Broadband Driver Amplifier with Voltage Offset for GaN-based Switching PAs

T. Hoffmann¹, F. Hühn, S. Shevchenko, W. Heinrich, A. Wentzel
Ferdinand-Braun-Institut (FBH), Leibniz-Institut für Höchstfrequenztechnik, 12489 Berlin, Germany
¹thomas.hoffmann@fbh-berlin.de

Abstract — The paper presents a GaN-based driver amplifier (PSA) module with potential shifting included, suitable for properly driving GaN-HEMTs with digital bit sequences in the microwave range. The PSA is capable of driving a GaN-HEMT with 5 Vpp input swing from a standard 1 Vpp signal. Additionally, it provides a controllable potential shift (DC-offset) between -1.9 V to -10.9 V when referenced to GND. A voltage gain of 10.7 and 4.9 with a load of 1 kΩ || 0.25 pF and 50 Ω is achieved, respectively. Input of the PSA is referred to GND with 50 Ω input impedance. The bandwidth is DC - 3.2 GHz for a 3 dB voltage gain drop for both loads applied. The proposed PSA is an important part to complete digital signal chains and can be also used as analog amplifier.

Keywords — microwave amplifiers, drivers, switch-mode, digital, power amplifiers, potential shift, GaN, MMIC.

I. INTRODUCTION AND MOTIVATION

Transistors operated in switching mode, i.e., only in on- or off-state, are becoming more and more the core elements in latest circuits for various applications like power electronics [1], [2] or efficient microwave power amplification [3]-[7]. GaN technology offers solutions here also at high switching speeds. For example, GaN-based high frequency DC/DC converters [2] with active components monolithically integrated or the fully digital transmitter architecture [5]-[7] for the future mobile infrastructure are extending the present limits of system performance. However, all the circuits are facing the same challenge: to properly drive the GaN-HEMTs.

II. PREAMPLIFIER REQUIREMENTS IN GaN DIGITAL TX CHAIN

A. Potential Shift

GaN-based microwave digital power amplifiers (DPA) use n-channel transistors, because p-channel devices with the appropriate speed are not available. GaN-based DPAs usually consist of two to four stages. A typical example for a digital GaN PA which needs to be driven is shown in Fig. 2, using a simplified circuit diagram.

For the characterization of these DPAs in a signal frequency range of for example 1 GHz high speed input pulses with rise and fall times below 100 ps are required. In general fast arbitrary waveform generators (AWG) [8] are used to provide these fast pulses. The negative DC-offset of these signal generators is limited to -2 V. As described above, for digital operation the GaN-HEMTs need a gate-source voltage \( V_{gs} \) of around +1 V for on- and -4 V for off-state. That means a shift of -1.5 V with regard to GND potential. Furthermore, the combination of relatively large voltage swing and high switching speed exceeds the capabilities of the common technologies. This is the focus of our paper. Fig. 1 illustrates the function of the driver using the example of a digital transmitter chain which is the targeted application of the presented work. To clarify the need for a preamplifier between signal generator and GaN input stage in this case the key requirements are described in the following section.

Fig. 2. Simplified circuit diagram of a typical digital microwave PA which needs an input voltage swing of 5 Vpp. Drain and source supply voltages as well as gate potentials for on- and off-state of the final stage transistor (here: the lower GaN-HEMT) are shown.

For the characterization of these DPAs in a signal frequency range of for example 1 GHz high speed input pulses with rise and fall times below 100 ps are required. In general fast arbitrary waveform generators (AWG) [8] are used to provide these fast pulses. The negative DC-offset of these signal generators is limited to -2 V. As described above, for digital operation the GaN-HEMTs need a gate-source voltage \( V_{gs} \) of around -4 V for off- and +1 V for on-state. That means a shift of -1.5 V with regard to GND potential. Furthermore, most of the power amplifiers consist of two or more stages and for reaching good low frequency behaviour, which is necessary when applying broadband modulation schemes [7], they are DC-coupled. If the amplifier uses several stages in common source configuration, the negative potential shift for
commercially available high speed digital signal generators is minimal input amplitude has to be 5 Vpp, too. This results in a source configuration in the input stages which means the GaN-based DPAs as shown for example in [5] commonly use input voltage swing of 5 Vpp is required. Furthermore, the components from DC to the upper GHz range [7]. If DC parts are not transmitted, the bias voltage of driven DPA and input/ output impedance of the GaN-based DPA. But there is no DC path and it is not applicable to amplify modulated signals. Another solution is to split the signal in a low frequency (LF) path including DC and a high frequency (RF) path. After amplification and potential shift the signals are combined. The RF path is AC-coupled, so that RF amplifier input and output can be terminated to GND. The amplifier in the LF path realizes the potential shift function. For both paths the same gain is required. One drawback of this solution is complexity. Another drawback is the difficulty to design the transition range of LF to RF, in terms of gain, impedance and phase-shift. The insufficient available solutions as well as the requirements to complete the digital transmitter chain shown in Fig. 1 were the motivation for this work; to develop a single device solution that fulfills all the mentioned specs.

B. Voltage Gain and Output Impedance

The maximum single ended output amplitude of commercially available high speed digital signal generators is 0.5 - 2.2 Vpp. For proper switching of the GaN transistors an input voltage swing of 5 Vpp is required. Furthermore, the GaN-based DPAs as shown for example in [5] commonly use source configuration in the input stages which means the minimal input amplitude has to be 5 Vpp, too. This results in a minimum voltage gain of 10 for the PSA.

If the digital PA inputs do not have 50 Ω terminations the load for the PSA is only the input capacitance of the DPA, with the advantage of lower power losses. Then the voltage gain of 10 for the PSA is needed only on a high ohmic load. But in this case the output signal of the PSA is reflected back via the connecting cable with 50 Ω impedance. To avoid re-reflection the output of the PSA must have 50 Ω. If the DPA inputs are loaded with 50 Ω, the required voltage gain of the PSA is doubled, or the signal generator must have at least output amplitude of 1 Vpp, e.g. the AWG from [8], and this option we have chosen for the PSA under consideration here. For large potential shifts on the DPA input(s), a DC termination with 50 Ω is not useful, because of the high power losses on the termination resistors. But if the terminations are AC coupled, the previously mentioned problems for transmitting modulated signals occur. Thus DPAs without termination resistors are to be preferred, demanding for signal sources which are able to drive loads only formed by the input capacitance(s) of the DPA.

C. Bandwidth

Broadband digital modulation pattern contain frequency components from DC to the upper GHz range [7]. If DC parts are not transmitted, the bias voltage of driven DPA and input/ output impedance of the PSA shift dynamically, resulting in suboptimal switching and disturbed pulses due to reflections at the connecting cables. For driving DPAs with clock frequencies around 1 GHz the upper cut-off frequency of the PSA has to be several GHz to maintain rectangular waveform.

To fulfill the key requirements described above, up to now, several commonly used approaches have been applied. One is to realize gain and potential shift by placing a broadband RF amplifier in series with a bias-T between the signal generator and the GaN-based DPA input. But there is no DC path and it is not applicable to amplify modulated signals. Another solution is to split the signal in a low frequency (LF) path including DC and a high frequency (RF) path. After amplification and potential shift the signals are combined. The RF path is AC-coupled, so that RF amplifier input and output can be terminated to GND. The amplifier in the LF path realizes the potential shift function. For both paths the same gain is required. One drawback of this solution is complexity. Another drawback is the difficulty to design the transition range of LF to RF, in terms of gain, impedance and phase-shift. The insufficient available solutions as well as the requirements to complete the digital transmitter chain shown in Fig. 1 were the motivation for this work; to develop a single device solution that fulfills all the mentioned specs.

III. DESIGN AND REALIZATION OF POTENTIAL SHIFTING PA

A. Design

As the central element of the proposed potential shifting preamplifier (PSA) we designed a MMIC which contains all active and most of the passive components. Fig. 3 shows the schematics of the MMIC.

![Fig. 3. Schematic of the developed potential shifting PA MMIC.](image)

The proposed PSA consists of three stages. The amplifier is DC coupled from input to output. All transistors are n-channel normally-on GaN-HEMTs. Terminals EE_CS, DD_AMP and EE_AMP are the supplies; IN and OUT are input and output, respectively; IN_RET is the input termination (to GND); and G_CS controls the potential shift.

The available potential shift range and maximum output amplitude is set by the supply voltages. If the full range potential shift or maximum output amplitude is not necessary one can apply lower supply values which reduces the power consumption.

1) Potential Shifting Stage

The first stage with its parts R2, C3, V1 and R3 realizes the potential shift. V1 and R3 form a current source. Their current is controlled by the voltage between terminals G_CS and EE_CS. The current causes a voltage drop across R2. This voltage drop produces the wanted input to output potential shift for DC and the low frequency range. Because the DC...
current through R2 is constant and the following stage has a high ohmic input impedance, we keep the voltage drop across R2 constant. The input signal flows from the IN terminal to the next stage without affecting the signal form and amplitude. But at higher frequencies, the current through the output capacitance of V1 and the input capacitance of V3 causes AC currents leading to an AC voltage across R2 which results in decreased gain. The parallel connection of C3 prevents this behaviour. The values of R2 and C3 have been chosen in a way that a broad overlap of LF and RF range is guaranteed. L1 compensates the input capacitance.

2) Voltage Gain Stage

The second stage delivers the voltage gain. Main element is V3, which is operated in source configuration. R4, V2, R5 and L2 act as an active pull-up circuitry.

3) Output Buffer

The third stage buffers the amplified signal and realizes an output impedance of about 50 Ω. It is built with V4 in drain configuration and R6. Moreover, V5 and R7 form a pull-down current source. The output impedance is established by the source impedance together with R6. The current source as pull-down element ensures that output amplitude and impedance are independent from the chosen potential shift.

B. Realization

Fig. 4. Photograph of fabricated GaN PSA MMIC; area: 1.73 x 1.13 mm².

Fig. 5. Realized PSA module (w/o cover) including GaN PA MMIC and DC circuitry on a PCB; size: 20 x 35 x 15 mm³.

The proposed PSA from Fig. 3 has been realized utilizing our in-house 0.25 μm GaN-on-SiC HEMT process. The chip is shown in Fig. 4 and has a size of 1.73 x 1.13 mm².

The MMIC is soldered on the bottom of the device package made of copper. A PCB circuitry is used as transmission-line for input and output, and most passive components like SMT components are soldered on the board. The chip is connected to the PCB by wire bonding. Input and output connections are SMA connectors. Supplies and the potential shift control voltage are fed by a micro-USB connector. The complete module exhibits a size of 20 x 35 x 15 mm³ and is shown in Fig. 5.

IV. Measurements

Different small- and large-signal measurements were conducted to characterize the PSA module. The test setup uses Keysight’s M8195A AWG to generate the input bit stream, i.e., to emulate the modulator in a digital signal chain. At the output the time-domain signal is characterized using Tektronix’ DPO77002SX real-time scope and the spectrum is displayed with an analyzer from Advantest. For measurements with 50 Ω load, the output signal of the PSA module was splitted with a bias-T into an RF and a DC path. The RF path was terminated by the 50 Ω inputs of the scope and the spectrum analyzer, respectively. The DC part of the signal was connected to a high ohmic scope input. The overall power consumption of the module is 2.3 W. For a pure capacitive load this value is nearly independent of input signal and potential shift.

Fig. 6. Measured small-signal voltage gain vs. frequency for the two different loads with 1 kΩ || 0.25 pF and 50 ohms.

Fig. 7. The realized PSA achieves a maximum voltage gain of 11.7 and 5.8 with load 1) 1 kΩ in parallel with 0.25 pF which is provided by a Teledyne LeCroy probe (PP066), 2) the reference impedance of 50 Ω. First, the small signal voltage gain was measured for both loads by applying a sinusoidal input signal with 0.7 Vpp input amplitude with varying frequency. The results are plotted in Fig. 6.

The realized PSA achieves a maximum voltage gain of 11.7 and 5.8 with load 1) and 2), respectively. The 3 dB bandwidth in both cases is 3.2 GHz. This makes the preamplifier suitable for digital PA operation in a 1 GHz signal frequency range. As the PSA is used to amplify digital bit sequences it is important to check the time-domain signals, especially within the possible potential shifting range. As an example, Fig. 7 shows the signals for 100 MHz frequency and the load 1 kΩ || 0.25 pF load.
Fig. 7. Oscillogram of input (blue) and output for a 100 MHz rectangular pulse signal; potential shift = -1.9 V (purple), -6.4 V (green) and -10.9 V (red); load: 1 kΩ || 0.25 pF.

Fig. 8. Measured input (blue) vs. output (red) signal of realized PSA for a 20 MHz WCDMA modulated signal with 6.5 dB PAPR; f_s = 0.9 GHz.

Fig. 7 illustrates that the preamp generates clean rectangular signals at the output. The pulse amplitude stays the same (5 Vpp), independent of the potential shift, which is varied from -1.9 V to -10.9 V by applying a control voltage (G_CS in Fig. 3) between 3.3 – 3.5 V. The small steps on the upper and lower plateau of the pulses are caused by reflections on the cables used in the setup. Rise- and fall-times were determined from Fig. 7 to be 130 ps (10% - 90%) and 80 ps (20% - 80%), respectively. Moreover, rectangular pulse shapes were found to look comparable to Fig. 7 for a 1 GHz input signal. Finally, in order to investigate the linearity, we characterized the PSA using a 900 MHz WCDMA modulated signal with 20 MHz modulation bandwidth and 6.5 dB peak-to-average power ratio (PAPR) for the 1 kΩ || 0.25 pF load. This is important since it represents a common operation scenario in the targeted digital transmitter chain for mobile communications. In Fig. 8, input and output signals vs. frequency are plotted (note that no signal correction (DPD or comparable) was applied). One clearly sees from Fig. 8 that the proposed PSA behaves very linear. The measured adjacent channel leakage ratio (ACLR) of 46 dB fulfills the requirements.

V. CONCLUSIONS

A broadband PA to drive GaN-HEMTs in switch operation and shifting the DC potential is presented. It bridges the gap between high-speed digital signal sources and the digital GaN part and has been realized together with control electronics as a compact module. The proposed PSA uses a GaN-MMIC as core element and achieves a 3 dB bandwidth in terms of voltage gain from DC to 3.2 GHz. It delivers output amplitude of 5 Vpp for a 1 kΩ || 0.25 pF load which represents a typical GaN-HEMT input. Under these conditions a potential shift from -1.5 V to -10.9 V can be achieved. Overall power consumption is 2.3 W. Applying a WCDMA modulated input bit sequence with 20 MHz modulation bandwidth and 6.5 dB PAPR the PSA exhibits an ACLR of 46 dB at the output without any correction. Summarizing the results we can state that the proposed PSA is an essential building block to drive GaN-HEMTs in switch-mode with pulse input signals requiring 5 Vpp input amplitude and beyond. The PSA completes digital transmitter chains for applications such as power electronics or efficient microwave PAs.

ACKNOWLEDGEMENTS

This work was partly funded by the German Federal Ministry of Education and Research (BMBF) under the project reference 16FMD02 (Forschungsfabrik Mikroelektronik Deutschland).

REFERENCES