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GaN Power Amplifiers: Results and Prospective

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Abstract - **This article is focused on GaN-based power amplifiers for applications up to 10 GHz. Several PAs developed in both MMIC and hybrid technologies for different RF and microwave frequency bands will be described. In particular, the designs of two ultra-wideband (UWB) PAs are reported together with experimental results. The first one is based on commercial GaN-on-SiC technology while the other one is developed exploiting a GaN-on-Si technology. Examples of GaN-based Doherty PAs for cellular base-stations are also discussed and state-of-the-art performances are reported. Finally, a GaN MMIC PA for Synthetic Aperture Radar (SAR) systems at X-Band is described with related experimental investigation.**

Index Terms – **Power Amplifiers, GaN, MMIC, Ultra-Wide Band, HMIC, Doherty.**

I. INTRODUCTION

The performance of microwave devices realized on compound semiconductors like Silicon-Germanium (SiGe), Gallium Arsenide (GaAs), Silicon Carbide (SiC) and Gallium Nitride (GaN) are usually evaluated through Figures of Merit (FoMs). Among other, the most used to classify the goodness of transistors at high-frequency and for high-power applications is the Johnson's Figure of Merit (JFoM)[1]. It gives a number that represents the power-frequency limit of a transistors based on certain semiconductor by taking into account the material properties only. The higher is the JFoM value the better are the active devices. GaN on SiC substrate shows a JFoM ten times higher than GaAs material [2]. Maybe this result can help to understand why GaN technology is becoming the market's leader of the microwave industry for almost every application in both civil and military field. Commercial products developed using GaN technologies are nowadays taking part in cellular base station, television transmitters, point-to-point network connections, radar and electronic warfare equipment.

Characteristics like high current density and high breakdown voltage owned by GaN based transistor technology can drastically help to improve performance of many kinds of sub-systems actually realized by using GaAs devices.

The excellent properties of GaN material have been exploited to design RF microwave integrated circuits such as low noise amplifiers (LNA) [3], switches [4], power amplifiers (PAs) [5], and many others [6].

In the receiver chain, thanks to the high degree of robustness, GaN LNAs allow to avoid the limiter protection circuitry, significantly enhancing the overall transceiver noise performance. Moreover, it is reported that GaN LNA MMICs can survive to high levels of overdrive input powers, with no degradation effects on MMIC performance up to several watts of input power [7].

GaN HEMTs technology is also an excellent resource to implement microwave and RF control circuitry. Switches with over 25W linear power handling and good performance in terms of insertion loss and isolation have been reported in literature up to K-band [8].

Among other RF and microwave sub-circuits, HEMTs based on GaN material represent a groundbreaking solution to implement high-performing PAs. In fact, the high power density allows a reduction of the active area required to

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achieve a fixed output power level, thus reducing the combining structures and related losses. As a consequence, the watts per chip area ratio can be improved up to 5 times and more with respect to GaAs technology [6]. Moreover, due to the high breakdown voltage, high power density is usually accompanied with high conversion efficiency since the ratio between drain bias voltage and knee voltage can be increased [9]. Currently, commercial GaN devices are capable to operate with 50V of drain bias. On the other hand, high efficiency allows the reduction of the heat-sink size leading to a more compact and efficient transmitter units. Finally, the combination of high power density and high bias voltage makes the output impedance transformation ratio to 50-ohm more easier improving the bandwidth capabilities of the devices and, at the same time, reducing the mismatch losses of the output matching networks.

GaN high electron mobility transistors are usually fabricated on either Si or SiC substrates. Obviously, both technologies have their relative strengths and weaknesses [10], [11] but actually Si-based technology shows several limitations as compared to the SiC-based technology especially for MMIC realizations due to the higher losses of the passive components and the lower working frequency of the active devices [2], [12].

This article reviews several PAs developed by using GaN technology for different RF and microwave frequency bands. In particular, Section II is focused on ultra-wideband (UWB) PAs for Radar and Software Define Radio (SDR) systems presenting two PAs, one is utilizing a commercial GaN-on-SiC technology and the other is realized using a GaN-on-Si technology under development at Selex-ES. Section III is dedicated to the GaN-based Doherty architecture for cellular base-station applications while Section IV reports an example of a GaN MMIC PA for Synthetic Aperture Radar (SAR) systems at X-Band.

II. ULTRA-WIDEBAND PAs

Nowadays, UWB PAs with high power and efficiency levels represent a breakthrough for the realization of compact transmitters able to cover efficiently a multi-octave frequency band. In order to realize solid state PAs with similar capabilities, the availability of active devices able to provide simultaneously high power density, efficiency and wideband behavior represents the basic requirement. AlGaN/GaN HEMTs on SiC substrate possess all these three key features.
So far, two different solutions have been investigated and proposed in literature for the design of broadband power amplifier. The first one is based on distributed approach, as reported in [13]. Such solution, thanks to its topology, presents the advantages of flat gain behavior, linear phase and high return losses in the overall bandwidth. However, its main drawbacks are low efficiency and output power, which have limited its use in radar and military applications. In order to improve the efficiency and output power, the broadband matching networks approach can be used, as implemented in [14]. In this case, two (input-output) matching networks have to be synthesized to maximize the active device performances in the overall bandwidth. The major disadvantage of this strategy is the networks' complexity being strongly dependent from the adopted active device.

In
Fig. 1 is shown the photo of a hybrid single stage high power amplifier [15]. The amplifier was demanded to operate in the whole L-band (1 to 2 GHz), delivering a saturated output power in the range of 48-52 dBm, a saturated gain of 10 dB minimum and an associated power added efficiency of 40%. The active device chosen for this project is a commercial general purpose unmatched high power GaN transistor by Cree (CGH40120F) [16].

Fig. 2 shows the comparison between the simulated and measured Scattering parameters at the nominal bias condition.

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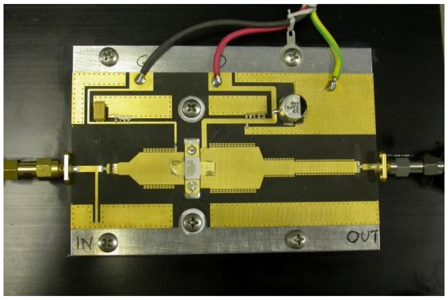

Fig. 1: photo of the L-Band UWB PA.

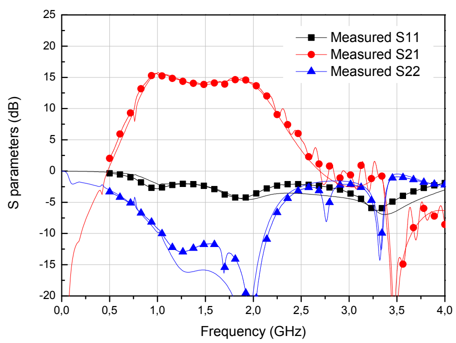

Fig. 2: S-parameters measurements

The GaN amplifier has also been tested under large signal condition. The RF input signal was pulsed at 10% of PRI=1ms while DC bias signal were always applied. In

Fig. 3 are reported the measured output power and power added efficiency (PAE) as a function of frequency for different available input power levels with 32V of supplied drain bias voltage. The saturated output power overcomes 100 W with associated PAE higher than 60%.

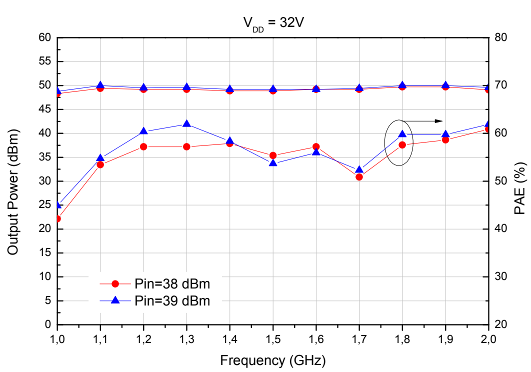

Fig. 3: Pulsed measurements at V_d=32V V_g=-2.8V

As emphasized in the introduction, actually, the best solution to grow GaN devices is the use of a Silicon Carbide substrate. Anyway, as a proof of concept, we report here the experimental results obtained from a PA designed for UWB applications by exploiting the GaN on Si-substrate technology under development at SELEX-ES foundry [17]. The active device selected is a 1mm gate periphery which has been fully characterized by nonlinear load-source pull measurements from 1 GHz up to 7 GHz and bias dependent Scattering parameters measures up to 20 GHz.

The amplifier was designed using the experimental load-pull and bias-dependent scattering parameter data. The load-pull measurements were used to identify the device's optimum input and output loads, in order to maximize the output power and efficiency in the frequency range from 1 GHz to 7 GHz. The bias-dependent Scattering parameters were used to check the amplifier's stability and its frequency behavior outside the operating bandwidth.

In

Fig. 4 a photo of the realized hybrid PA is reported.

Fig. 5 shows the measured Scattering parameters from 0.1 GHz up to 10 GHz at the nominal bias point (V_{DD}=30V, V_{GG}=-4V) and in pulsed condition. The input return loss is better than 5 dB from 1 GHz to 7 GHz while the output return loss is around 8 dB in the whole frequency band. In the same frequency range the S_{21} parameter is around 8 dB.

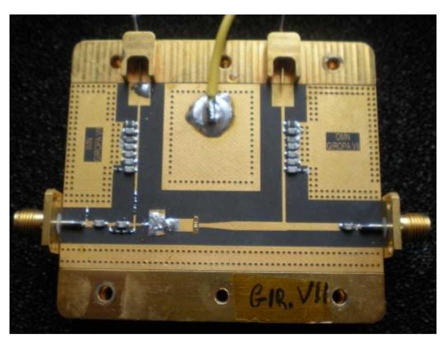

Fig. 4: Photo of the designed PA.

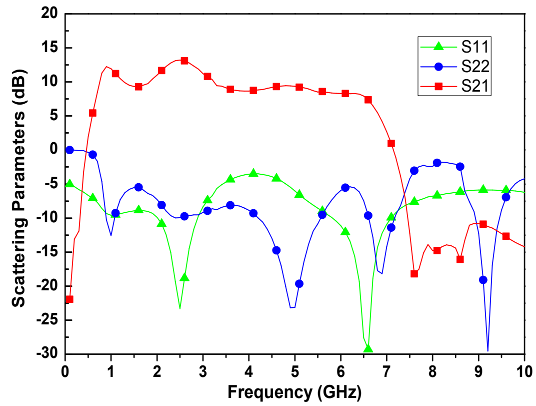

Fig. 5: Weasured S-Parameters of the designed PA.

Fig. 6 reports the pulsed measured power performance of the PA @ 3 GHz. The saturated output power is close to 36 dBm with an associated efficiency of about 33%.

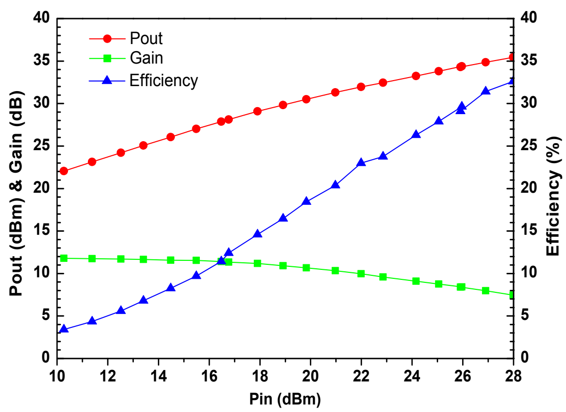

Fig. 6: Power performance of the designed PA @ 3 GHz.

III. DOHERTY AMPLIFIERS

Modern wireless communication systems require PAs that operate linearly and with high efficiency in a wide range of output power. Techniques capable to improve average efficiency are therefore an important issue in modern PA designs, and, towards this goal, the Doherty amplifier (DPA) demonstrates to be an effective solution [19]. It is becoming the most used PA for both handset and base station transmitters [20].

The DPA is usually implemented by a proper combination of two active devices designed to operate as a class AB (Main) and as a class C (Auxiliary) power stage, respectively. These two PAs are connected at the output through a quarter-wave transmission line (λ/4 TLine), with the aim to properly exploit the active load modulation concept performed by the Auxiliary amplifier on the Main one [9]. As a result, almost constant and high levels of efficiency can be obtained in a wide range on output power (typically 6 dB).

In

Fig. 11 is shown a photography of a DPA prototype realised exploiting a new output combining network [21].

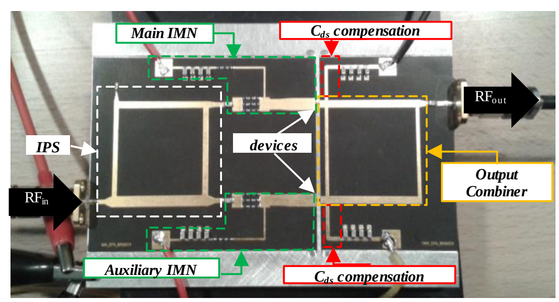

Fig. 7: Photo of the realized DPA.

Fig. 8 shows the Continuous Wave (CW) measured performances at 2 GHz for the nominal bias point (V_{DD} = 28 V, $V_{GG,Main}$ = -2.63 V and $V_{GG,Aux}$ = -5 V). In particular, an output power level around 42 dBm has been obtained at 33 dBm of available input power (P_{av}), with a related efficiency of about 68%. Moreover, the efficiency is higher than 48% in the 6 dB of output back-off (OBO) range, i.e., for P_{av} = 26 dBm, with a gain compression of about 1.5 dB only.

Fig. 9 shows the DPA performances versus frequency for a constant available input power

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level of 33 dBm and 26 dBm, respectively. As it can be noted, 65%-48% of efficiency at about 42-36 dBm of output power have been measured from 1.95 GHz to 2.25 GHz. In the whole 300 MHz bandwidth, the gain compression is lower than 1.5 dB. Finally, the DPA has also been tested using a WiMAX signal with 8.8 dB PAPR and 5 MHz bandwidth around 2.1 GHz [21].

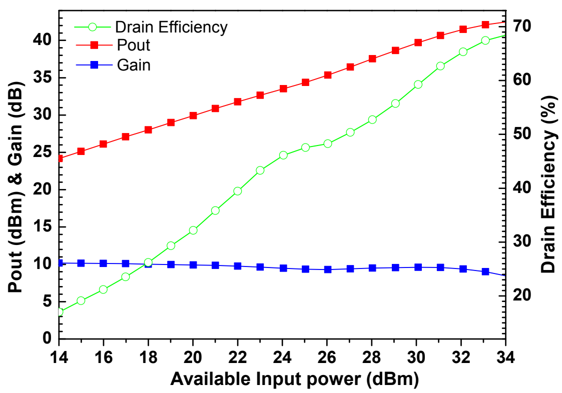

Fig. 8: CW measured performances vs. input power at 2 GHz.

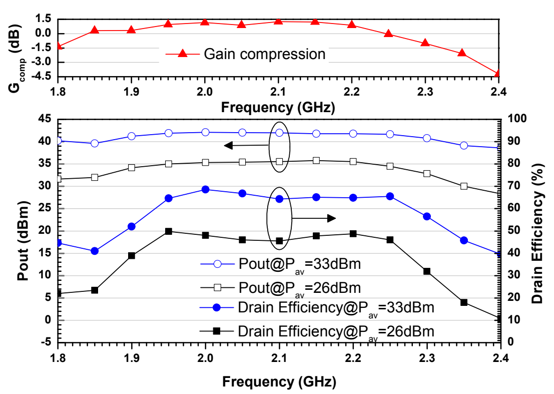

Fig. 9: CW measured performances vs. frequency at 33 dBm of input power.

Fig. 10 shows the measured Low and High Adjacent Channel Leakage Ratio ($ACLR_{L/H}$), average efficiency and gain behaviors as a function of the average output power. At 37 dBm output power, the average efficiency is around 50% with $ACLR_{L/H}$ values below -30 dBc. The experimental results confirm the potentiality of the proposed solutions, showing performances that are in-line with already published DPA realizations in the S-band [20].

IV. MMIC GAN PA

As highlighted in the introduction, GaN-on-SiC is more stable and performing technology as compared to GaN-on-Si. Moreover, thanks to the lower losses of the passive components and the higher working frequency of the active devices, the GaN-on-SiC process can be used to realized MMIC PA up to the Ku-Band.

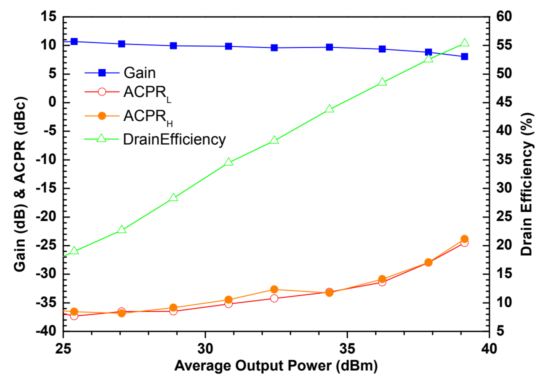

Fig. 10: WiMAX measured performances at 2.1 GHz.

In order to prove such capabilities, an X-Band (8.6 GHz 10.6 GHz) MMIC PA was designed. It was developed using the 0.25 μm GaN HEMT process featured by a 4W/mm power density at 25 V drain bias.

The amplifier was developed considering the performances that should be required for the future X-Band Synthetic Aperture Radar (SAR) systems. In particular, the desired saturated output power was 41 dBm with a linear gain higher than 17 dB and a PAE of 40%. The photo of the realized HPA is reported in
Fig. 11 [18].

The chip area is 9.25 mm^2 (3.7 mm x 2.5 mm). The MMIC was tested in pulse condition at the nominal bias point given by V_{DD}=25 V, V_{GG}= -2.1 V, with a corresponding quiescent current I_D= 1000 mA, including 200 mA for the first

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stage and 800 mA for the power stage. The comparison between measured and simulated small signal gain and input/output return loss versus frequency in a wide frequency range is shown in

Fig. 12. As it can be noted, a good agreement was achieved. The small signal gain is higher than 20 dB, while input and output return losses are better than 10 dB from 7.5 to 11.2 GHz.

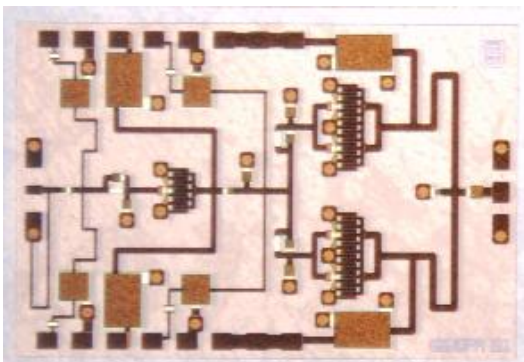

Fig. 11: photo of the realized HPA.

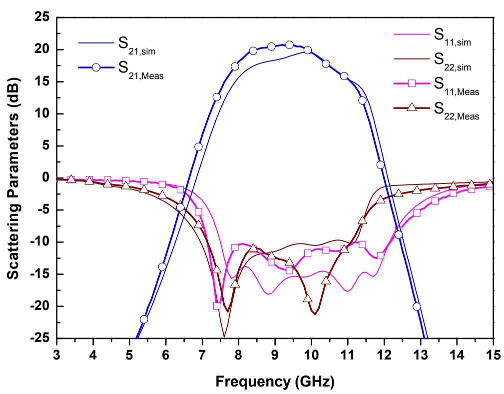

Fig. 12: comparison between simulated and measured scattering parameters.

In

Fig. 13, the comparison between the simulated and measured power performances are reported as a function of frequency and for a constant input power of 26 dBm (roughly corresponding to 3 dB of gain compression). As it can be noted, the output power is constant and around 42 dBm in the whole frequency band, while the associated power gain is 16 dB with a ripple lower than 0.5 dB. The measured PAE remains higher than 33% in the overall bandwidth.

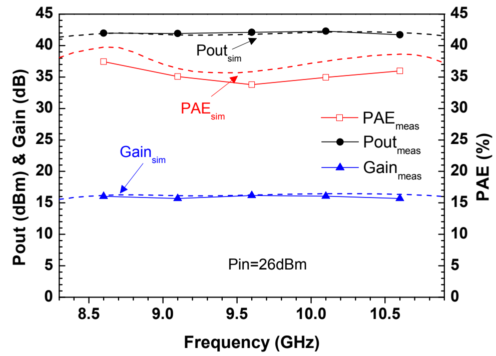

Fig. 13: HPA power performances vs. frequency for a constant input power of 23 dBm.

V. CONCLUSION

In this contribution, several GaN-based power amplifiers for applications up to 10 GHz have been shown. Both MMIC and hybrid technologies have been investigated at different RF and microwave frequency bands. In particular, the designs of two ultra-wideband PAs exploiting both commercial GaN-on-SiC technology and GaN-on-Si technology have been discussed. An examples of GaN-based Doherty PA for cellular base-stations with a novel output combining network has also been discussed. Finally, a GaN MMIC PA for Synthetic Aperture Radar systems at X-Band has been described with related experimental investigation.

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