MESFET High-Power High-Efficiency MMIC Amplifiers at X-band with 30% Bandwidth

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Abstract

A 3-Watt and a 5-Watt high-efficiency high-power amplifier are presented. The amplifiers are manufactured in a GaAs MESFET process. The 3-Watt amplifier exhibits 4 Watt output power at 10.6 GHz with an associated PAE of 43% and more than 3 Watt output power with more than 30% PAE from 8 GHz to 11.3 GHz. The 5-Watt amplifier exhibits 7W output power at 8.8 GHz with an associated PAE of 40% and more than 5 Watt output power with more than 30% PAE from 7.8 GHz to 10.6 GHz.

Introduction

The high-power amplifiers (HPA) presented in this paper are developed within the scope of the WEAG/TA1/CTP8.1 programme. This programme was carried out by a consortium consisting of Siemens, Dassault Electronique, Fraunhofer-IAF and TNO-FEL. The goal of the 3-Watt and 5-Watt amplifiers described below was to demonstrate the feasibility of *wideband* (>30% bandwidth) high-power amplifiers at X-band with the *best obtainable* power added-efficiency (PAE) in a pulsed mode of operation *and* in a CW mode of operation and manufactured in a *reliable*, *cost-effective* and *mature* technology. These amplifiers are intended to be used in transmit-receive modules (TR modules) for wideband active phased-array applications. Especially to contribute in such systems to a significant reduction of the required prime power.

Technology and manufacturing

The 3-Watt HPA and the 5-Watt HPA are manufactured in the Siemens DIOM20HP process. This process consists of 0.5 μm MESFETs, a self-aligned gate technology, localised ion implantation, MIM capacitors, via holes and air bridges. This technology assures a very good reproducibility, high reliability and low manufacturing costs [1].

Circuit Design

The starting points for the design of the 3-Watt HPA and for the 5-Watt HPA are described below.

Two-stage single-ended amplifiers are envisaged to obtain sufficient gain and hence to reduce output power and DC power consumption of the necessary driver amplifier in a TR module application. MESFETs with a reduced drain-source spacing, but well within the maximum tolerable temperature limits, are used to minimise amplifier size. The output matching of the transistors is based on measured load-pull data. The load-pull data is obtained with an in-house developed unique high-power on-wafer active load-pull system that is capable of providing load impedances with reflection coefficients up to 1, see Figure 1. Multiple-order input, interstage and output matching networks are used in order to obtain the required bandwidth. Slope compensation networks are included to obtain optimum efficiency over the full bandwidth and to reduce gate currents when the amplifiers are in compression.

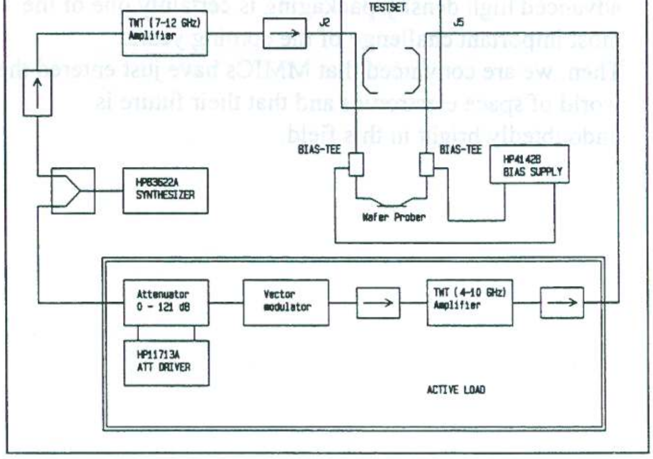

Figure 1 Block diagram TNO-FEL high-power measurement set-up

Careful attention is paid to make the amplifiers stable. Stability analysis is carried out for all odd and even modes using open-loop transfer function techniques [2].

All passive networks are also simulated with an EM-field simulator to take into account distributed effects, discontinuities and coupling effects. EM field simulations turned out to be necessary to obtain an accurate match over the 30% frequency bandwidth between the desired optimum load impedance and the realised load impedance for both amplifier stages.

Amplifier design is carried out with HP-EEsof software using the EEFET3 transistor models. Parameter extraction for this model is optimised to obtain a good agreement over the required bandwidth between model predictions and measured transistor performance under high power conditions and simultaneously under optimum load conditions [3].

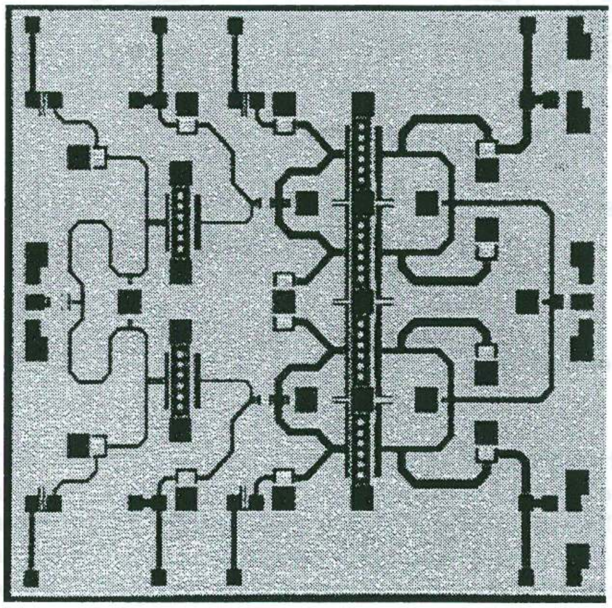

Figure 2 Chip photograph of the manufactured 3-Watt HPA, chip size equals 9 mm².

MMIC performance

Chip photographs of the realised 3-Watt HPA and 5-Watt HPA are shown in Figure 2 and in Figure 3 respectively. The amplifier chips have been die attached with solder on a Copper Molybdenum carrier. This carrier provides a good heat sink; the thermal expansion coefficient of this carrier material corresponds well with the thermal expansion coefficient of GaAs. The samples are on-chip tested with the high-power on-wafer measurement set-up with controllable baseplate temperature that is available at TNO-FEL.

The capabilities of this set up include pulsed and CW error corrected measurement of: S-parameters, power levels up to 5 Watt, large-signal transducer gains and large signal input impedances. As a result of the error-corrections, the PAE can be accurately calculated

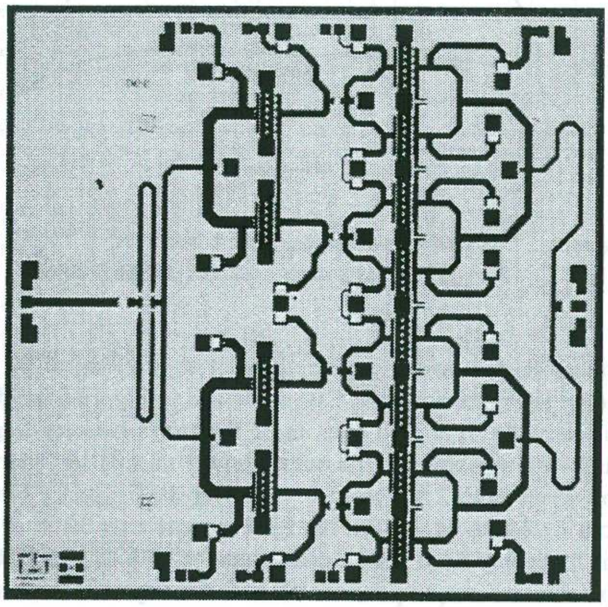

Figure 3 Chip photograph of the manufactured 5-Watt HPA, chip size equals 22 mm².

The performed test included a full characterisation of the samples. The characterisation consisted of S-parameter measurements and the following large-signal measurements: output power, transducer gain and PAE. All test are performed under CW and under pulsed conditions. Baseplate temperatures were varied form 25°C to 50°C.

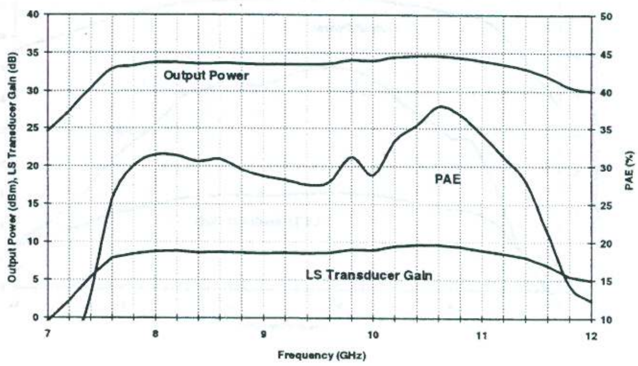

Figure 4 CW power performance of the 3-Watt HPA, @ T=50°C, Pin=25dBm, Vd=9V

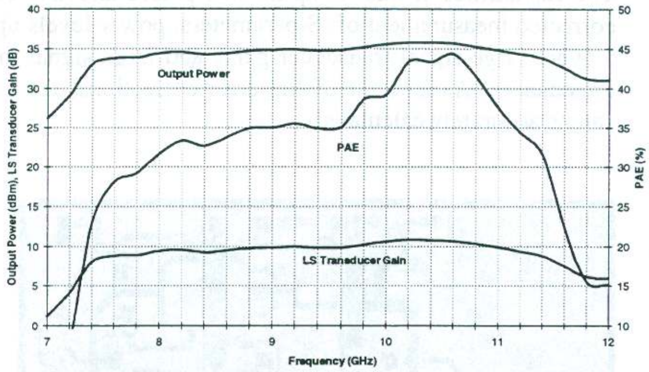

Figure 5 Pulsed power performance of the 3-Watt HPA, @ T=25°C, PRF=10 kHz, pulse width=10μs, Pin=25dBm, Vd=9V

The measured power performance of the 3-Watt HPA is shown in Figure 4 for the CW mode and in Figure 5 for the pulsed mode. It is seen from these figures that a very large bandwidth is obtained; the output power in a pulsed operation varies from 2.8 Watt to 4 Watt over the frequency band from 8 GHz to 11.3 GHz, the PAE is more than 30 % over this frequency band with a peak value of 43% at 10.6 GHz. The obtained output power is close to the expected theoretical maximum for the used technology and FET sizes.

The measured power performance of the 5-Watt HPA is shown in Figure 6 for the CW mode and in Figure 7 for the pulsed mode. It is seen from these figures that more than 5 Watt output power and more than 30% PAE is obtained. At 8.8 GHz the 5-Watt HPA exhibits 7W with 40% PAE. These results are in good agreement with the simulations and are believed to be the best obtainable results for this GaAs process and the chosen amplifier topology.

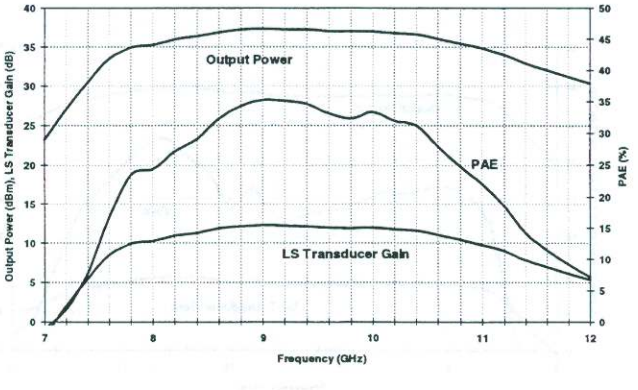

Figure 6 CW performance of the 5-Watt HPA, @T=50°C, Pin=25dBm,Vd=9.7V

The temperatures given in Figure 6 Figure 7 are the observed temperatures of the baseplate for the reported measurements. In other words, when changing the operation mode from pulsed to CW the baseplate heats up from 25°C to 50°C for the 5-Watt HPA. The difference in temperature between the CW and the pulsed measurement results can be completely explained by the difference in ambient temperature and the difference in dissipated power.

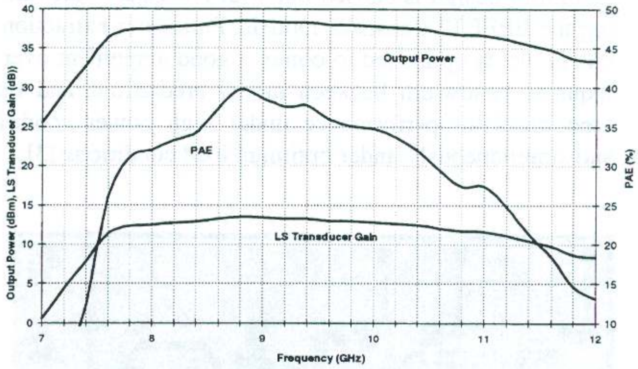

Figure 7 Pulsed power performance of the 5-Watt HPA, @ T=25°C, PRF=10 kHz, pulse width=10μs, Pin=25dBm, Vd=9.7V

Conclusions

The main results of the 3-Watt HPA and of the 5-Watt HPA are summarised in Table 1 and in Table 2 below. A 3-Watt HPA and a 5-Watt HPA with more than 30% PAE and more than 30% bandwidth in a pulsed mode at 25°C are demonstrated in a cost-effective mature and robust MESFET process.

The same amplifiers exhibit more than 20% bandwidth at X-band in a CW mode of operation at a baseplate temperature of 50°C.

The CW performance tends to converge to the pulsed performance when the baseplate temperatures are forced to be the same in both modes of operation.

The amplifiers are stable with respect to microwave oscillations, parametric oscillations and bias oscillations (through off-chip by-pass capacitors).

The size of the amplifiers is reasonable with respect to manufacturing.

Table 1 Summary of the pulsed performance of the 3-Watt HPA, pulse width=10µs, PRF=10 kHz, Pin=25dBm

	Pulsed (@25 °C)	CW (@50 °C)
Frequency (GHz)	8.0 - 11.3	7.8 - 11.3
Output Power (W)	2.8 - 4.0	2.0 - 2.9
PAE (%)	30 - 43	28 - 38
LS Gain (dB)	9.3 - 11.1	7.8 - 9.6
Size (mm^2)	9	9
Bias	9 V	9 V

These results are considered to be a state-of-the-art competitive performance with respect to published HFET (ref. [4]: 5-Watt, 35% PAE, 13 dB gain, 8-10.5 GHz) and HBT (ref. [5]: 5-7W, 44% PAE, 11-14 dB gain, 7-11 GHz) similar wide-band MMIC high-power amplifiers.

As a result it can be concluded that a 5-Watt MESFET HPA is developed which complies with all requirements in pulsed and in CW operation for application in wideband active phased-array antennas.

Table 2 Summary of the performance of the 5-Watt HPA, pulse width=10µs, PRF=10 kHz, Pin=25dBm

	Pulsed (@25 °C)	CW (@ 50° C)
Frequency (GHz)	7.8 - 10.6	8.4 - 10.4
Output Power (W)	5.0 - 7.1	4.3 - 5.4
PAE (%)	30 - 40	30 - 35
LS Gain (dB)	12.0 - 13.5	11.3 - 12.3
Size (mm^2)	22	22
Bias	9.7 V	9.7 V

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References

[1] K.J. Schöpf, E. Pettenpaul, *“MMICs for Phased Array Radar Systems”*, COST 245 Workshop on Applications of MMICs in Active Antenna Systems (sponsored by EC-DG13), 11-13 October 1995, Friedrichshafen, Germany.

[2] M. Ohtomo, "Stability Analysis and Numerical Simulation of Multidevice Amplifiers", IEEE Trans. Microwave Theory and Tech., Vol. 41, No 6/7, June/July 1993, p.p. 983 -991.

[3] J. Verduyn, A.P. de Hek, "Experimental Verification of Microwave Large-Signal MESFET models under High Power and Optimum load Conditions at the Fundamental Frequency", 2nd IEEE joint European chapter workshop on " CAE Modelling and Measurement Verification", 1994.

[4] C. Suckling et.al., “High Linearity and Efficiency Power Amplifiers using GaAs Heterostructure FETs”, Microwave Journal, April 1995, p.p. 256-262.

[5] J.J. Komiak, L.W. Yang, “5 Watt High Efficiency Wideband 7 to 11 GHz HBT MMIC Power Amplifier”, IEEE 1995 Microwave and Millimeter-wave monolithic Symposium, p.p. 17-20.