provided by Cree. The input matching circuit topology drives the two transistors in push-pull switching

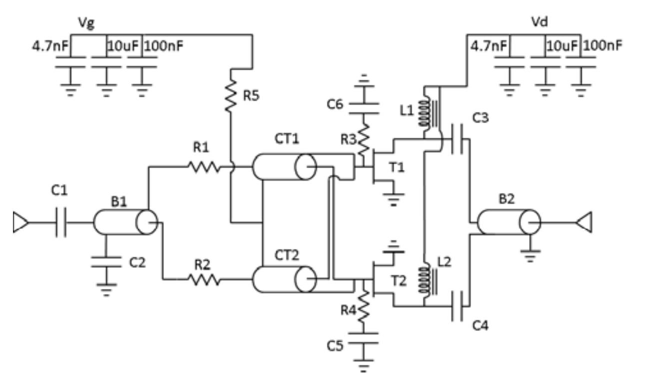


Fig. 1. Simplified schematic of the switching mode PA. T1 and T2 are Cree GaN HEMT devices with lumped elements combined with coaxial balun input and output matching networks. R5 provides gate bias voltage through the coaxial balun.

mode as shown in Fig. 1. The simulated waveforms in saturation prove that the transistors are operating in push-pull mode where both currents and voltages of the two devices are out of phase and are approximately square shaped with a peak voltage of 75 Volts. Fig. 2 shows the waveforms at 200 MHz for various input power levels. It was found that similar waveforms are obtained over the full bandwidth.

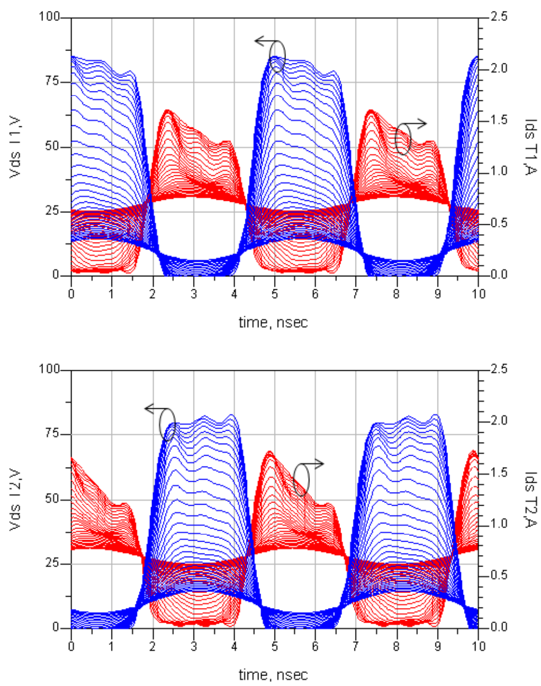
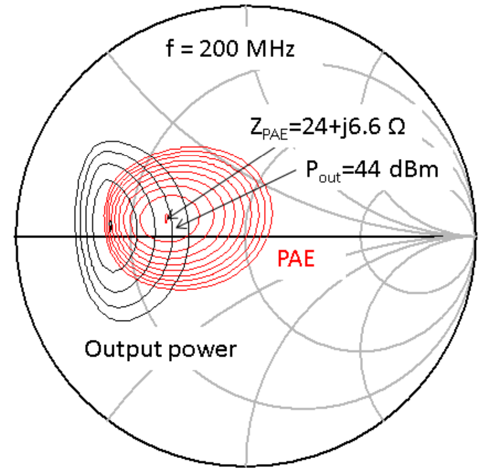


Fig. 2. Simulated voltage and current time domain waveforms of transistor T1(top) and T2(bottom) at 200 MHz with varying input power from 0 to 30 dBm.

The output matching network is designed according to load pull simulation using the Cree model $CGH40025F\_r6\_CGH40\_r6$ and assuming model validation is usually unknown under 500 MHz. Fig. 3 shows PAE and output power contours simulated at 200 MHz and summarized optimum drain impedances for best efficiency over frequency suggests that an impedance transformer with a ratio 1:2 is well suited at the output. Such matching is realized using the 50-Ω coaxial balun B2 Fig. 1 with multi-core ferrites which provides 25 Ω at its balanced output. Smith chart analysis shows that the matching condition for best PAE leads to a 2 dB drop in maximum achievable output power. According to Fig. 3, the normalized impedance magnitude values for peak PAE and output power are 0.33 and 0.6-respectively. All harmonics for the data in Fig. 3 are 50-Ω terminated. The drain voltage is supplied to both transistors using L1 and L2 (0.5 μH) inductors wound on a broadband toroidal core.



Freq (MHz)	10	50	100	200	300	400	500
Zout	22.2+j0.5	25.3+j1	24.5+j3.3	24+j6.6	24.2+j7.1	24.08+j9.2	23.4+j11

Fig. 3. Load pull simulations of the CGH40025 device at the (28 V, 250 mA) bias point at 200 MHz. The red and black contours are constant PAE and Pout. The optimal impedance for peak PAE is 24+j6.6Ω at 44 dBm output power.

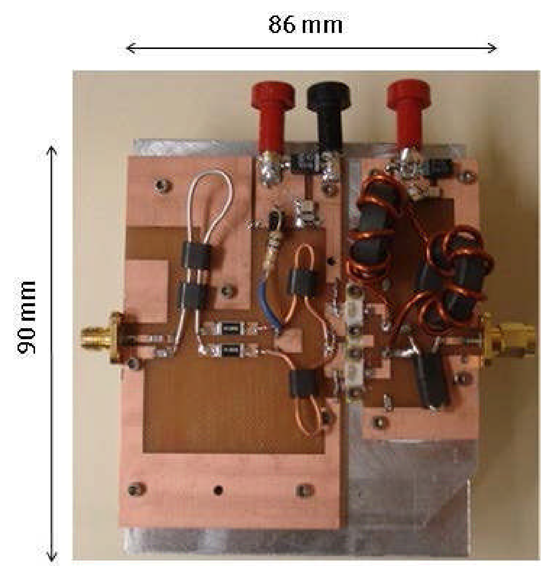


Fig. 4. Photograph of the PA fabricated on a 62 mil FR4 substrate corresponding to the block diagram Fig. 1.

III. Measured Broadband PA

Fig 4 shows the photograph of the PA. The PA has been measured in large signal conditions starting at 50 MHz with a bias point V_{dd} =28 V and I_q=500 mA. CW measurements demonstrate a PAE in the range of 83%-64% over a decade bandwidth. The compressed gain remains at 15 dB$\pm$0.5 with 45 dBm average output power, as illustrated in Fig 5. The PAE remains higher than 80% from 50 MHz to 300 MHz. Below 50 MHz the input return loss (IRL) degrades due to the limited bandwidth of the low loss ferrite material on the coaxial-balun. An improvement in insertion loss can be made by stacking different ferrite materials in the future.

TABLE II
SUMMARIZED MEASURED PERFORMANCE VS VDD

Vdd (V)	Pavg (W)	PAE (%)	Gain (dB)
15	10	82%-59%	12.5
20	18	90%-64%	14
28	30	83%-64%	15

The PA module has also been tested to characterize the dependence of PAE and output power on the drain-supply voltage. The drain-bias voltage was varied between 15V, 20V and 28V, the output power and PAE were computed. The result suggests that this PA module can be used in a multi-power system since the PAE remains high as the supply voltage is reduced. The measured output power (P_{avg}), averaged over the decade bandwidth, is 10 W with PAE = 82%-59% at V_{dd}=15V, compared to 30 W with PAE = 83%-64% at the nominal 28 V. When we biased the PA at 20V intermediate supply voltage, the average output power was 18W and the corresponding PAE in the range of 90%-64% Fig 6(a), Fig 6(b). The power averaged over the decade bandwidth and corresponding efficiencies are summarized in Table II.

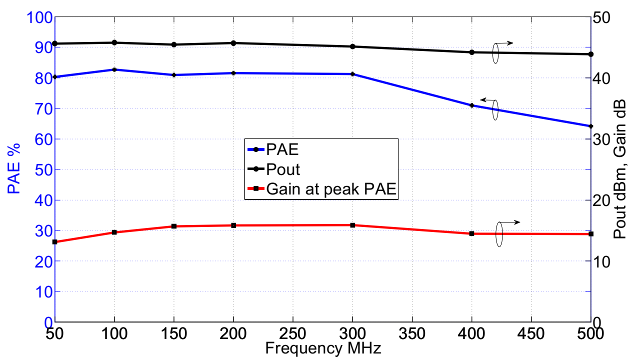
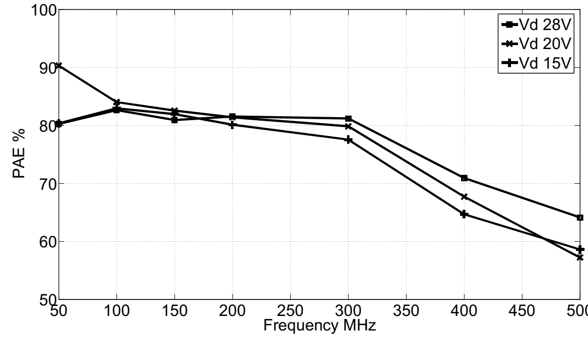


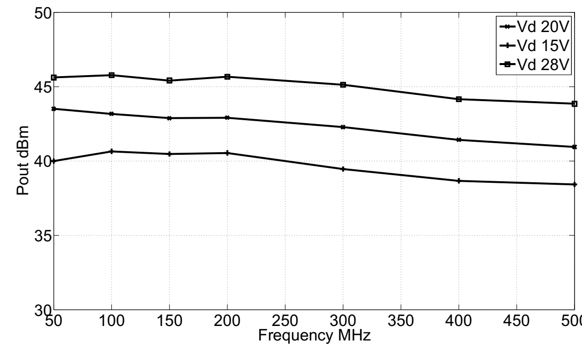
Fig. 5. Measured peak PAE, output power and compressed gain from 50 MHz to 500 MHz at (28 V, 500 mA) bias point.

IV. DISCUSSION

We have successfully demonstrated a decade-bandwidth VHF/UHF power amplifier using GaN HEMT transistors. The PA module demonstrated PAE of 83%-64% with 45 dBm average output power in 50 MHz-500 MHz frequency band. To the best of the authors' knowledge, this is the highest reported PAE over this bandwidth with this output power. Furthermore, the PA module demonstrates a flat 15 dB$\pm$0.5 compressed gain over the entire bandwidth. Additionally, power measurements have been done using different drain voltages supply and results show that the device can operate in a multi-power mode with PAE in the same range as when biased at nominal conditions.



(a)



(b)

Fig. 6. Measured decade bandwidth frequency response of the PAE (a) and output power (b) for three different drain supply voltages.

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