

94 GHz power amplifier MMIC development in state of the art MHEMT and AlGaIn/GaN technology

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INTRODUCTION

Solid-state power amplifiers at W-band (75 - 110 GHz) are attractive for the generation of local-oscillator (LO) power for super-heterodyne receivers operating at sub-millimetre wave frequencies, as needed for example in future space instruments for Earth observation. Apart from space applications there is a growing interest for these devices in for example millimetre wave imaging, communication and radar systems. A power amplifier with an output power of the order of 1W, followed by a chain of frequency multipliers, can provide sufficient LO power for a Schottky receiver up to terahertz frequencies. Gallium-Nitride (GaN) technology is especially interesting, and has shown power levels that exceed those achievable with other technologies, like Indium-Phosphide (InP) and Gallium-Arsenide (GaAs). Watt-level output power at W-band has been demonstrated by advanced GaN technologies of HRL, Raytheon, and Fujitsu [1-3].

This paper will present the technology, design, and demonstration of 94 GHz power amplifier Monolithic Microwave Integrated Circuits (MMICs) in two different technologies: a state-of-the-art and proven GaAs MHEMT technology and a newly developed 0.1 μm AlGaIn/GaN technology on SiC substrate. Because of the lower power density of the MHEMT technology a scenario with 4 MHEMT power amplifiers in parallel will be compared to a single GaN power amplifier MMIC. All MMICs will be mounted in W-band waveguide modules. For the MHEMT-based power amplifier module a 1-to-4 power waveguide splitter and combiner has been designed.

BACKGROUND

The number of applications that are using the millimetre-wave (30-300 GHz) part of the spectrum are continuously growing. These applications include amongst others personal communication (60 GHz WLAN), automotive radar (77 GHz), medical and security imaging (94 GHz) and weather and earth observation. The increase in applications and use of this part of the spectrum is mainly driven by the increased high-frequency capability of semiconductors, such as InP and GaN that allow the realization of highly integrated transceivers.

Millimetre-wave instruments for earth observation and space science in the W-band (75-110 GHz) that are using heterodyne receivers need high power LO sources to drive the down-conversion mixers. Current systems make use of Gunn diodes or multiplication of lower frequency LO sources. The continuous improvements in semiconductor processing technology now make it possible to generate the required LO power directly at the millimetre wave frequencies, which enables a solid-state integrated receiver. An already established technology for this purpose is Metamorphic HEMT (MHEMT), based on the InAlAs/InGaAs material system with excellent high speed characteristics. Higher output powers are possible by using GaN HEMT with scaled gate length, although this technology, especially for millimetre-wave applications, is still in development.

Apart from the use as LO power generation for passive receiver instruments, these technologies and products can also be used for other systems, such as 94 GHz radar and telecommunication.

MHEMT TECHNOLOGY

The 94 GHz power amplifier circuits were fabricated using an InAlAs/InGaAs material system with $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{0.65}\text{Ga}_{0.35}\text{As}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ composite channel HEMTs grown by molecular beam epitaxy (MBE) on 4-inch semi-insulating GaAs substrates. For the metamorphic buffer a linear $\text{In}_x\text{Al}_y\text{Ga}_{1-x}\text{As}$ ($x = 0 \rightarrow 0.52$) transition in composition was used. The active devices consist of T-shaped $0.1 \mu\text{m}$ Pt-Ti-Pt-Au gates, which were defined by e-beam lithography and passivated with 250 nm CVD deposited silicon nitride. With an indium content of 65 % in the channel an average extrinsic transit frequency of $f_t = 220$ GHz and a maximum oscillation frequency of $f_{max} = 300$ GHz were achieved for a $2 \times 30 \mu\text{m}$ common source device at $V_{ds} = 1$ V. The gate-drain breakdown voltage defined at a gate current of 1 mA/mm was 4.3 V. With a drain bias of 1 V and a peak- g_m gate bias of 0.2 V an extrinsic transconductance of 1200 mS/mm was measured. In contrast to existing power amplifier designs using dual-gate transistors [4] the power amplifier MMIC design in this work has used standard common source transistors.

ALGAN/GAN TECHNOLOGY

The dedicated epitaxial structures used for the fabrication of the deep submicron AlGaN/GaN technology are grown by metal organic chemical vapor deposition (MOCVD) on 3-inch semi insulating SiC substrate. A 2 DEG sheet carrier concentration of $8 \times 10^{12} \text{ cm}^{-2}$ and an electron mobility of $1800 \text{ cm}^2/\text{Vs}$ were determined by Hall measurements for the presented AlGaN/GaN-HEMTs. The device definition is carried out by using optical stepper for all steps apart from the gate definition which is performed by electron beam lithography to form a 100 nm T-gate. A DC-peak g_m as high as 550 mS/mm and high saturated drain current-density of more than 1600 mA/mm were measured. The typical bias operation voltage for a common-source transistor is $V_{DS} = 10 \dots 15$ V. The current gain cutoff frequency f_T is above 80 GHz. The development and optimization of the structure to suppress short-channel effects is discussed in [5]. Apart of the active elements, the passive technology further features high-density high-voltage MIM-capacitances ($V_{break} > 50$ V) and NiCr-resistors. For the backside the SiC is thinned to $75 \mu\text{m}$ (3-mil) and $30 \times 30 \mu\text{m}^2$ through-wafer via holes are applied. This forms grounded coplanar-waveguide (GCPW) technology with a ground-to-ground spacing of $50 \mu\text{m}$ to suppress undesired substrate modes.

MODULE TECHNOLOGY

The final power amplifier will be delivered in a waveguide (WR10) package. The AlGaN/GaN power amplifier MMIC will be mounted in a single chip module. This is a straightforward design using waveguide launchers and two DC biasing boards.

The MHEMT power amplifier however will be mounted in a 4-to-1 power splitting/combining module. The challenge is to design low-loss combiners and connect all the bias signals at both DC sides of each MMIC. The overall design is shown in Fig. 1. A close-up of the bias connection and magic tee construction is shown in Fig. 2. The isolated ports are perpendicular to the shown plane and will be terminated with loads.

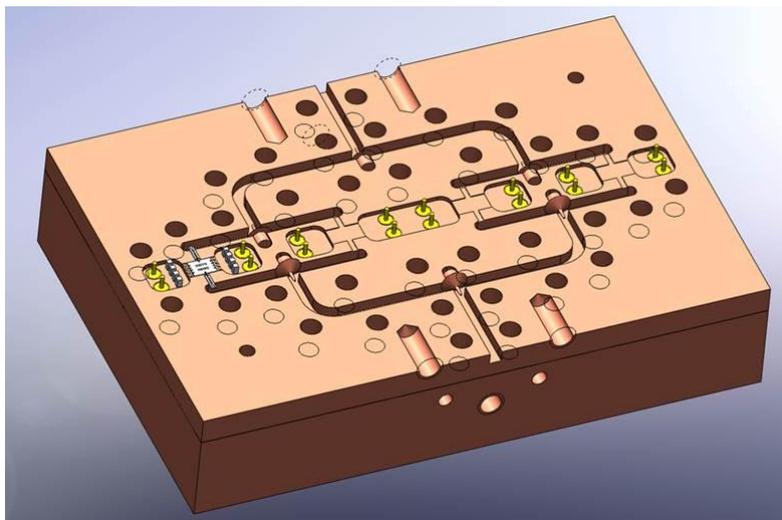


Fig. 1 : Waveguide module with 1-to-4 splitter and combiner for the 4 MHEMT power amplifiers.

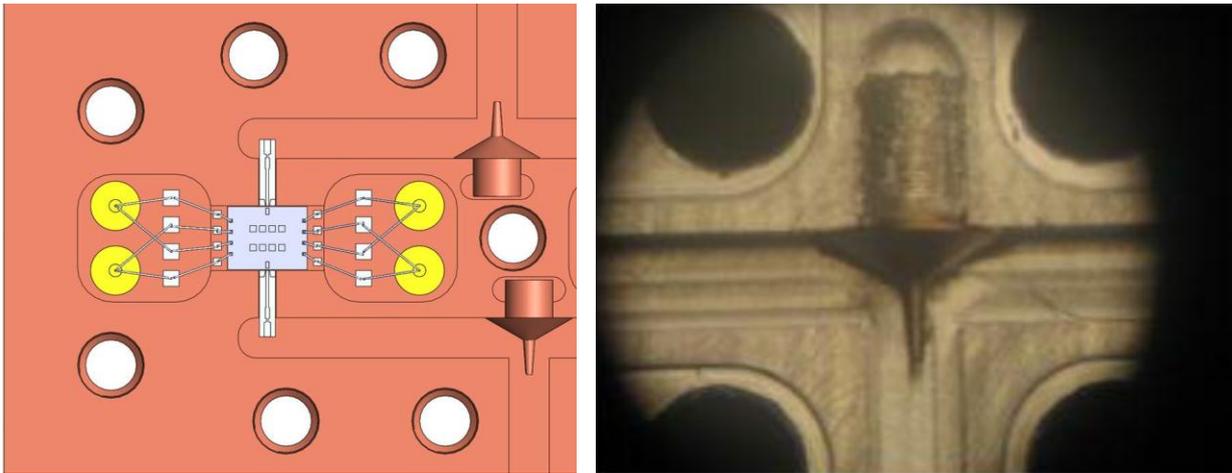


Fig. 2 : Close up of the DC bias connection and realization of the magic-tee power splitter.

A single waveguide power splitter has been fabricated and measured in W-band. The results for the insertion loss for both branches and the matching of all ports is shown in Fig. 3. The insertion loss is around 0.5 dB and the matching for the RF ports is better than 10 dB from 80 to 103 GHz.

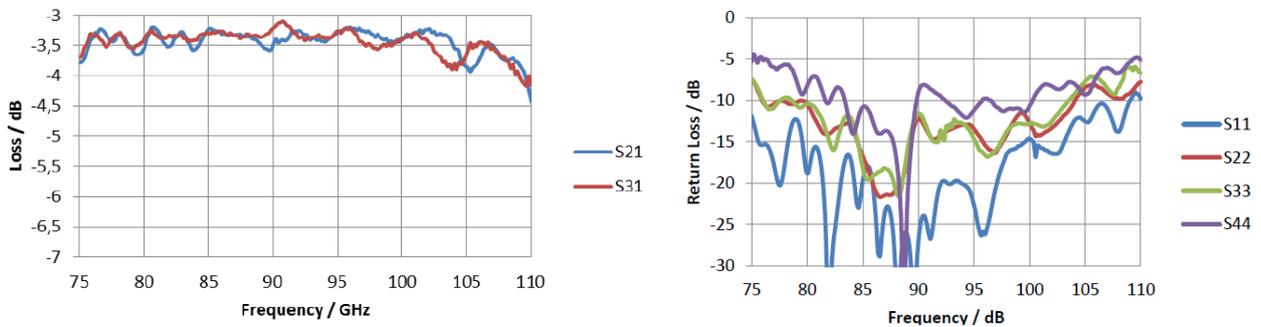


Fig. 3 : Insertion loss and matching of the power splitter (port 1 = input, port 2 and 3 = output, port 4 = isolated).

MMIC DESIGN

For both the MHEMT and the AlGaIn/GaN technology the MMIC design is based on a Process Design Kit for Agilent ADS, including models for the grounded coplanar passives as well as non-linear models for the active devices. Two processing iterations have been performed, with several HPA versions on each iteration. Each processing iteration has been done on several wafers including also technology variants.

MHEMT Design

The MHEMT design has used common-source transistors, to explore the millimetre wave performance of this topology versus existing designs using dual-gate devices. Specifications, shown in table 1, have been given for the 4-chip waveguide module.

Table 1. MHEMT power amplifier module specification.

Specification	Value
Centre frequency	94 GHz
-3 dB bandwidth	10%
Output power at 3dB compression	> 400 mW
Gain at nominal output power	> 12 dB
PAE	> 8%
Input and output return loss	> 10 dB

From these module specifications the MMIC specifications have been derived, with a target of more than 200 mW output power for each MMIC to account for the losses in the waveguide combiner.

The amplifier is a 2-stage design using 8 dual gate transistors of $4 \times 37 \mu\text{m}$ in parallel, for both stages. A 1:1 ratio has been used for the first to second stage dimensioning, to prevent that the overall performance is limited by early compression of the input stage. The simulated losses for the input stage, interstage and output stage matching networks are respectively 2.1 dB, 2.5 dB and 1.2 dB. Odd-mode oscillation suppression resistors have been connected between all gates. A photograph of the realized design is shown in Fig. 4.

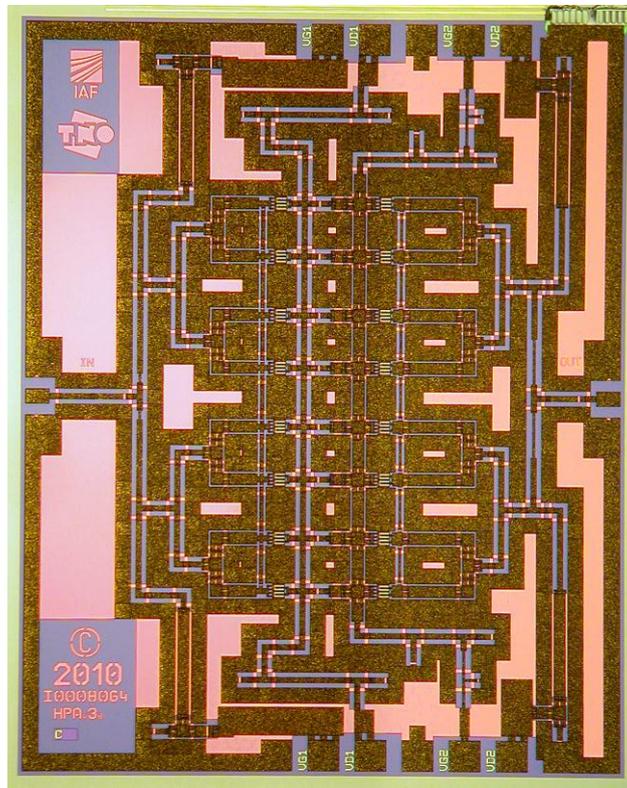


Fig. 4 : MHEMT power amplifier MMIC photograph, 2.0 mm by 2.5 mm in size.

The simulated performance is shown in Fig. 5, showing an output power of 23 dBm, PAE of 13% and small signal gain of 10 dB.

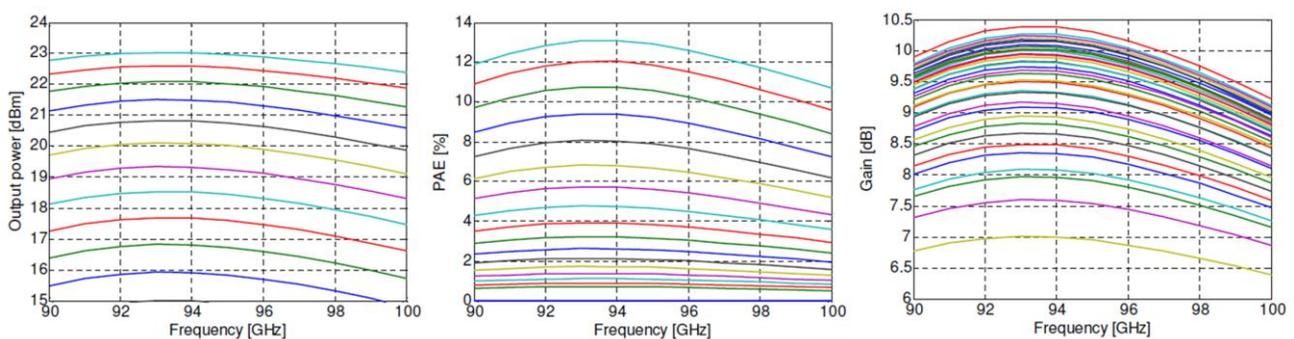


Fig. 5 : MHEMT amplifier simulated performance at $V_d=1.25\text{V}$, $V_g=0.2\text{V}$, for source power up to 15 dBm in 1 dB steps.

Thermal simulations have been performed to check the maximum junction temperature. The simulation includes the gate fingers, $50 \mu\text{m}$ thick GaAs substrate with $25 \mu\text{m}$ thick AuSn layer, mounted on a CuMo carrier. The backside of the carrier is fixed at 70°C . The total power dissipation is 1.5 W. For simplicity a smaller piece of GaAs has been used, which causes a pessimistic (too high) temperature result. The maximum simulated junction temperature is 120°C , which is a safe value.

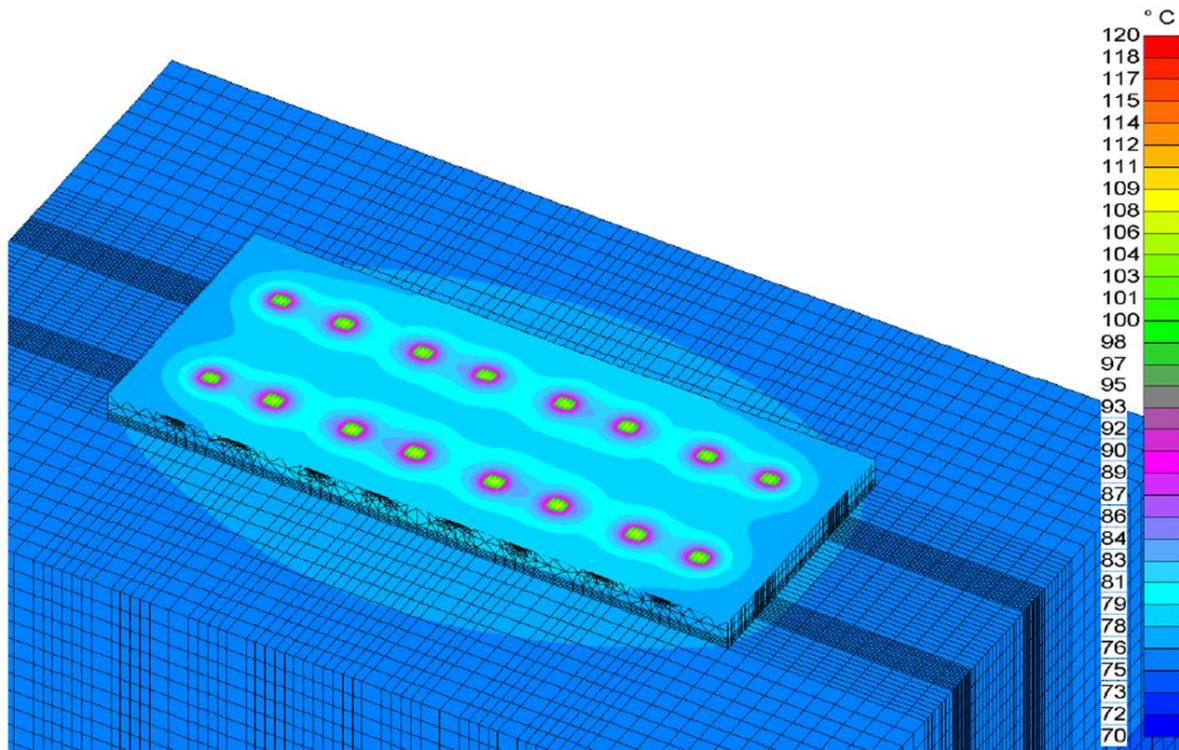


Fig. 6 : Thermal simulation of part of the MHEMT MMIC with the input and output transistors.

AlGaN/GaN Design

As basic transistor cell for the AlGaN/GaN power amplifier design a dual-gate $4 \times 45 \mu\text{m}$ HEMT has been selected. The specifications for the single chip GaN power amplifier are similar to the 4-chip MHEMT module specifications, as given in table 1.

From the beginning of the design it was already known that the gain and power added efficiency specification would be a challenge as we operate the device beyond the current-gain cut-off frequency. To limit the design risk and MMIC size it was chosen to make a dual-stage design. Experience from earlier designs in a similar technology [6][7] have shown a saturated output power density of 530 mW/mm at 94 GHz using 12 V bias. The current $0.1 \mu\text{m}$ GaN technology allows operation of the dual-gate devices up to 20 V (limited by thermal constraints only) and a higher output power density is expected. Therefore it was decided to use four dual-gate devices of $4 \times 45 \mu\text{m}$ unit gate width in parallel.

Two different topology versions have been explored: a safe 1:1 ratio between first and second stage (v1), and a version with 1:2 ratio (v2). For the first version the losses of the input, interstage and output matching networks are respectively 1.1 dB , 1.7 dB and 1.4 dB . For the second version the losses are respectively 0.9 dB , 1.7 dB and 1.4 dB . The main difference between these two designs is the power margin between the first and second stage. This margin is taken here as the source power difference of the output stage 3 dB gain compression point and the input stage onset of compression point. In the ideal case under nominal operation (e.g. in the 3 dB compression point) the input stage is at the onset of compression. For the safe design with the 1:1 ratio the power margin is 4 dB . For the second design this margin is close to zero. The chip photographs of the 2 designs are shown in Fig. 7, and the simulation results are summarized in table 2.

Also for the AlGaN/GaN MMIC design thermal simulations have been performed, using a similar layer stack as for the MHEMT simulations, expect using a $75 \mu\text{m}$ thick SiC substrate instead of the GaAs substrate. As input for the simulation the total heat dissipation is given as 10.8 W . At 70°C backside CuMo carrier temperature the maximum junction temperature becomes 142°C . When including the whole waveguide module an extra junction temperature increase of about 30°C is expected.

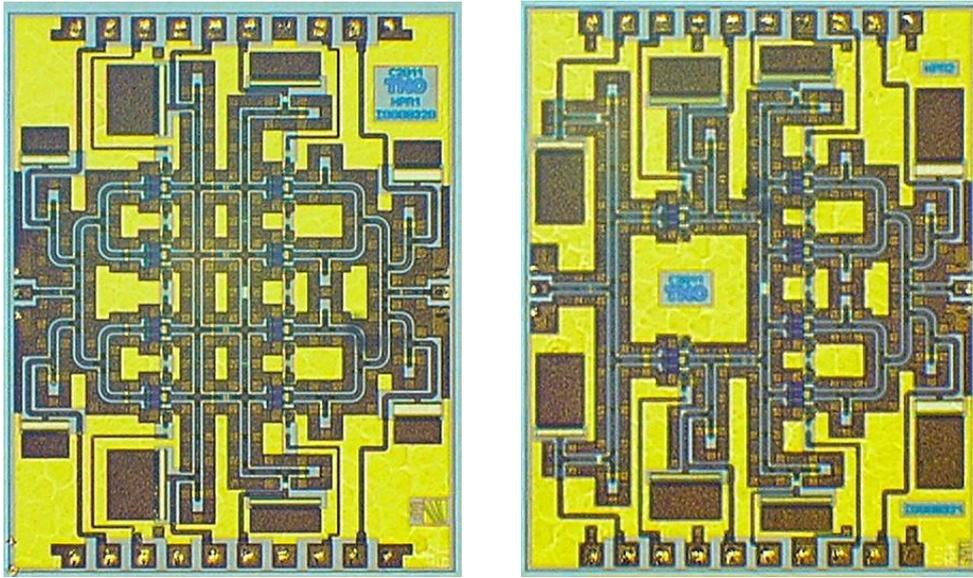


Fig. 7: AlGaIn/GaN HPA v1 (left) and v2 (right), both 2.0 mm by 2.5 mm in size.

Table 2. AlGaIn/GaN power amplifier MMIC simulation results ($V_d=20V$, $V_g=-1V$).

Specification	HPAv1	HPAv2
Centre frequency	94 GHz	94 GHz
-3 dB bandwidth	>13%	> 14%
Output power at 3dB compression (P3dB)	> 437 mW	> 408 mW
Gain at nominal output power (P3dB)	> 10.3 dB	> 9.6 dB
PAE	> 3.3%	> 4.2%
Input return loss	> 20 dB	> 25 dB
Output return loss	> 10 dB	> 9 dB

MMIC MEASUREMENT RESULTS

All MHEMT MMICs (42 cells) on a full wafer have been measured, showing a very good yield of 100% and very good uniformity across the wafer. The S-parameter measurements of all cells and a power sweep for one sample are shown in Fig. 8. The centre frequency of the design has shifted slightly upwards, with the gain peaking at 100 GHz. Input and output matching around 100 GHz are good. The power sweep has been performed at 100 GHz and at an increased drain supply voltage of 1.6 V to evaluate the maximum performance of the technology. The measured output power is 21 dBm, with a PAE of 8%.

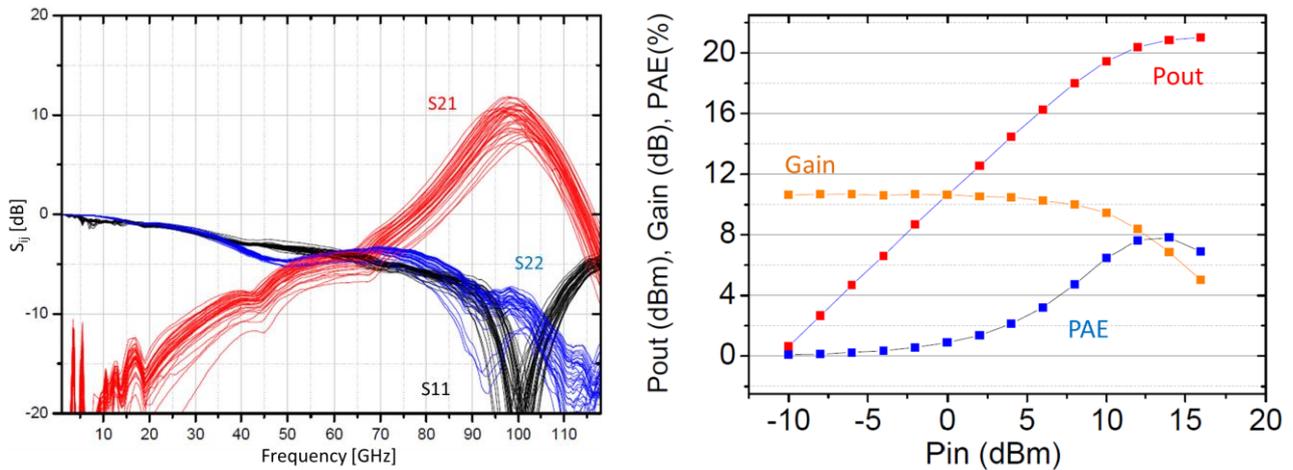


Fig. 8: MHEMT power amplifier measurement results, S-parameters at $V_d=1.2V$ (left) and power sweep at 100 GHz and $V_d=1.6V$ (right).

The AlGaN/GaN power amplifier designs have also been measured for all cells on the wafer. The S-parameter results for two typical samples are shown in Fig. 9. The gain is very high (>15 dB at 90 GHz) with excellent input matching. The output matching looks bad, but the results corresponds to simulations, and these simulations show that the active output impedance improves with increasing drive level. In W-band the small signal performance of the two design versions is very similar.

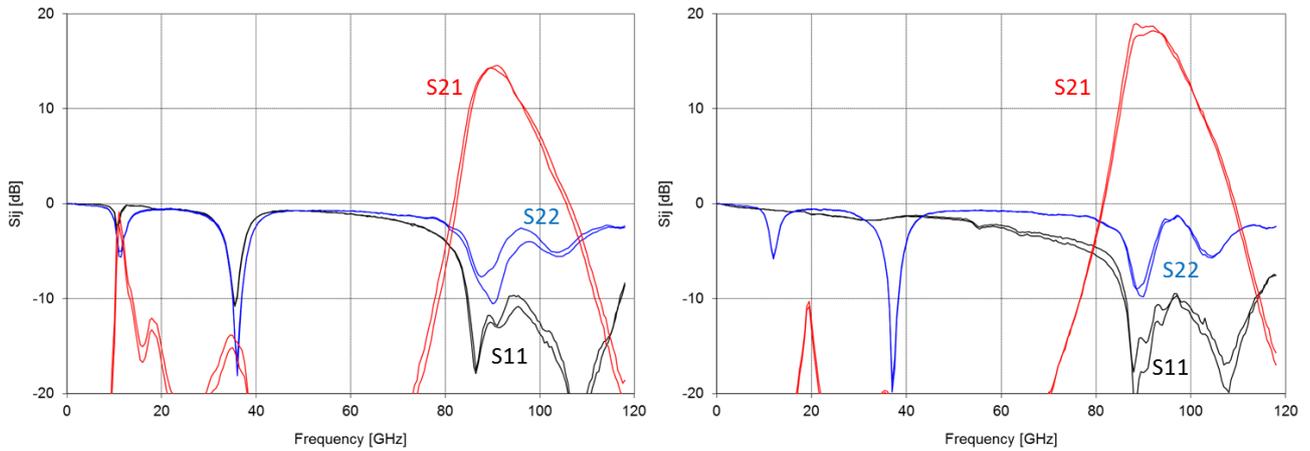


Fig. 9: AlGaN/GaN power amplifier S-parameter measurement results, HPAv1 (left) and HPAv2 (right), both at $V_d=20V$, $V_g=-2V$.

The large signal measurements on both designs are shown in Fig. 10. Both designs show similar performance, with a maximum output power of more than 26 dBm at 90 GHz. Design version 2 shows slightly better gain and efficiency, as expected.

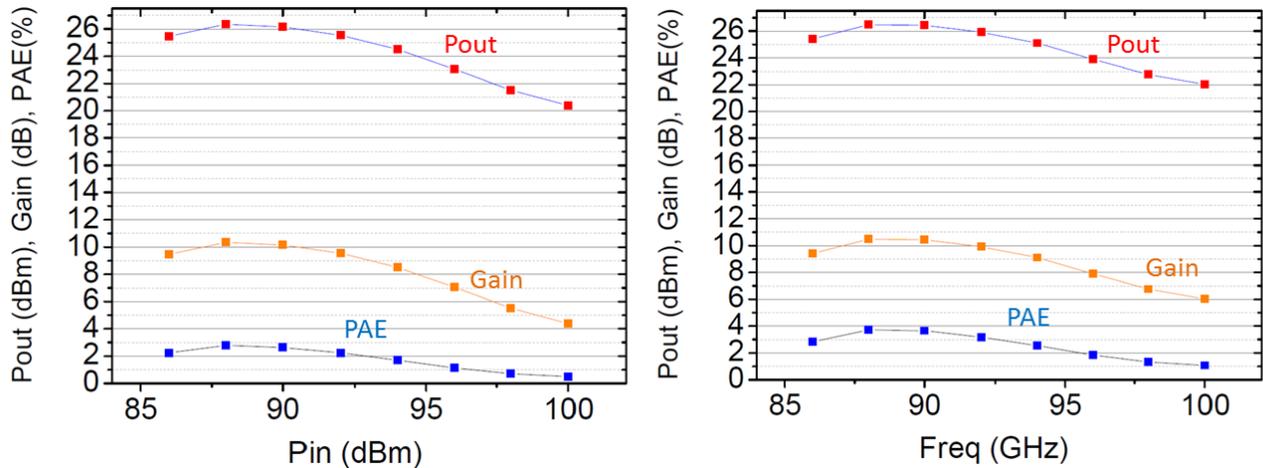


Fig. 10: AlGaN/GaN power amplifier power measurement results, HPAv1 (left) and HPAv2 (right), both at $V_d=20V$, $V_g=-1V$ and input power of 16 dBm.

MODULE RESULTS

Currently the first MHEMT power amplifiers have been mounted in single chip modules, and the testing of these modules is in progress. The results are shown in Fig. 11.

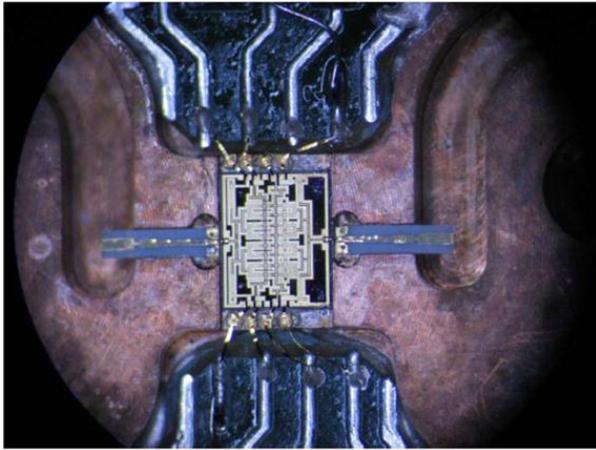


Fig. 11: Single chip waveguide module showing the mounted MHEMT power amplifier MMIC.

CONCLUSIONS

Although this project is still on-going, already encouraging results have been obtained. Major challenge has been to design W-band power amplifier MMICs in a “commercial foundry mode” way of working. This requires a stable processing technology, very good transistor models and a complete process design kit for the passives. The results so far have shown that this exercise has been successful. The MHEMT design shows an excellent yield and uniformity. The common-source MHEMT power amplifier designs yield output power level beyond 21 dBm within the margins of reliable operation at frequencies of 90-100 GHz.

The AlGaIn/GaN power amplifier MMICs show European state-of the art performance, with an excellent output power of more than 400 mW, at 90 GHz and 20 V drain supply using dual-gate devices. Power added efficiency of these designs, partly due to the dual-gate approach, is however still low, and needs to be improved, mainly by further processing technology development.

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REFERENCES

- [1] A. Brown, K. Brown, J. Chen, K.C. Hwang, N. Koliaş, R. Scott, “W-band GaN power amplifier MMICs,” 2011 IEEE MTT-S International Microwave Symposium Digest (MTT), 5-10 June 2011.
- [2] Y. Nakasha, S. Masuda, K. Makiyama, T. Ohki, M. Kanamura, N. Okamoto, T. Tajima, T. Seino, H. Shigematsu, K. Imanishi, T. Kikkawa, K. Joshin, N. Hara, “E-Band 85-mW Oscillator and 1.3-W Amplifier ICs Using 0.12µm GaN HEMTs for Millimeter-Wave Transceivers,” 2010 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS), 3-6 Oct. 2010.
- [3] M. Micovic, A. Kurdoghlian, K. Shinohara, I. Milosavljevic, S.D. Burnham, M. Hu, A.L. Corrión, W.S. Wong, A. Schmitz, P.B. Hashimoto, P.J. Willadsen, D.H. Chow, A. Fung, R.H. Lin, L. Samoska, P.P. Kangaslahti, B.H. Lambrigtsen, P.F. Goldsmith, “W-band GaN MMIC with 842 mW output power at 88 GHz,” 2010 IEEE MTT-S International Microwave Symposium Digest (MTT), 23-28 May 2010.
- [4] A. Tessmann, A. Leuther, C. Schwörer, H. Massler, “Metamorphic 94 GHz power amplifier MMICs”, IEEE MTT-S International Microwave Symposium Digest 2005.
- [5] C. Haupt, S. Maroldt, R. Quay, W. Pletschen, A. Leuther, O. Ambacher, “Development of a high transconductance GaN MMIC technology for millimeter wave applications”, *Physica status solidi. C* 8 (2011), Nr.2, pp.297-299.
- [6] R. Quay, A. Tessmann, R. Kiefer, S. Maroldt, C. Haupt, U. Nowotny, R. Weber, H. Massler, D. Schwantuschke, M. Seelmann-Eggebert, A. Leuther, M. Mikulla, O. Ambacher, “Dual-Gate GaN MMICs for MM-Wave Operation,” *IEEE Microwave and Wireless Components Letters*, vol.21, no.2, pp.95-97, Feb. 2011.
- [7] D. Schwantuschke, C. Haupt, R. Kiefer, P. Brueckner, M. Seelmann-Eggebert, M. Mikulla, I. Kallfass, R. Quay, “A 56-65 GHz high-power amplifier MMIC using 100 nm AlGaIn/GaN dual-gate HEMTs,” *Proc. 2011 European Microwave Integrated Circuits Conference (EuMIC)*, Manchester, 2011, pp. 656-659.