S-Band AlGaN/GaN Power Amplifier MMIC with over 20 Watt Output Power

M. van Heijningen[1], G.C. Visser[1], J. Würfl [2], F.E. van Vliet[1]

[1]*TNO Defense, Security and Safety*
Oude Waalsdorperweg 63, 2597 AK, The Hague, The Netherlands
Marc.vanHeijningen@tno.nl

[2]*FBH Ferdinand-Braun-Institut für Höchstfrequenztechnik,*
Gustav-Kirchhoff-Straße 4, 12 489 Berlin, Germany
joachim.wuerfl@fbh-berlin.de

Abstract— **This paper presents the design of an S-band HPA MMIC in AlGaN/GaN CPW technology for radar TR-module application. The trade-offs of using an MMIC solution versus discrete power devices are discussed. The MMIC shows a maximum output power of 38 Watt at 37% Power Added Efficiency at 3.1 GHz. An output power of more than 20 Watt has been simulated from 2.5 to 3.7 GHz. The robustness against high output VSWR values up to 4:1 has been checked and simulations show a maximum drain-gate voltage of around 60 V.**

I. Introduction

The wide-bandgap semiconductor technology Gallium-Nitride (GaN) is a relatively new and very promising technology for high frequency power applications. The advantages of GaN are already described by many authors, such as [1], and are mainly the high power density, high breakdown voltage and good thermal properties of the mostly used Silicon-Carbide (SiC) substrate. Although the processing technology is still under development and continuously improving, the first GaN commercial products are already available. These products are mainly individually packaged transistors or power-bars for telecommunication infrastructure applications, such as WiMAX base-station amplifiers. GaN MMIC technology is available but has not yet been used much for S-band power amplifiers. This paper presents an S-band GaN MMIC power amplifier, together with the trade-offs and comparison to power-bars, and the application of GaN MMIC in S-band radar Transmit-Receiver (TR) module front-ends.

II. GaN Technology in TR-Modules

Due to the excellent power performance and robustness of GaN technology it is expected that GaN MMICs will replace a number or all GaAs MMICs that are currently used in TR-modules for radar front-ends. Not only the power amplifier, but also the low-noise amplifier [2] can be realized in GaN technology. The high power handling of the GaN technology also makes it possible to replace the isolator/circulator with a GaN switch. This will however require a careful analysis and design of the output matching network of the HPA, which is no longer isolated from the antenna [3]. Because of the robustness of the technology it will be possible to remove, or shrink, the limiter, which is often needed in front of a GaAs LNA. Overall, the use of GaN MMICs will lead to smaller and more light-weight TR-modules.

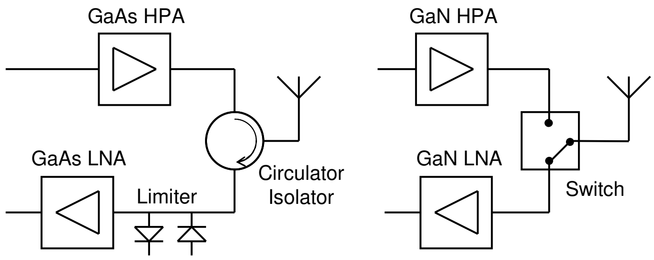

Fig. 1 Example of a classical GaAs frontend and robust GaN frontend.

For radar applications in L-band mostly discrete devices or power-bars are being used for the power amplification. For X-band mostly MMIC HPAs are being used. S-band is in between these two other bands and the choice for a discrete power device [4] or an MMIC is not easy. At these frequencies GaN also has to compete with LDMOS power devices, which are widely used today. The major advantage of GaN over LDMOS is the output impedance, which is for GaN much closer to 50 Ω and allows wide-band designs.

The choice between an MMIC solution and a discrete power device for S-band applications is mostly determined by the system design considerations such as the available area for the power amplification part and weight: Discrete devices often need external matching, which uses much more area than an MMIC solution. When designing for example a tile-based radar panel an MMIC HPA will be the preferred solution.

The choice whether or not to use GaN technology in radar systems is determined by the benefits at system level. The higher output power alone is not necessarily a reason to use a GaN HPA, since this will also lead to higher power dissipation and changes the thermal system design. Keeping the output power the same as used in a GaAs HPA but using a smaller MMIC size will be advantageous for many systems. Several radar performance improvements, when using higher output power per TR element, are presented in [5].

The current GaN development is mostly driven by commercial applications for broadband wireless access, using discrete devices, and only very few HPA MMICs around S-band are presented so far [6].

III. AlGaN/GaN Processing Technology

The AlGaN/GaN structures are grown on a 2-inch semi-insulating SiC substrate by metal–organic vapour phase epitaxy. The principle process flow towards GaN devices is very comparable to standard III/V devices. Of course the type of ohmic contact and Schottky gate metallization and, very important, the surface passivation has to be matched to the GaN/AlGaN material system and to the epitaxial layer sequence. The technology of the surface passivation is decisive, since any surface and interface charges directly control the concentration of the 2DEG in the channel. Additionally any traps introduced by epitaxy and/or processing may lead to strong dispersion effects and compromise microwave performance. Fig. 2 shows a schematic cross section of active and passive elements that may be integrated in a GaN based MMIC process. The FBH GaN-HEMT process relies on mixed wafer stepper and electron beam lithography to define the structures [7]. The passivation and the MIM dielectrics consist of an optimized SiNx layers deposited by PECVD. Typically, gate field plates are applied to eliminate dispersion and to enhance breakdown voltage.

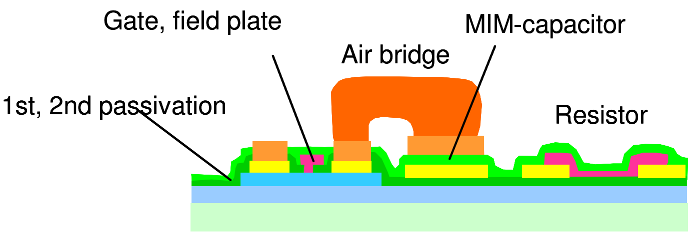

Fig. 2 Front end processing techniques at FBH.

IV. MMIC Design

Starting point for the MMIC design is a collection of models and measurement data for inductors, capacitors and resistors, processed on a previous run. 2.5D EM Momentum simulations have been used to simulate other passives and parts of the matching networks.

For the active devices, S-parameter measurement data and a modified Angelov large signal model for an 8x125 um device are available. Design target for the S-band HPA MMIC is at least 20 Watt output power around a center frequency of 3.1 GHz. This performance is close to the current state of the art that can be realized on a GaAs HPA MMIC in this band. However, the goal is to realize this on an MMIC area that is at least half of what would be needed to realize the same output power on GaAs, which is estimated to be around 30 mm^2.

The design has started by analysing the performance of the 8x125um basic FET size. Loadpull simulations have been performed to determine the load for maximum output power and maximum efficiency. A compromise load in between these two impedance values has been chosen and corresponds to 47.4 +32.2 j Ω at 3.1 GHz. The power sweep simulation performed at this load at 3.1 GHz is shown in Fig. 3.

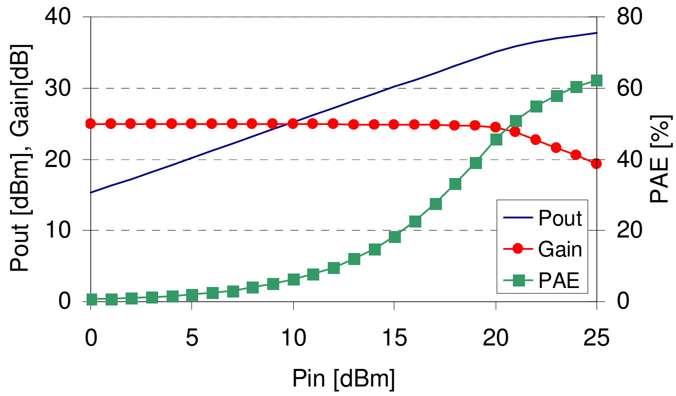

Fig. 3 Simulated output power, gain and power added efficiency of the 8x125um FET at the compromise load at 3.1 GHz and 26 V drain bias.

The small signal gain is around 25 dB and the 1 dB compression output power is 36 dBm at 51 % power added efficiency. The maximum PAE of over 60 % occurs at a gain compression of 5 dB. For S-band applications a unit gate width of 125um is not the optimum choice. Therefore two 8x125um FETs have been placed in parallel, creating an 8x250um FET. The output-stage of the HPA consists of four 8x250um FETs and has a total gate width of 8mm. This output-stage should deliver at least 20 Watts.

The next step has been to make the unit FET unconditionally stable, for frequencies above approximately 500 MHz. At lower frequencies the stability can be improved by off-chip measures, e.g. decoupling in the biasing network. The unit cell has been made unconditionally stable by adding a parallel R-C network in series with the gate and, to increase low-frequency stability, a shunt resistor to ground of 370 Ω at each gate-bias pad. Because the used processing technology is still under development a large safety margin has been used in the design of the stability network, resulting in a gain loss of about 6 dB per stage.

The resulting MMIC layout is shown in Fig. 4, and has a size of 5.0mm x 3.3mm. This is about half the size of a GaAs S-band HPA MMIC for the same output power. After the complete circuit and layout design extra stability analyses have been done to check for odd-mode oscillations and loop gains over the power supplies. These analyses have shown that extra external power supply decoupling and filtering of especially the gate bias lines are required to prevent possible oscillations.

In this first stage of the HPA two 8x250um FETs have been used. The output power of this first stage has to compensate the relatively large losses of the stability network, but still there is a large power margin between the first and second stage. In a future redesign the dimension of this first stage can be reduced.

The losses of the input, interstage and output matching network are respectively 1.0 dB, 1.5 dB and 1.5 dB, not counting the extra loss of the stability network. Monte Carlo simulations have been performed to guarantee the performance of these networks over a wide spreading range for the passive components.

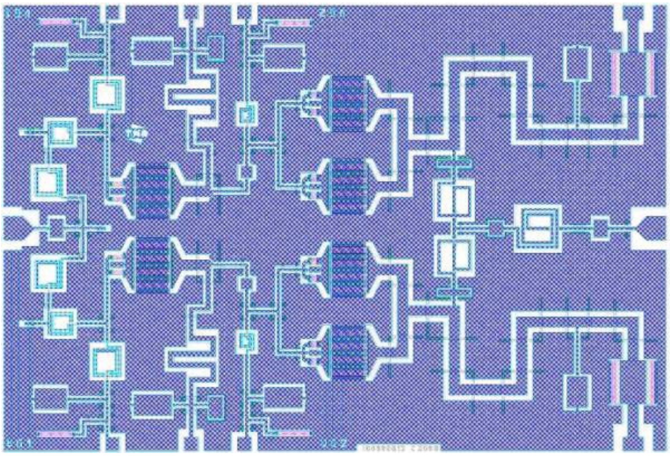

Fig. 4 Layout of the 2-stage S-band HPA MMIC (5.0 mm x 3.3 mm).

V. Simulation Results

Currently the design is in processing and only simulation results can be shown. The large signal power sweep is shown in Fig. 5. The saturated output power is 45.8 dBm with 37 % PAE at 4 dB gain compression and 26 V drain bias. The overall gain is around 20 dB, which seems to be low compared to the gain of a single device. This is mainly caused by the fact that large safety margins have been used in the design of the stability network, to cope with large process spreading. Once the processing technology has been stabilized, a redesign can be made with more gain.

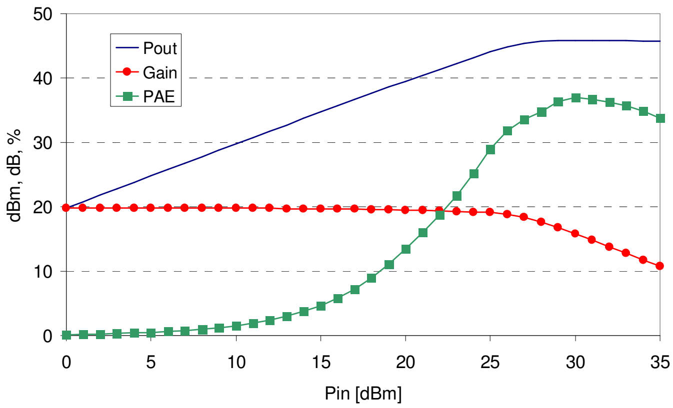

Fig. 5 Simulated output power, gain and power added efficiency at 3.1 GHz.

The large signal performance versus frequency is shown in Fig. 6, for a fixed input power level of 27 dBm. It can be seen that the HPA delivers at least 43 dBm output power over a wide frequency range from 2.5 to 3.7 GHz.

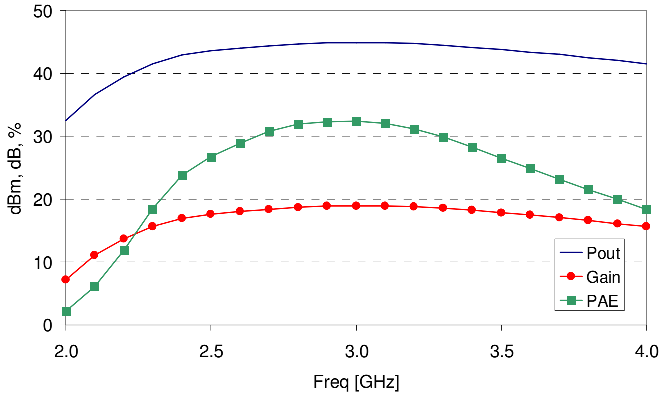

Fig. 6 Simulated output power, gain and power added efficiency at 27 dBm input power.

Fig. 7 and Fig. 8 show the small signal input and output matching and gain of the MMIC. The matching is better than 10 dB from 2.6 to 4.3 GHz. The extra gain peak around 1.5 GHz is not intentionally, but appears because the input is matched at this frequency and because of the large gain of the single devices. It has been verified that this peak does not cause any stability problems.

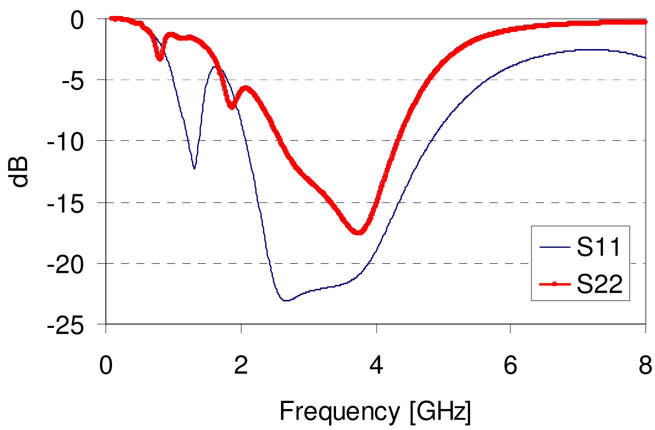

Fig. 7 Simulated small signal input and output matching.

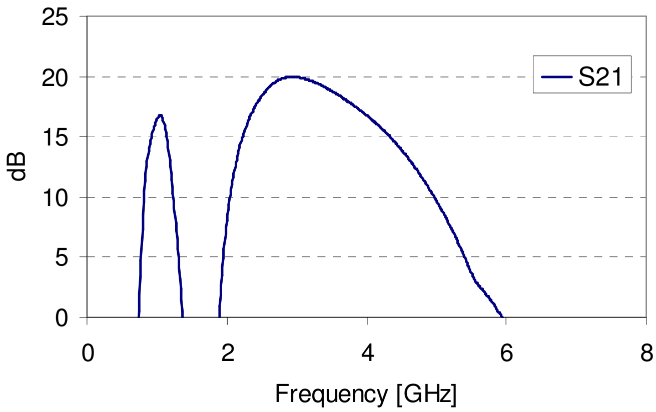

Fig. 8 Simulated small signal gain.

Also the behaviour of the amplifier at high output VSWR ratios has been checked. This has been simulated in the middle of the frequency band at 3.1 GHz with a source power of 26 dBm. The output load has been swept from a VSWR value of 1.0 to 4.0 for all load angles. The result is shown in Fig. 9 and it can be seen that the output power drops to around 41 dBm for a VSWR of 4.0. Fig. 10 shows the maximum drain-gate voltage for this same simulation. Even at the very high VSWR value of 4.0, the maximum voltage is only around 60 V, which is still below the expected breakdown voltage of this process.

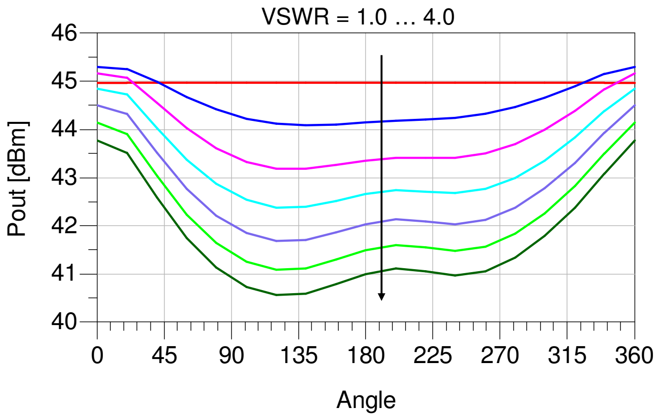

Fig. 9 Simulated output power at 3.1 GHz and 26 dBm source power for an output VSWR from 1.0 to 4.0 in steps of 0.5.

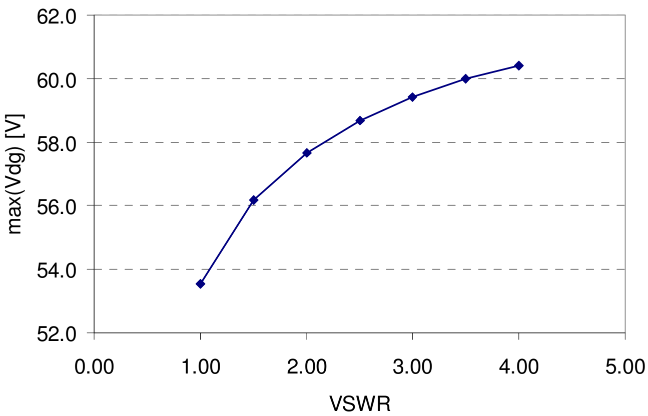

Fig. 10 Simulated maximum drain-gate voltage of the output FETs.

Finally, thermal simulations have been performed to check the maximum junction temperature. In the simulation the MMIC has been soldered on a CuMo carrier. A very pessimistic thermal conductivity of 330 W/m/K has been used for the SiC substrate. The result is a maximum temperature of 210°C, at a worst case base plate temperature of 80°C, assuming a constant DC dissipation of 8 Watt per FET. Using a more optimistic thermal conductivity of 490 W/m/K the maximum temperature is 180°C, also at a base plate temperature of 80°C. These simulations assume CW input power, while the amplifier is intended for pulsed operation only.

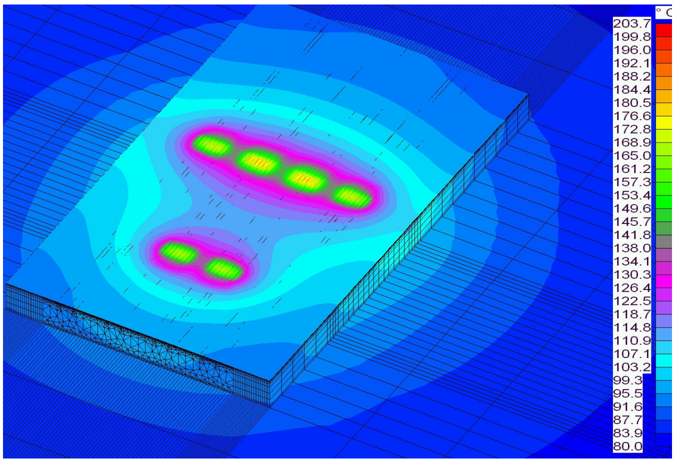

Fig. 11 Thermal simulation at 80°C base plate temperature.

VI. Conclusions

The design and simulation results of an S-band HPA MMIC in AlGaN/GaN technology have been presented. First the trade-offs between using an MMIC or discrete power device have been discussed. The final choice for a discrete power device or an HPA MMIC will be determined by system considerations. For applications where size and weight are important, such as airborne radars, GaN HPA MMICs will become the preferred solution.

The MMIC shows a maximum output power of 38 Watt at 37% Power Added Efficiency at 3.1 GHz. An output power of more than 20 Watt has been simulated from 2.5 to 3.7 GHz. No breakdown is expected for high output VSWR values up to 4:1.

Acknowledgment

This work has been support by Thales Nederland BV and the Dutch Ministry of Economic Affairs.

References

[1] U.K. Mishra, L. Shen, T.E. Kazior, and Y.-F. Wu, "GaN-Based RF Power Devices and Amplifiers", Proc. of the IEEE, vol. 96, no. 2, pp. 287-305, Feb. 2008.

[2] M. Rudolph, R. Behtash, R. Doerner, K. Hirche, J. Würfl, W. Heinrich, and G. Tränkle, "Analysis of the Survivability of GaN Low-Noise Amplifiers", IEEE Trans. Microwave Theory Tech., vol. 55, no. 1, 37-43, Jan 2007.

[3] G. van der Bent, M. van Wanum, A.P. de Hek, M.W. van der Graaf and F.E. van Vliet, "Protection Circuit for High Power Amplifiers Operating Under Mismatch Conditions", Proc. 2nd European Microwave Integrated Circuits Conference, pp. 158-161, Munchen, Oct. 2007.

[4] E. Mitani, M. Aojima, and S. Sano, "A kW-class AlGaN/GaN HEMT Pallet Amplifier for S-band High Power Applications", Proc. 2007 European Microwave Int. Circuits. Conf, EuMIC2007, pp. 176-179.

[5] M. E. Russell, "Future of RF Technology and Radars", IEEE Radar Conference 2007, pp.11- 16.

[6] J.W. Milligan, S. Sheppard, W. Pribble, Y.-F. Wu, St.G. Muller, and J.W. Palmour, "SiC and GaN Wide Bandgap Device Technology Overview", IEEE Radar Conference 2007, pp.960-964.

[7] R. Lossy A. Liero, J. Würfl, G. Tränkle, "High power, high gain AlGaN/GaN HEMTs with novel power bar design", IEDM 2005, Technical digest, pp. 589-591.