International Journal of Microwave and Wireless Technologies, 2010, 2(1), 115–120.
doi:10.1017/S175907871000019X

Design and realization of GaN RF-devices and circuits from 1 to 30 GHz

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The design, realization, and characterization of highly efficient powerbars and monolithic microwave integrated circuit (MMIC) high-power amplifiers (HPAs) with AlGaN/GaN high electronic mobility transistors (HEMTs) are presented for the frequency range between 1 and 30 GHz. Packaged powerbars for the frequency range between 1 and 6 GHz have been developed based on a process called GaN50 with a gate length of 0.5 μm. Based on a GaN25 process with a gate length of 0.25 μm, high-power MMIC amplifiers are presented starting from 6 GHz up to advanced X-band amplifiers and robust LNAs in microstrip transmission line technology.

Keywords: Gallium nitride, Power amplifier, Power-added efficiency, MMIC, Broadband, LNA, MM-wave

Received 20 January 2010; Revised 12 February 2010; first published online 7 April 2010

I. INTRODUCTION

Gallium nitride (GaN) hybrids and monolithic microwave integrated circuits (MMICs) find various applications for energy-efficient high-power microwave amplification [1, 2]. Hybrid powerbar transistors achieve very high power-added efficiency (PAE) values of >60% for large powerbars with output power levels of >100 W in the frequency range from 1–4 GHz, e.g. [3, 4]. HPA MMIC results with output power levels of 50 W at X-band have been demonstrated [5]. A significant number of outstanding MMIC results are not fully visible [1]. Further developments, especially, in the US and Japan, stretch the application frequencies to the mm-wave up to 110 GHz [6]. This paper gives an overview on the results obtained on packaged powerbar and on MMIC level.

II. EVOLUTION OF DEVICE TECHNOLOGY

The critical step toward the realization of state-of-the art of III-N hybrids and MMIC amplifiers are achievements with respect to the optimization of the active device technologies. With the strong thermal constraints based on the high-power densities achieved with GaN [1], the improvement of PAE and gain became much more important than the simple increase of the power densities. This is true for all frequencies, however, for the particular gate length, for the upper ranges of the targeted frequencies of operation. For powerbars based on gate lengths in the range of 0.5 μm, this critical area is the frequency range of 4–6 GHz. MMIC-related frequencies in this paper range from 6 to 30 GHz. They are realized using gate lengths of 0.25 and 0.15 μm which are appropriate for this frequency range. As a reference, Fig. 1 gives the overview of loadpull data measured at 2, 10 and 28 GHz in CW-operation achieved at Fraunhofer in order to visualize the status in device technology for gate lengths of 0.5, 0.25 and 0.15 μm on MMIC level. We also see that the operation bias for the particular technology reduces with increasing frequency. The breakdown voltages taken at an operation temperature of 150°C are typically a factor of three higher for the technologies given. The results in Fig. 1 are given for gate peripheries which are relevant for large gate width power bars and MMICs.

III. POWERBAR TECHNOLOGY (1–6 GHZ)

Hybrid powerbars are particularly attractive for the frequency range between 0.9 and 6 GHz. The key issues are the increase of efficiency at package level, gain improvement, oscillation control for unmatched and prematched devices, and ruggedness for large VSWR ratios. These factors are of course interdependent. As an example for the results of optimization, Fig. 2 gives the CW-power results of a GaN power bar in microstrip transmission line technology measured at 2 GHz and $V_{DS} = 50$ V. We observe a linear gain of more than 20.7 dB at 2 GHz, a maximum power of 50 W, and an associated power density of 4.2 W/mm at an efficiency level of 60%. The microstrip transmission line technology ensures good linear gain for the device in package. Figure 3 gives the overview of the PAE and DE of various powerbar designs in package as a function of output power achieved for the frequencies 2 and 4 GHz when operated in CW between

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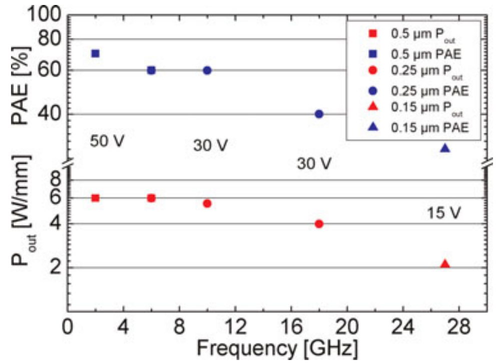

Fig. 1. Device CW-power and PAE for MMIC applications for three gate lengths over frequency.

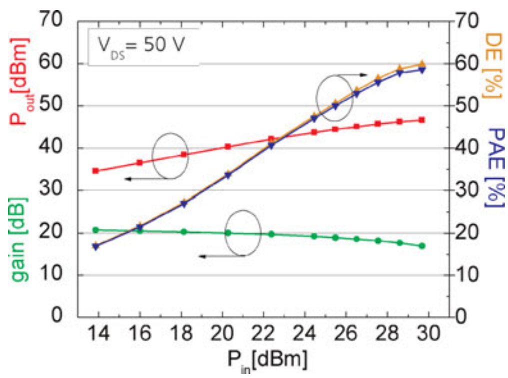

Fig. 2. Device CW-power, gain, DE, and PAE at 2 GHz for a 12 mm powerbar in microstrip transmission line technology, measured in package.

V_{DS} = 40 and 50 V. The drain efficiencies are also given in order to highlight the impact of the gain on PAE at the two frequencies.

The PAE and DE levels at 2 GHz are in the range of >65% for devices up to 50 W and roll-off slightly to the 120 W level. At 4 GHz, the typical efficiency level is in the range of 50% up to the power range of 50 W. Further work on the packaging and layout side shows that the roll of PAE versus power roll of can be reduced to the level of the smaller devices.

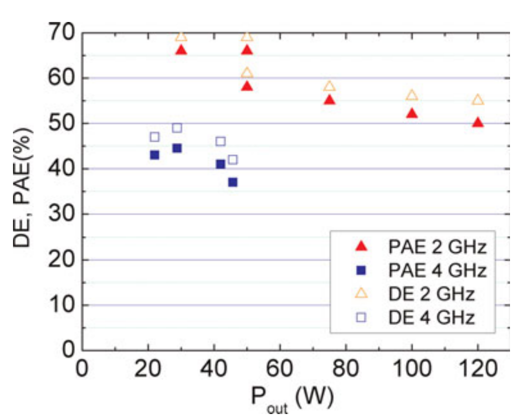

Fig. 3. PAE and DE in CW over output power for packaged power bars measured at 2 and 4 GHz.

IV. EVOLUTION OF MMIC LIBARIES AND MODELING

A) Passive development and library extraction

For the MMIC design library-specific III-N passive components require development in order to allow the same design flow and flexibility as in the GaAs MMIC world. Both coplanar and microstrip transmission line components have been made available, including all technology-specific elements like metal–insulator–metal (MIM) capacitors, resistors, and inductances. The issues in GaN libraries include the realization of high-power transmission lines, MIM capacitors with high-breakdown voltage per area, high-power resistors, and area-efficient high-current inductors. As the MMIC processes are maturing, spread analysis techniques and advanced passive components gain importance. Specific advanced passive components such as MIM-on-top-of via and individual source-vias require more specific development. Modeling of the passive components is mostly based on conventional ADS models, which are conventionally extracted and used.

V. EVOLUTION OF CIRCUIT DESIGN FOR GaN MMIC POWER AMPLIFIERS

A) Large-signal modeling

The models used for this work are based on an in-house two-dimensional voltage-lag model after an extensive phase of development. Thermal effects and low-frequency dispersion, and their impact on gain as well as PAE are well described. Following the general theory presented in [7], long-term memory effects are described by internal states. The parameters of this model are extracted from pulsed-DC, pulsed and CW-small-signal S-parameters, and time domain measurements including the harmonics over wide bandwidth. This model allows a state-dependent description of the intrinsic drain current and the gate-source and gate-drain space charges. The state quantities are the low-pass filtered voltages V_{GS} and V_{DS}. This approach facilitates a correct description of retarded responses as well as the instantaneous responses relevant for RF power performance.

B) Discussion of specific design issues

In several ways, GaN design differs from the MMIC design performed for GaAs and silicon. GaN offers very high intrinsic levels suitable for broadband matching to 50 Ω loads. Typical power cells for X-band design operated in the range of 30–40 V offer real impedance very close to 50 Ω. At the same time transformation networks lead to strong changes for these theoretical impedances at the reference planes. The complicated compression of the power gain due to dispersion and thermal effects over input power are major challenges for the design of amplifiers with high PAE at low gain compression. The introduction of field plates, formerly only used in silicon LDMOS technology at a few GHz into GaN technology up to at least 30 GHz, has led to the delicate balance of improving power compression and reliability while reducing the effective parasitic capacitances to a minimum for the individual process and frequency range.

C) GaN X-band (8–12 GHz) MMICs

The realization of X-band MMICs with high power and high bandwidth has been one of the major drivers for the development of GaN technology [8]. Bandwidth, center frequency, and PAE are key for the development of MMICs [9, 10, 12]. The ultimate goal for such frequencies is to convert more energy into microwaves than into heat over a reasonable bandwidth for real multi-stage MMICs operated at a bias of up to 40 V. The realization of dual-stage designs is further key due to the gain requirements of TRX-chains. Figure 4 gives the evolution of linear gain, PAE, and output power of dual-stage X-band MMICs over time as developed at Fraunhofer IAF over the last five years. The values are consistently given for long-pulse operation (100 μs) for a duty cycle of 10%, all measured between 9 and 10 GHz. The minimum bandwidth for each design is 2 GHz. Figure 4 suggests a continuous development on MMIC level over time with significant improvements, while the realization of higher PAE and gain has found more attention than the simple increase of output power. This is caused by lack of primary power in most systems. In Fig. 4 we see a very consistent increase of the linear gain level up to >27 dB at the center frequency, which needs to be carefully balanced versus bandwidth and the maximum PAE at the upper band edge at X-band frequencies, e.g. >11 GHz.

VI. BROADBAND POWER AMPLIFIERS 1–18 GHZ

GaN is particularly attractive to the realization of broadband amplifiers. GaN is probably the first semiconductor technology, which can provide broadband operation at similar power levels and in frequency ranges as traveling-wave tube amplifiers and replace tubes at least for the lower power ranges. For very principal reasons, solid-state power amplifiers will always be less efficient than tubes, providing broadband matching losses, while they yield advantages such as compactness, size, omission of high-voltage supplies, and overall relevant lifetime. Thus, again PAE over bandwidth is a key for the application.

A) HPAs for the frequency range 1–6 Hz

Broadband power amplifiers in the frequency range 1–6 GHz are attractive for multi-band communication amplifiers, e.g. for base stations as well as for military radio and electronic warfare applications. Both cost and PAE on device and module level are key and typically lead to hybrid approaches. At the same time, the loss mechanisms have to be identified. For example, to obtain good PAE at the upper frequency range of the C-band, advanced MMIC approaches have been used to provide reference designs.

Figure 5 gives the pulsed output power measurement of a single stage MMIC at 6 GHz with an output periphery of 6.4 mm for a gate length of 0.25 μm. The MMIC delivers more than 40% PAE in a broadband matching situation with a linear gain of 10 dB and an output power of more than 45.5 dBm or 35 W when operated at $V_{DS} = 40$ V. This translates into a power density of 5.5 W/mm under pulsed operation. The MMIC situation allows very precise matching and to consider the phase differences for the individual power transistors at 6 GHz. This shows the enormous power potential of GaN broadband designs. Hybrid designs based on gate lengths of 0.25 or 0.5 μm with their packaging may be more cost effective, however, should provide similar PAE values as given in Fig. 5.

B) Broadband power amplifiers 6–18 GHz

For the higher frequency band, e.g., 6–18 GHz a broadband solution using a MMIC approach is typical due to the stringent needs to control the phase accurately with very low losses. Figure 6 gives the micrograph of a nonlinear amplifier realized already in 2004 based on a gate length of 150 nm and III-N cascodes FET. The MMIC provides a linear gain of >9 dB between 2 and 20 GHz, which makes such devices very suitable for driver stages in broadband amplifier chains. It provides output power levels of about 1 W in this case. A similar MMIC design was recently published by Triquint [11] at the power level of 17 W.

VII. ROBUST LNA MMIC

Next to power amplifier robust low-noise amplifiers have been realized as MMICs with the particular target to achieve very high survivability at reasonable noise figure level [13]. Typical targets for the survivability are in the 5–10 W range of input power to a particular MMIC. Figure 7 provides an overview of typical noise figures NF_{50} and gain per MMIC stage, which are measured in low-noise operation for the frequency range

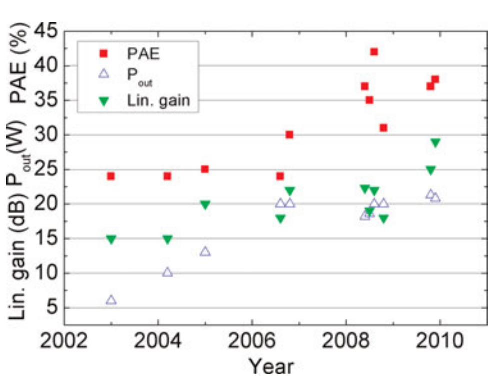

Fig. 4. Evolution of PAE, output power, and linear gain at Fraunhofer IAF over time for dual-stage MMICs with a bandwidth of >2 GHz for a duty cycle of 10%, all with center frequency between 9 and 10 GHz.

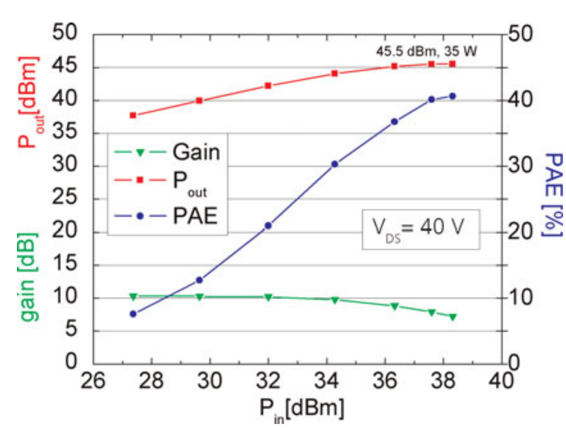

Fig. 5. Output power results of a single-stage MMIC at 6 GHz measured at $V_{DS} = 40$ V in pulsed operation.

https://doi.org/10.1017/S175907871000019X Published online by Cambridge University Press

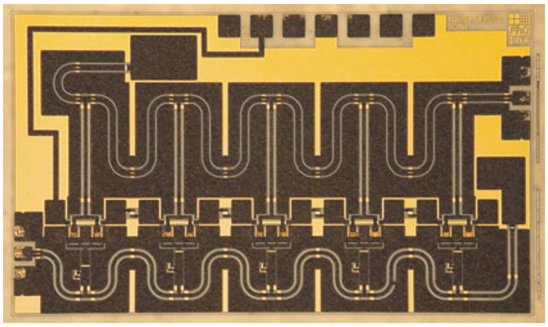

Fig. 6. Early European CPW-broadband MMIC with a gate length of 0.15 μm.

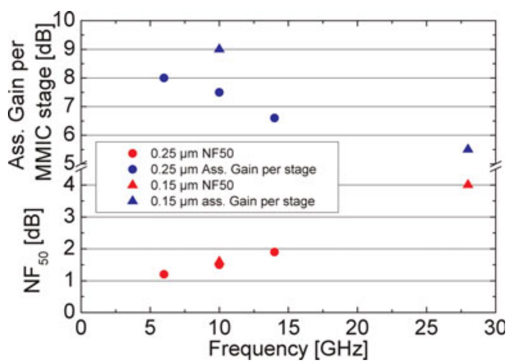

Fig. 7. MMIC LNA results at frequencies between 1 and 30 GHz.

of 1–30 GHz. This comparison is done on MMIC level with particular emphasis of reaching the robustness mentioned. We see a consistent noise level of less than 2 dB is obtained up to 14 GHz of operation with a reasonable associated gain per stage (on MMIC level) for low-noise operation. A third gate length of 0.15 μm is added leading to a shrinked process of GaN15. The higher frequency range up to 30 GHz can be addressed. The MMICs given in Fig. 7 all support a CW-input power level beyond 40 dBm (10 W), which is even increased in pulsed operation. This work shows the enormous potential to realize robust LNAs with good noise figure up to Ka-band frequencies.

VIII. CONCLUSIONS

The design, realization, and characterization of highly efficient powerbars and MMIC HPAs with AlGaN/GaN high electronic mobility transistors (HEMTs) has been presented for the frequency range between 1 and 30 GHz. Powerbars for the frequency range between 0.9 and 6 GHz have been developed based on a process GAN50 which deliver PAE values beyond 60% for 50 V operation with a linear gain of >20 dB for the 50 W class at 2 GHz. Based on a GaN25 MMIC process several high-power MMIC amplifiers with power levels >30 W are presented starting from 6 GHz up to advanced X-band amplifiers in microstrip transmission line technology. Low-noise amplifiers provide noise levels below 2 dB up to 14 GHz of operation with a robustness of >10 W input power.

ACKNOWLEDGEMENTS

The authors acknowledge the continuing support of the Federal Ministry of Defense (BMVg), the support of the Federal Ministry of Education and Research (BMBF), the Federal Office of Defense Technology and Procurement (BWB), and the Bundeswehr Technical Center for Information Technology and Electronics (WTD 81). Continuous collaboration with United Monolithic Semiconductors (UMS) is highly appreciated.

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