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Article

## Evolution of Monolithic Technology for Wireless Communications: GaN MMIC Power Amplifiers For Microwave Radios

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**Abstract:** This paper presents the progress of monolithic technology for microwave application, focusing on gallium nitride technology advances in the realization of integrated power amplifiers. Three design examples, developed for microwave backhaul radios, are shown. The first design is a 7 GHz Doherty developed with a research foundry, while the second and the third are a 7 GHz Doherty and a 7–15 GHz dual-band combined power amplifiers, both based on a commercial foundry process. The employed architectures, the main design steps and the pros and cons of using gallium nitride technology are highlighted. The measured performance demonstrates the potentialities of the employed technology, and the progress in the accuracy, reliability and performance of the process.

**Keywords:** gallium nitride; microwave communications; MMIC (microwave monolithic integrated circuits); power amplifiers

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### 1. Introduction

Mobile communications' constant growth and the increasing demand of higher data rates (e.g., for “smart-phone” applications) is deeply affecting the entire network infrastructure design, especially concerning the so-called backhaul, *i.e.*, the link between the backbone network and the peripheral subnetworks [1,2]. In a few years, network infrastructures will have to be deeply revised to cope with the growing capacity demand.

Microwave point-to-point links, which already cover around 50% of worldwide backhaul [1], are expected to continuously gain market share in the realization of the backhaul [3]. In fact, if compared to hardwired solutions, microwave links offer high flexibility to the service providers, which can easily reconfigure the position of the basestations. This also reflects on lower management cost, due for example to the avoidance of cables placement and repairing.

The radio front-end is a crucial section of the point-to-point link equipment: the available frequency bands range from few GHz to the millimeter waves. Some important figures of merit, like power efficiency of the radio system and spectral purity of the transmitted signal, are mainly determined by the RF (radio frequency) transceiver. In particular, the power amplifier (PA) results as the most critical component, due to its high impact on the power consumption and linearity of the system.

In this framework, RF and mm-wave PAs based on microwave monolithic integrated circuits (MMICs) can have an important role in the design of the radio front-end of backhaul transmitters. In fact, the MMIC solution yielding high reliability and repeatability will also profit from the reduced cost ensured by mass production.

In this paper, we discuss the advantages deriving from the adoption of gallium nitride (GaN) MMICs for the PA design in microwave backhaul systems, in terms of power density, power gain and power efficiency. We focus on GaN on silicon carbide (SiC) substrate, as SiC provides a good lattice match to GaN and high thermal conductivity. The former limits the number of defects during the growing of the epi-layer, while the latter is needed to remove the heat from the active regions of the transistor. GaN on SiC technology already demonstrates state-of-the-art performance at device level and for discrete transistors, but monolithic implementations are still limited to few examples [4]. However, GaN on SiC is dedicated to high-performance applications, due to the high cost and limited diameter (up to 3 inches) of SiC substrates. If low cost applications are targeted, other solutions are based on Si or sapphire substrates. Examples of working PAs based on GaN on Si devices can be found in [5], at L-band, and in [6] at W-band. GaN technology reliability has also improved significantly in the last few years. While the first examples of devices showed a large number of issues [7], more recent results showed that technology is ready for commercialization. In fact, foundries as TriQuint Semiconductor, Selex ES, and United Monolithic Semiconductors have processes and devices on the market, and some of them qualified for space applications. These achievements have been possible thanks to private investments, as well as international project like the European KorriGaN network [8]. In particular, we will show three design examples, highlighting the evolution of the GaN MMIC technology and its applicability to different design strategies. The first example is a 7 GHz Doherty developed on the 0.25  $\mu\text{m}$  HEMT (high electron mobility transisto) MMIC process of GigaHertz Center, *i.e.*, a research foundry [9]. In the second design, another 7 GHz Doherty PA is developed on a more recent commercial 0.25  $\mu\text{m}$  HEMT GaN MMIC process of TriQuint [10], while the third example adopts the second generation of the same process for the implementation of a 7–15 GHz dual band combined PA.

In Section 2, the design of the three MMICs is described, starting from the specifications and motivating the implementation choices, with a particular focus on the crucial advantages of GaN. In Section 3, the performance of the three PAs is presented and discussed in details, showing the progress of the GaN MMIC technology across the years, and its capability to provide state of the art results with relatively simple implementations. Finally, in Section 4, some conclusions are drawn.

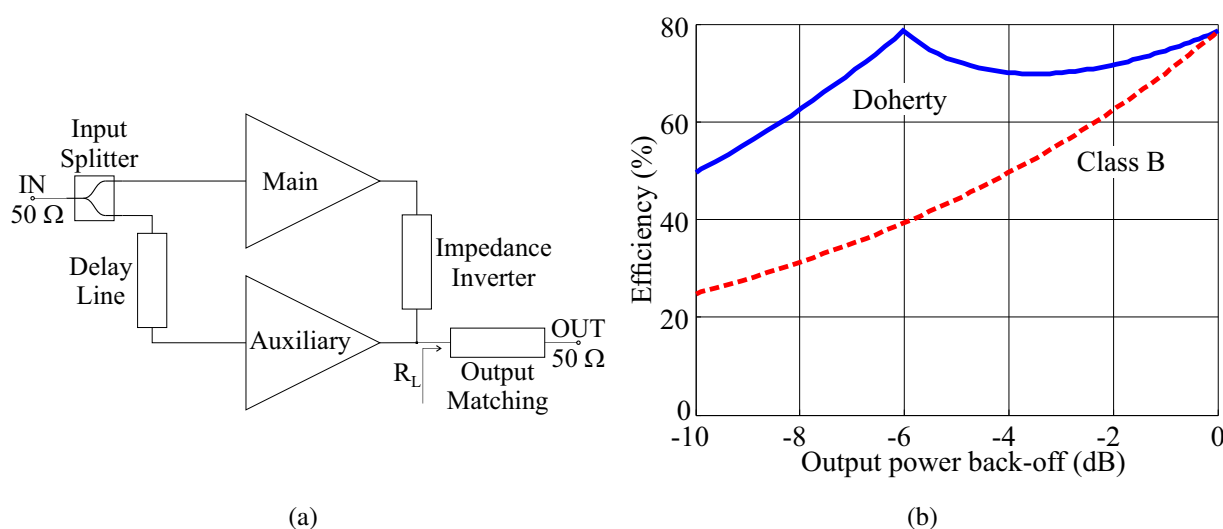
## 2. Design

### 2.1. 7 GHz Doherty: Research Foundry

The Doherty PA is widely adopted for the amplification of modulated signals with large peak-to-average power ratio (PAPR), since it is able to significantly enhance the average power efficiency with respect to a combined PA realized with same devices [11,12]. However, with respect to combined PA solutions, it suffers from some drawbacks like limited bandwidth and reduced gain.

The basic scheme of a Doherty PA consists of two stages, namely the main and the auxiliary, see Figure 1a. At low power level, the auxiliary amplifier is turned-off (it is usually biased in class C), and the main amplifier works on a load  $R_M = 2R_{OPT}$ , where  $R_{OPT}$  is the main optimum load. At the so-called break-point, that commonly is set at an output power 6 dB lower than the saturated one, the main amplifier reaches its maximum voltage excursion and its maximum efficiency. At the same power level, the auxiliary turns on and starts to inject current into the common load. This provides two effects. First, the power increases due to the auxiliary current. Second, the load seen by the main stage is modulated by current injected into the common load by the auxiliary, and at saturation it reaches  $R_{OPT}$ . The impedance inverter at the main output is crucial for the correct load modulation. The resulting power efficiency vs. output power of a Doherty is represented in Figure 1b, compared to the one of a tuned-load combined class B PA: while at maximum output power the efficiency is identical, at output power back-off the Doherty PA shows a much higher efficiency.

**Figure 1.** Block scheme of Doherty PA (power amplifier): (a) Efficiency vs. output power; (b) comparison between ideal Doherty PA and ideal class B PA.

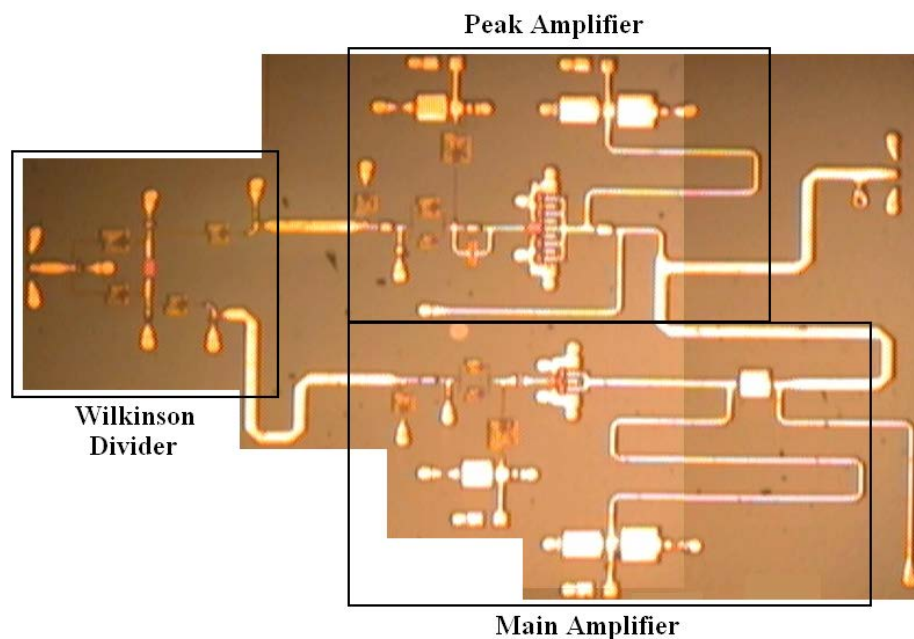


In the current design, the specifications ask for an output power of around 5 W at 7 GHz, with bandwidth larger than 5%, acceptable gain, and maximum efficiency at 7 dB power back-off. The GigaHertz Centre process [9] utilizes 0.25 μm GaN HEMTs with power density of 5 W/mm at 10 GHz (drain bias voltage of 28 V), source-drain spacing of 3 μm, with an on-resistance of 2.2 Ω·mm, and cut-off frequency around 23 GHz.

It can be seen that, for the target power level, GaN technology provides an important benefit, since the Doherty  $R_L$  results around  $50 \Omega$ , while it would be ten times lower in gallium arsenide (GaAs) technology [13–15]. This is permitted by the possibility to bias the GaN device at high voltage, thanks to its intrinsic high breakdown voltage ( $>70 \text{ V}$ ). This allows for much reduced losses in the final output matching to  $50 \Omega$ , with important advantages also in terms of bandwidth.

The 7 dB back-off and gain specifications led us to the adoption of an uneven Doherty scheme, *i.e.*, with the auxiliary device with larger size than the main device. In particular, according to the calculations shown in [16], sizes of  $4 \times 100 \mu\text{m}$  and  $10 \times 100 \mu\text{m}$  for the main and auxiliary have been chosen, respectively. Moreover, for a further gain improvement, the input power splitter delivers more power to the main than to the auxiliary. It can be noticed the simplicity of the adopted structure: thanks to the high power density of GaN, the power target could be achieved by using single device main and auxiliary stages. The same power level in GaAs technology would ask for the combination of several devices in every branch, thus complicating the matching networks and inevitably reducing the performance. The final layout ( $3 \times 4.5 \text{ mm}^2$ ) is shown in Figure 2.

**Figure 2.** Microscope picture of the Doherty PA MMIC (microwave monolithic integrated circuits) fabricated with the GigaHertz Centre foundry process. The building blocks are highlighted.

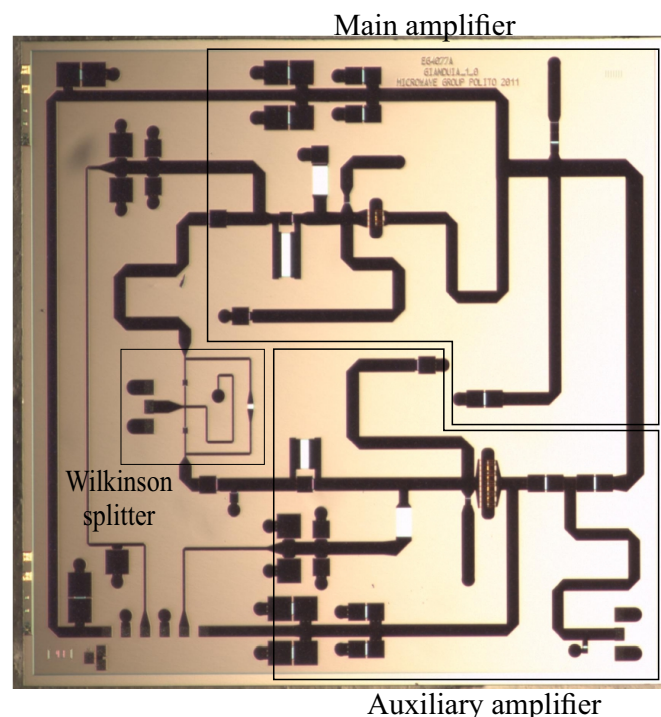


The output matching networks are realized with distributed elements, in order to minimize losses. The by-pass and direct current (DC) block capacitances are realized with metal-insulator-metal (MIM) integrated capacitors. The input Wilkinson splitter, realized with two sections for uneven splitting, is implemented in an equivalent, low-pass, lumped form, that includes MIM capacitors, chip inductors and a thin film resistor. The input matching of the devices is realized in a semi-lumped form, and includes the stabilization networks. Due to the research nature of the employed process, no information about process variability, both for passive and active components, was available at the time of the design, and consequently robustness analysis could not be executed.

### 2.2. 7 GHz Doherty: Commercial Foundry

The second design example started from an adaptation of the previous design to the first generation of the GaN commercial process of TriQuint. It includes  $0.25\ \mu\text{m}$  GaN HEMTs with  $4.5\ \text{W}/\text{mm}$  power density at  $30\ \text{V}$  of drain bias, cut-off frequency around  $24\ \text{GHz}$  and pinch-off gate voltage of around  $-3.2\ \text{V}$ . A vast passive components library based on the 3 metal layers process used for GaAs substrates is available for this process and moreover, the foundry also provides data about process dispersion, particularly useful for robustness analysis. The design specifications are maintained with respect to the experimental foundry tape-out: given the similar power density, the device peripheries also result the same, *i.e.*,  $4 \times 100\ \mu\text{m}$  for the main and  $10 \times 100\ \mu\text{m}$  for the auxiliary [17]. The designed layout ( $4.8 \times 4.6\ \text{mm}^2$ ) is shown in Figure 3.

**Figure 3.** Microscope picture of the Doherty PA MMIC fabricated with the TriQuint foundry process, first generation. The building blocks are highlighted.



While the output matching section is rather similar to the previous design, the input splitter has been modified, relying in this case on a semi-lumped, high-pass, even Wilkinson implementation. While this solution slightly reduces the gain of the stages, it improves the robustness of the design to process variations. The MIM capacitors are guaranteed for a maximum voltage of  $20\ \text{V}$ : since the drain bias voltage is set at  $30\ \text{V}$ , the capacitances on the output section are realized with series of two MIM capacitors.

### 2.3. 7–15 GHz Dual Band Power Amplifier

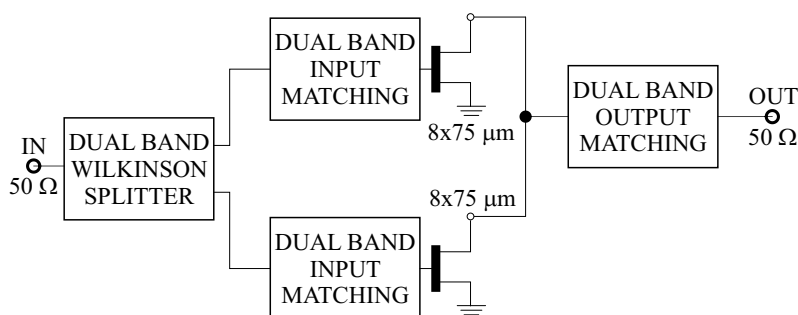
Dual-band PAs are widely investigated in literature, with several examples available (see, *e.g.*, [18,19]) and impressive performances for hybrid solutions and frequencies however below few GHz. Higher frequency realizations resort to CMOS (Complementary Metal Oxide Semiconductor)



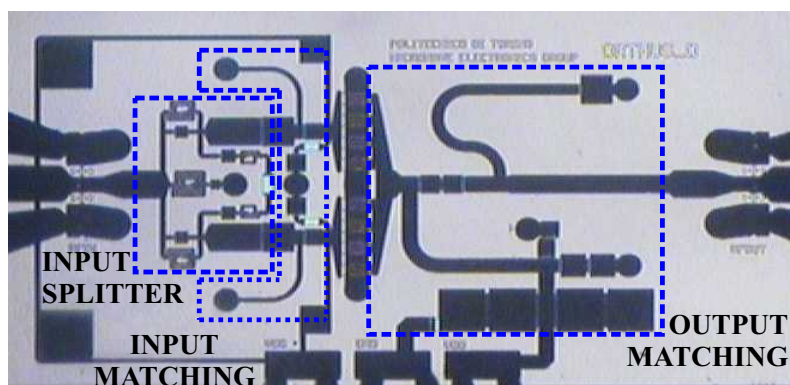
technology, exhibiting limited output power and efficiency [20,21]. Focusing on backhaul applications, the availability of multi-band PAs ensuring back-compatibility with the systems in use (antennas, duplexers, cables, *etc.*) and, at the same time, working at higher frequency where more bandwidth is available, represents a very attractive scenario.

In this framework, we present as an example a GaN MMIC dual-band PA working at 7 and 15 GHz, where it exhibits good power and linearity performances. The design has been developed on the second generation of the TriQuint GaN process, and it is based on a combined architecture to reach the 4 W power target. A pair of  $8 \times 75 \mu\text{m}$  is exploited: a simplified model of the device is used to design a first realization of the building blocks of the PA. This strategy is very common among PA designers because it makes possible to adopt a linear small-signal simulation environment for the first evaluation of different design choices, with significant advantages in terms of computational speed. When the structures are fixed, performance are then optimized through harmonic balance non-linear simulations [22] of the complete amplifier. Figure 4 shows a simplified block scheme of the PA, while Figure 5 reports the layout (size:  $2.7 \times 1.5 \text{ mm}^2$ ) of the MMIC with highlighted building blocks. The output matching network, realized in a distributed form, controls the fundamental and second harmonic terminations of both frequency bands. The input splitter and the input matching network are designed separately. The input matching is realized with a  $\Pi$ -shaped inductor-capacitor-inductor high-pass matching network, where the inductances are realized by means of short-circuit ended stubs. The Wilkinson input splitter is realized with lumped elements following the guidelines of [23]. In addition, in this case, process variation analysis has been widely adopted, highlighting an higher sensitivity of the lower band (7 GHz) performance.

**Figure 4.** Block scheme of the dual-band PA.



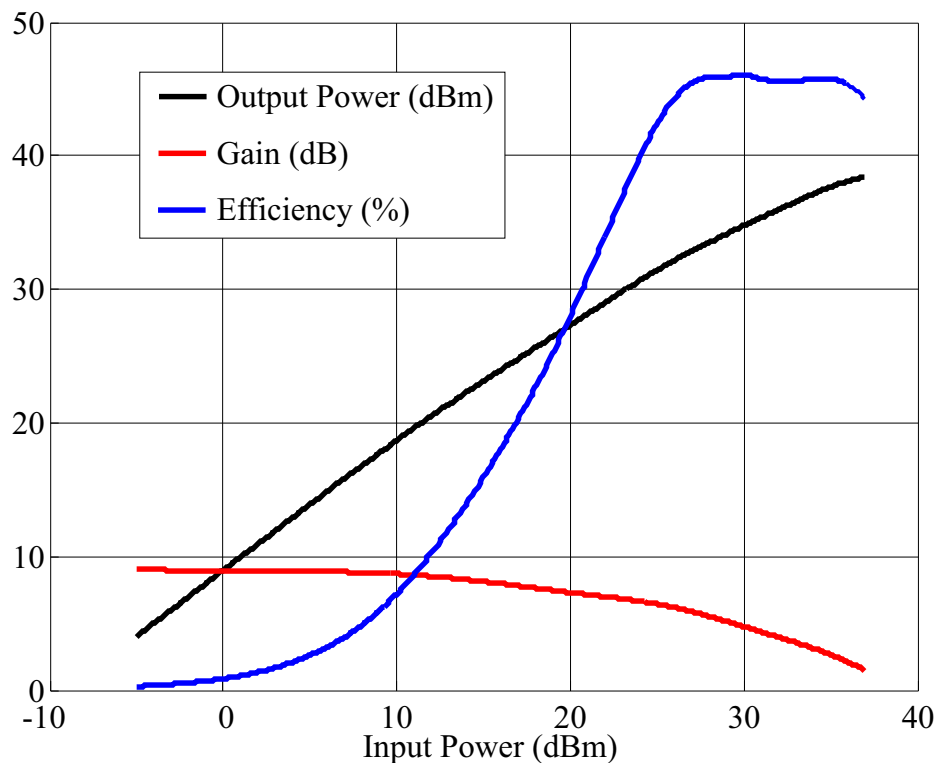
**Figure 5.** Microscope picture of the Doherty PA MMIC fabricated with the TriQuint foundry process, first generation. The building blocks are highlighted.



### 3. Performance and Discussion

The Continuous Wave (C.W.) simulated performances of the Doherty PA developed on the GigaHertz Centre foundry process are reported in Figure 6, showing an output power of 39 dBm and an efficiency exceeding 45% over a 7 dB back-off range from maximum output power.

**Figure 6.** Simulated performances at 7 GHz of the experimental foundry Doherty PA. Output power, power gain, and efficiency vs. input power.



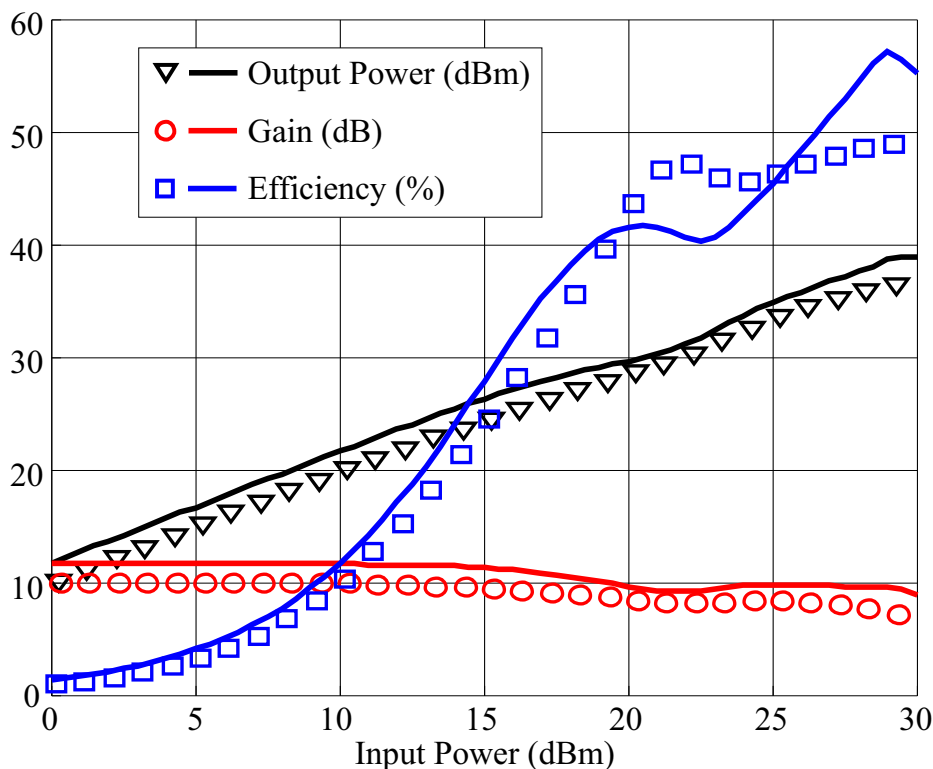
The bias is set at 30 V for the drain voltage, while the main bias current is at 40 mA, and the auxiliary is in class C, at  $-5$  V of gate voltage.

Unfortunately, several issues have been encountered during the characterization of the MMIC, in particular regarding failures on the large-value MIM capacitors. Moreover, measurements on test structures also denoted discrepancies between the large-signal simulations and the characterization results, that can be probably ascribed to a non-accurate modeling of the active device and to a low repeatability of the process. The Doherty PA realized with TriQuint MMIC has been extensively characterized in small and large signal CW conditions in the laboratories of the Politecnico di Torino, adopting a large signal set-up with on wafer load-pull capabilities [24]. This test-set allows for real-time measurement of incident and reflected waves at the DUT reference planes, by means of two reflectometers. From these data, all the information required ( $P_{in}$ ,  $P_{out}$ , Gain, PAE,  $\Gamma_{in}$ ,  $\Gamma_L$ ) are extracted. The amplifier showed state-of-the art performance. The drain bias voltage is 30 V, the main drain current is 40 mA, while the auxiliary gate voltage is at  $-6.5$  V. Figure 7 displays the comparison between measured and simulated C.W. performance. The agreement is rather good, demonstrating the evolution of the technology and the good accuracy of the model library. In particular, the provided foundry model is based on a Eesof GaAs HEMT model, well suited to GaN HEMT devices



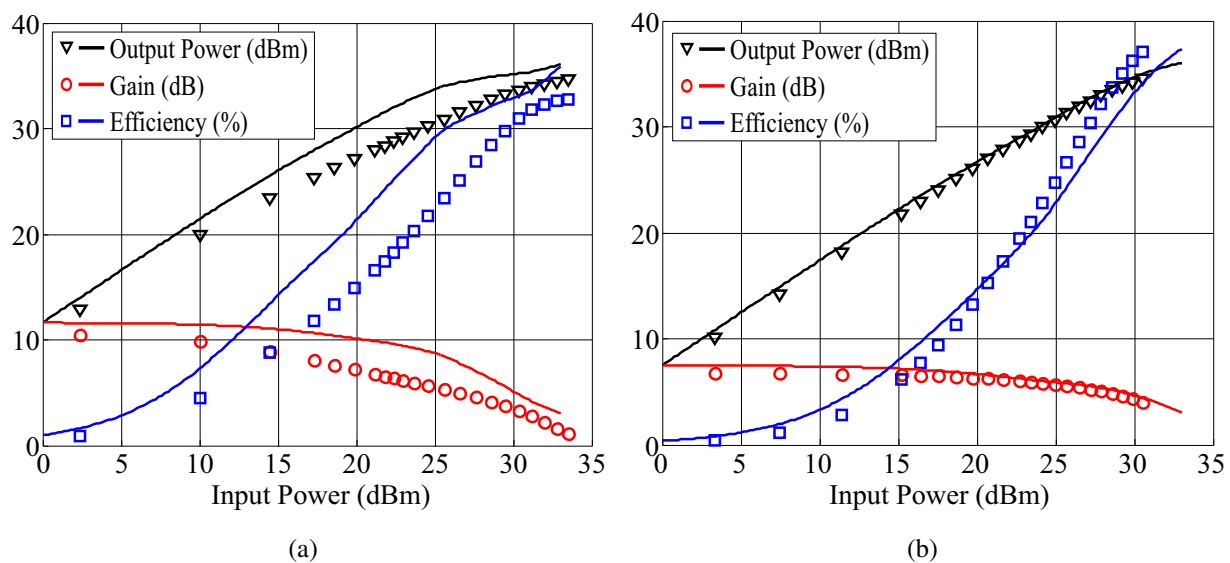
modeling [25]. The measured output power exceeds 37 dBm, with a gain of 10 dB and saturated efficiency of 45%. At 7 dB output power back-off, that is the operative power level in presence of modulated signal, the efficiency is higher than 47%. This values are in line with similar Doherty MMICs realized on the same technology [26,27], further proving the reliability of the process and of its design kit models.

**Figure 7.** Commercial foundry Doherty PA C.W. characterization at 7 GHz: output power, gain and efficiency vs. input power. Simulations (solid lines) and measurements (symbols).



The dual band PA, realized on the second generation of the TriQuint GaN process, also demonstrates good overall performance. The bias is set at drain voltage of 30 V and drain current of 80 mA. As expected from the sensitivity simulations, the higher band (15 GHz) demonstrated a better measurement vs. simulations agreement, due to its higher robustness to process variations with respect to the lower band (7 GHz): the best performance in the upper band is measured at 14.9 GHz. At 7 GHz, a frequency shift of the center frequency is experienced, and the best performance is measured at 7.7 GHz. The characterization results at these two frequencies are compared with simulations in Figure 8. The saturated power, in both bands, exceeds 34.6 dBm; the efficiency results higher than 32% and 37% at 7.7 GHz and 14.9 GHz, respectively. The comparison with simulations shows that the frequency shift in the lower band also affected the power performances; on the other hand, in the upper band, the measurements are more in agreement with simulations. This design demonstrates that the 0.25  $\mu\text{m}$  GaN MMIC technology can give satisfactory results also for frequencies around 15 GHz, and that the process and its design kit provide useful tools for accurate design of advanced PA solutions.

**Figure 8.** Continuous wave results of the dual-band PA at lower (a) and upper (b) band. Simulated: solid lines, measured: symbols.



#### 4. Conclusions

In this paper, the advances of GaN MMIC technology for the implementation of power amplifier for point-to-point radios have been investigated. In particular, we have shown three design examples, highlighting the advantages of GaN with respect to other semiconductors, like GaAs. Moreover, we have shown significant measurement results, in the 7 and 15 GHz bands, that place the presented designs in the state of the art of solid state MMIC PAs. The progress of the process accuracy and reliability has been discussed.

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#### Author Contributions

Vittorio Camarchia participated to the design and to the characterization of the circuits, and reviewed and corrected the article. Marco Pirola supervised the design and the characterization, and reviewed and corrected the paper. Roberto Quaglia participated to the design of the circuits and to their characterization; he wrote the paper.

#### Conflicts of Interest

The authors declare no conflict of interest.

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