Robust AlGaN/GaN Low Noise Amplifier MMICs for C-, Ku- and Ka-band Space Applications

E.M. Suijker[1], M. Rodenburg[1], J.A. Hoogland[1], M. van Heijningen[1], M. Seelmann-Eggebert[2], R. Quay[2], P. Brückner[2], F.E. van Vliet[1]

[1]*TNO Defence, Security and Safety*
Oude Waalsdorperweg 63, 2597 AK, Den Haag, The Netherlands
`Erwin.Suijker@tno.nl, Tel. +31(0)70 3740498, Fax. +31(0)70 3740653`

[2]*Fraunhofer Institute of Applied Solid State Physics*
Tullastraße 72, 79108 Freiburg, Germany

***Abstract*—The high power capabilities in combination with the low noise performance of Gallium Nitride (GaN) makes this technology an excellent choice for robust receivers. This paper presents the design and measured results of three different LNAs, which operate in C-, Ku-, and Ka-band. The designs are realized in 0.25 µm and 0.15 µm AlGaN/GaN microstrip technology. The measured noise figure is 1.2, 1.9 and 4.0 dB for the C-, Ku-, and Ka-frequency band respectively. The robustness of the LNAs have been tested by applying CW source power levels of 42 dBm, 42 dBm and 28 dBm for the C-band, Ku-band and Ka-band LNA respectively. No degradation in performance has been observed.**

I. INTRODUCTION

Due to the current trends in the global security scenario the interest in secure and robust satellite communication systems is increasing. A space-born receiver is one of the most important, but also one of the most sensitive components in the satellite communication chain. These receivers must also be functional during severe jamming and no degradation is allowed due to high input powers from hostile electromagnetic attacks.

Currently enabling technologies like GaN and SiC are being developed for both military as well as governmental and commercial applications. GaN is expected to improve the performance regarding robustness together with microwave capabilities comparable to currently used technologies like GaAs, InP and Si. Due to the combination of high power and low noise operation GaN is very suitable for the realization of secure robust RF front-end (RFFE) modules. In addition, the overdrive capability and survivability levels are exceptionally high. The development of both GaN HEMTs as well as MMIC processes makes it possible to realize GaN low noise receivers at millimeter wave frequencies. Such receivers are very attractive for secure communication systems due to the changing trade-off between performance and cost. Therefore GaN based receivers offer important potential for next generation satellite communication systems.

This work aims at technology demonstrations at C-, Ku- and Ka-band by designing, building and testing GaN low noise amplifier MMICs, as part of the receiver front-end. Section II describes the RFFE and improvement in robustness by using GaN components. Section III describes the AlGaN/GaN technology used for the MMICs. A detailed description of the design of the three LNAs for each frequency band is given in section IV. Section V shows the small signal as well as the large signal measurement results. Finally conclusions are given regarding the low noise performance and survivability levels.

II. ROBUST RECEIVERS

The advantages of GaN enable the improvement of the receiver performance. The high power capabilities allow the receiver to handle high input power levels without any degradation in RF performance. The combination of high power and low noise allows optimizing the trade-off between NF and IP3. Figure 1 shows a simplified block diagram of a RFFE receiver. As can be seen in the figure the proposed front-end modules based on GaN MMICs do not include a separate limiter, which improves the overall noise figure.

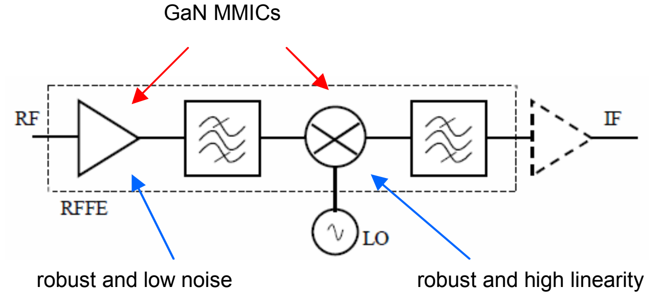

Fig 1. Simplified block diagram of a RFFE receiver.

The survivability capability of GaN LNAs has already been proven by others [1]-[7]. State-of-the-art performance for the input power capability is 37 dBm for CW mode and 41 dBm in pulse mode. For this work, the target performance for survivability of the C-band RFFE is 40 dBm CW power and 37 dBm CW power for the Ku- and Ka-band RFFE.

978-1-4244-5191-3/09/$26.00 ©2009 IEEE

III. ALGAN/GAN PROCESSING TECHNOLOGY AND MODELLING

The LNA MMICs have been processed in the AlGaN/GaN microstrip transmission line technology of Fraunhofer IAF. The C- and Ku-band designs have used 0.25 µm gate length and the Ka-band design 0.15 µm gate length.

A. AlGaN/GaN HEMT MMIC Technology description

AlGaN/GaN single heterostructures are grown on s.i. SiC by MOCVD in a 12×3-inch multi-wafer reactor. Three-inch wafers are processed for a combined 0.25 and 0.15 µm gate length HEMT technology. The gate modules comprise optimized field plates by which the two-terminal breakdown voltages of the produced power HEMTs are increased above ≥100 V. The MMIC technology yields a transit frequency f_T of 33 GHz and 50 GHz at V_{DS}= 28 V for gate lengths of 0.25 µm and 0.15 µm respectively.

Covering transistors from 21 wafer cells, a load-pull power mapping is routinely performed at V_{DS}= 28 V in CW-mode for a device with a gate width of 0.48 mm. Robustness, yield and power performance are assessed as part of a reproducibility check. An average high-gain performance is achieved with ≥15 dB linear gain at 10 GHz with a yield of about 90%.

After the front side processing the full three-inch s.i. SiC wafer is thinned to 100 µm thickness and the backside is processed for via-hole formation, in particular for contacting the source electrodes.

B. Device and MMIC Modeling

A large data base was established by measurement of noise- and S-parameter measurements in the frequency range from 2 to 26 GHz for drain voltages from 5 V to 15 V and drain current densities from 100 mA/mm to 200 mA/mm for several transistor geometries. From this data base compact small signal models were built comprising noise sources with bias dependent noise temperatures. Large-signal performance can be assessed by a two-dimensional voltage-lag model to accurately describe thermal effects and low-frequency dispersion. For the MMIC design a library of passive microstrip components is available, including all technology specific elements like MIM capacitors, resistors, and inductors.

IV. LNA DESIGNS

The C-band LNA is a three stage amplifier. All three stages use a 8x60 µm transistor with 0.25 µm gate length. The large FET generates sufficient gain at C-band and the larger gate length and gate periphery will improve the robustness of the amplifier. All three stages are biased at 10 V drain-source voltage and a drain current density of 150 mA/mm, which is about 15% of Idss. The matching of each stage is optimized for noise to improve the overall noise figure and still fulfill the gain specification. A photograph of the C-band LNA is depicted in figure 2.

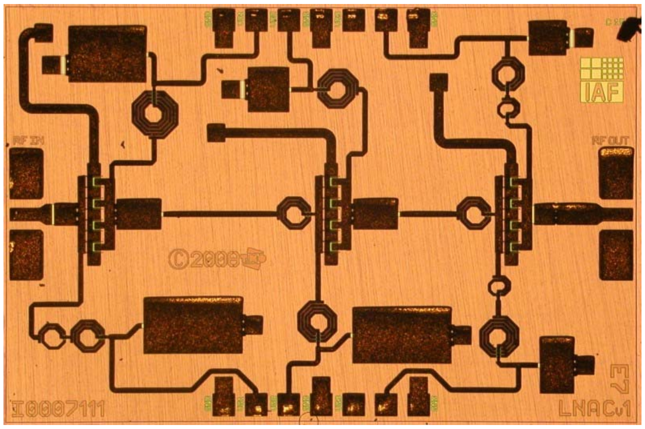

Fig. 2 Microscope photograph of the C-band LNA.

The Ku-band LNA is a three stage amplifier as well. The gate length of each stage is 0.25 µm, which provides sufficient gain at 14 GHz and improves the robustness of the LNA. The first two stages use a 2x50 µm transistor the get sufficient gain. The last stage is a 8x60 µm transistor to achieve an output power higher than 20 dBm at P_{1dB}. The first stage is matched for optimum noise figure and for the last two stages the matching is a compromise between gain and noise. All three stages are biased at 10 V drain voltage and 150 mA/mm drain current density. Figure 3 depicts a photograph of the Ku-band LNA.

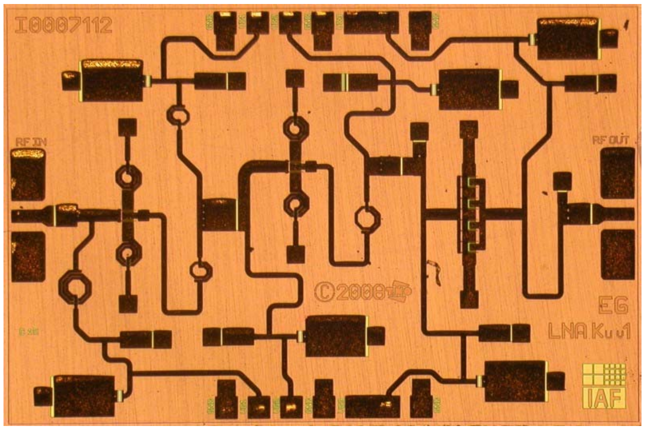

Fig. 3 Microscope photograph of the Ku-band LNA.

At Ka-band frequencies four stages are required to achieve an overall gain higher than 19 dB. The gate length of the used transistors is 0.15 µm to increase the gain at these high frequencies. The gate periphery is 2x50 µm and is equal for all four stages. All stages are biased at V_{DS}= 10 V and a drain current density of 200 mA/mm. The higher current results in more gain without sacrificing the noise performance. All stages are matched for optimum noise figure. A photograph of the Ka-band LNA is depicted in figure 4.

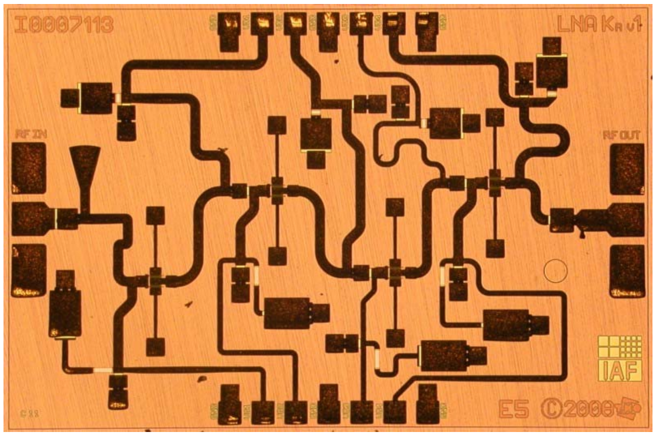

Fig. 4 Microscope photograph of the Ka-band LNA.

For each frequency band the performance of the LNA will be demonstrated within an RF frontend (RFFE) module. To reduce the complexity of fabrication of each module the dimensions of the MMIC LNAs are made equal and are 3x2 mm^2.

V. MEASUREMENT RESULTS

Measurements on the three LNA versions are performed and compared to the simulated results. First the complete wafer was measured (21 MMIC's for each LNA version) to determine the known good dies. Five of the known good dies have been mounted on a CuMo carrier, which works as a heat sink. Besides the mounted samples two bare dies of each LNA version have been characterized for mounting in the RFFE module. To stabilize the LNAs, the gate connections are decoupled with 10 pF low pass networks. For each LNA version, the following measurements are performed: S-parameters, noise figure, output power compression, third order intermodulation and electrical stress. Table 1 lists a summary of all measured parameters.

Table 1: Specifications of all three LNAs

	C-band		Ku-band		Ka-band	
Parameter	Sim	Meas	Sim	Meas	Sim	Meas
Freq [GHz]	6	6	14	14	27.5-28.5	28
NF [dB]	1.0	1.2	1.7	1.9	<2.7	4.0
Gain [dB]	23.3	>21	19.7	>19.8	21.9	18
P1dB [dBm]	25	>28	24	>28	-	>12.5
RL_{IN} [dB]	-15	<-11.5	-10.7	<-6	-11.2	-12
RL_{OUT} [dB]	-23	<-12	-18.2	<-13	-9.6	<-6.5

Based on functional S-parameters the overall yield of the C-band LNA is 86%. The S_{21} is higher than 18.8 dB and the nominal value is 21.8 dB. The noise figure is better than 1.6 dB and the nominal NF is 1.2 dB at 6 GHz. The output power at the 1 dB compression level is higher than 28 dBm, which is even higher than simulated. The noise figure and small-signal gain are depicted in figure 5.

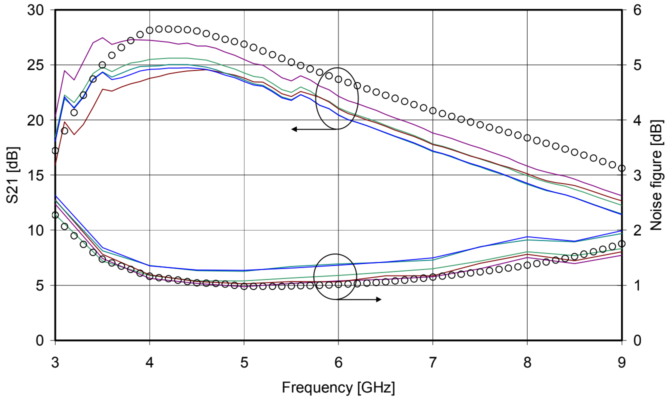

Fig. 5 Measured S_{21} and noise figure of the C-band LNA. The circles represent the simulations.

The yield of the Ku-band LNA is 100% based on functional S-parameters. The noise figure and small-signal gain of the mounted samples are depicted in figure 6. The measured noise figure varies from 1.9 dB to 2.4 dB and the gain varies from 21 to 27 dB. The output power at 1 dB compression is higher than 28 dBm at 14 GHz.

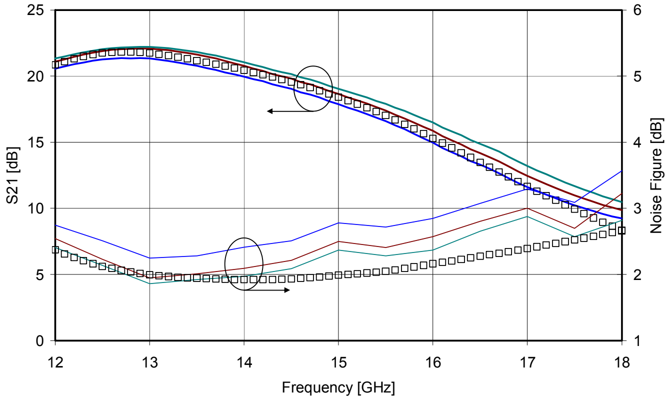

Fig. 6 Measured S_{21} and noise figure of the Ku-band LNA. The squares represent the simulations.

The measured S-parameters of the Ka-band LNA show the least variation of the three designs. One sample shows an unexpected behavior for the output return loss, which results in an overall yield of 95%. The gain at 28 GHz varies over all samples from 18.9 to 22.5 dB. The noise figure varies between 4 and 5 dB, which is quite high compared to the simulation. New extracted noise models of the transistors have different optimum noise impedance and simulations with these models predict a noise figure of 4 dB. The noise figure and small-signal gain are depicted in figure 7. The output power at the 1 dB compression level is 12.5 dBm. To improve the compression behavior the last stage will be biased at higher V_{DS}.

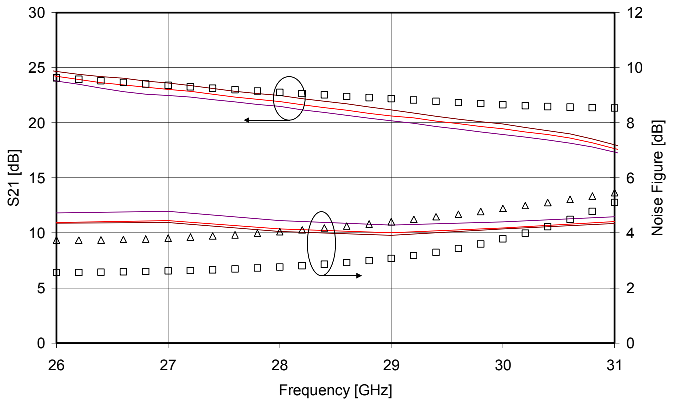

Fig. 7 Measured S_{21} and noise figure of the Ka-band LNA. The squares represent the simulations. Triangles represent a noise figure simulation with updated noise model.

The survivability performance of each LNA has been measured by monitoring gate currents, drain currents, output power and gain as a function of source power. The gate current can be limited by using a series resistor in the gate bias network. The resistor and gate current result in a voltage drop and decrease the gate bias voltage. Therefore the device is pinched-off and the output power drops at high input power levels, see figure 8.

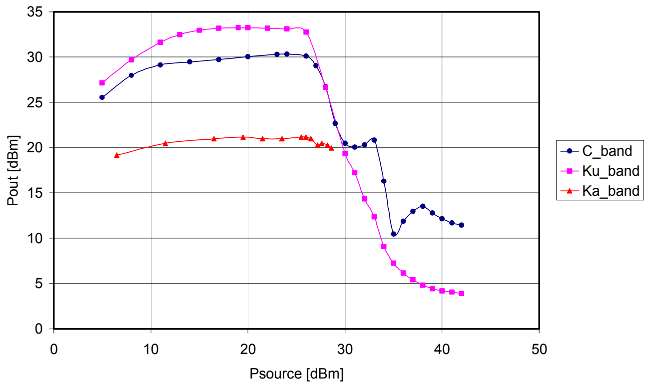

Fig. 8 Output power versus source power for each LNA versions.

Figure 9 shows the small-signal gain measured before and after the devices have been stressed with high input power levels. As can be seen no degradation in gain can be observed. The noise figure measured after the devices have been stressed is 1.1, 2.3 and 4.8 dB for the C-, Ku- and Ka-band LNA respectively. This means a variation of 0.1, 0.3 and 0.1 dB in noise figure for these selected devices. This variation is within the noise figure measurement uncertainty and also partly caused by the use of different measurement equipment. The C-band and Ku-band LNA can survive source power levels of 42 dBm without degradation in gain or noise figure. The survivability of the Ka-band LNA has been tested up to 28 dBm, which is limited by the capabilities of the measurement equipment.

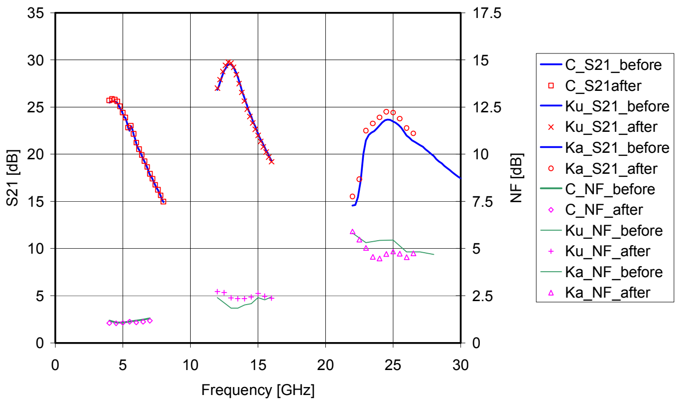

Fig. 9 Small-signal gain and noise figure of each LNA measured before and after the devices have been stressed with high source powers.

VI. CONCLUSIONS

Three LNA GaN MMICs have been designed, realized and measured. With a yield around 90% it is demonstrated that sub quarter-micron GaN MMIC technology is increasingly mature. The nominal noise figure is 1.2, 1.9 and 4.0 dB for the C-, Ku- and Ka-band respectively. Due to the absence of a limiter GaN will be an excellent choice for low-noise receivers. The noise figure of the C-band and Ka-band LNA are state-of-the-art results. The robustness for receiver applications is demonstrated by applying CW source powers of 42 dBm, 42 dBm and 28 dBm for the C-, Ku- and Ka-band LNA respectively without degradation in small-signal gain or noise figure. The survivability figures are also state-of-the-art results.

ACKNOWLEDGMENT

This work has been supported by European Space Agency project "GaN Technology for Robust Communication Receivers" (ITT-5322). The research program is executed in co-operation with Thales Alenia Space in Toulouse, France, United Monolithic Semiconductors in Ulm, Germany and Fraunhofer Institute of Applied Solid State Physics in Freiburg, Germany.

REFERENCES

[1] D. Krausse, et al., "Robust GaN HEMT Low-Noise Amplifier MMICs for X-band Applications", 12th GAAS Symposium – Amsterdam, 2004.
[2] S. Cha, et. al, "Wideband AlGaN/GaN HEMT Low Noise Amplifier For Highly Survivable Receiver Electronics", IEEE MTT-S Digest 2004.
[3] J.C. deJaeger, et al., "Noise Assessment on AlGaN/GaN HEMTs on Si or SiC substrates:Application to X-band Low Noise Amplifiers", 13th GAAS Symposium – Paris, 2005.
[4] M. Rudolph, et al., "Analysis of the survivability of GaN Low-noise Amplifiers", IEEE Trans on Microwaves Theory and Techniques, vol. 55, January 2007.
[5] M. Micovic, et al., "Robust Broadband (4-16GHz) GaN MMIC LNA", CSICS 2007.
[6] J.P.B. Janssen, et al., "X-band AlGaN/GaN MMICs with over 41 dBm Power Handling", CSICS 2008.
[7] M. Rudolph, et al., "Highly Rugged 30 GHz GaN Low-Noise Amplifiers", IEEE Microw. Wireless Compon. Lett., vol. 19, no. 4, Apr. 2009.