Robust Ku-Band Low-Noise Amplifier in GaN HEMT Technology

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***Abstract* — This paper presents a Ku-band low-noise amplifier (LNA) based on 150-nm GaN-on-SiC technology. The 4-stage monolithic microwave integrated circuit (MMIC) LNA is 3 x 1.5 mm^2 in area and it is waveguide packaged. On-wafer measurements show a small-signal gain of 35 dB and noise figure of 1.42 dB over the 13.25 to 13.75 GHz, with an average value below 1.57 dB within the whole Ku-band. Packaged characterization yields a minimum of 1.47 dB with 32.3 dB associated gain at 13.5 GHz for a 720 mW power consumption. Performed large-signal measurements demonstrate an output 1-dB compression point of 12.9 dBm. The LNA is stressed with a RF CW stepped input power up to 31 dBm, for 5 min, with no significant S-parameters and noise figure degradation. The robustness and noise performance of this amplifier make it a very competitive solution for its feasible integration in the next generation satellite communication systems.**

***Keywords* — Gallium nitride (GaN), HEMT, Ku-band, Low-noise amplifiers, Millimeter wave integrated circuits, MMIC, Noise figure, Silicon carbide, mm-wave, robustness.**

I. Introduction

Low noise amplifiers (LNA) are essential for achieving high-performance RF receiver front-ends within several frequency bands in Earth Observation systems, satellite communications and radar imaging. In particular, satellite communications commonly use Ku-band on the downlink to direct broadcast, tracking data applications, or high-resolution radar imaging [1]. It is also important to consider that in traditional Ku-band passive radiometer instruments, undesired signals from transmit signal leakage and Radio-Frequency Interference (RFI) can deteriorate or even damage the LNA. To prevent this, radio frequency protection circuits are implemented in front of it [2]-[5]. However, this solution introduces losses, degrades the noise figure performance and increases the overall dimensions of the front-end unit. To overcome these issues, gallium nitride (GaN) technologies are being employed, as an alternative to gallium arsenide (GaAs) or indium phosphide (InP) LNAs, to achieve full capability integrated devices, with both low noise performance and power handling.

In this context, GaN high electron-mobility transistors (HEMT) monolithic microwave integrated circuit (MMIC) LNAs have shown competitive noise performance in several frequency bands [6]. Moreover, their high-power handling capability in comparison to other HEMT technologies makes them very interesting devices for designing low-noise amplifiers. Furthermore, GaN LNAs have demonstrated higher survivability compared to GaAs and InP technologies, making them highly suitable for receiver front-ends without requiring a limiter at the input [7], [8]. Additionally, the integration of a transmit/receive (T/R) switch, LNA and a power amplifier in a complete front-end module is also possible using the same GaN technology [9]. Several GaN LNAs have been reported for their use as front-end modules within this frequency band and applications, with remarkable power handling and noise figure (NF) [10]-[13]. An extended summary of state-of-the-art Ku-band GaN LNAs is reported in Table 1.

This work presents a Ku-band LNA MMIC based on a 150-nm GaN-on-SiC HEMT technology. The MMIC LNA is also assembled in a waveguide module, shown in Fig. 1. Section II discusses the LNA design, while section III presents the measured results compared to simulations for the MMIC and the packaged LNA. This section also compares the results to the state of the art and finally, section IV describes the conclusions of this paper.

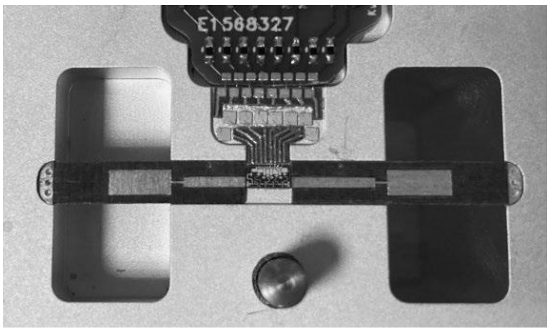

Fig. 1. Ku-band MMIC LNA based on 150 nm GaN technology assembled in a waveguide module. MMIC size: 3.0 mm x 1.5 mm

II. Ku-Band LNA Design

The Ku-band LNA MMIC comprises 4 stages with 150-nm gate length GaN-on-SiC HEMT technology from Fraunhofer IAF (GaN15). The technology uses a conservative metal–

organic chemical vapor deposition grown AlGaN/GaN epitaxial structure. The process typically offers a f_T of 50 GHz, a f_{MAX} above 160 GHz, and a maximum transconductance of 400 mS/mm. The process further includes two metal layers, accurate 50 Ω/sq NiCr thin-film resistors, 250 pF/mm^2 metal–insulator–metal (MIM) capacitors, and via-holes over a substrate thickness of 75 µm.

In order to design the amplifier, several transistor sizes and bias points are analyzed to choose the most suitable ones for the Ku-band. Initially, common source transistors are simulated for the available geometries and current densities. The figures of merit considered in the analysis are the minimum noise figure (NF_{min}), and the maximum gain (MaxGain). Moreover, for the first stage, an analysis of the transistor behavior is performed in terms of optimum reflection coefficient (S_{opt}) for minimum noise, the conjugate input reflection coefficient (S_{11}*) and MaxGain adding source feedback.

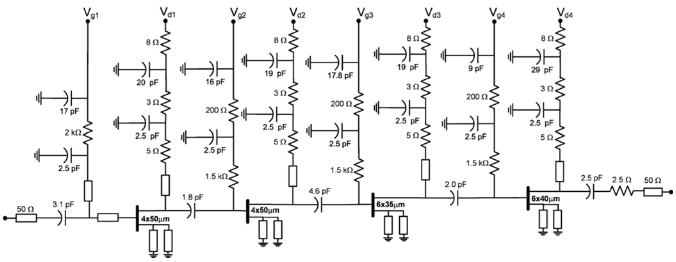

Fig. 2. Simplified schematic of the 4-stages Ku-Band MMIC LNA with GaN HEMTs of 150 nm gate length.

The simplified schematic of the designed LNA with four stages is shown in Fig. 2. The HEMT transistor gate widths are 4x50 µm, 4x50 µm, 6x35 µm, and 6x40 µm for the first, second, third, and fourth stages, respectively. All the stages have symmetric source feedback through two high impedance microstrip transmission lines connected to ground. The first stage is mainly optimized for minimum noise figure, while the second stage is matched partially for noise and the two last stages fully for gain. The source feedback in the first stage provides a closer optimum input reflection coefficient to the conjugate input reflection coefficient to achieve simultaneously minimum noise figure and input matching. Gain flatness and output reflection coefficient are also considered during the design optimization. Moreover, special care is taken during the design phase to ensure stability not only in band but also at all frequencies where the transistor models are defined. The inter-stage networks consist of microstrip transmission lines and MIM capacitors. Bias networks are stubs or resistors capacitively shorted with RF bypass MIM capacitors. Drain and gate bias networks have NiCr resistors. The design is optimized for the frequency range 13.25 to 13.75 GHz.

III. MMIC Characterization

The MMIC LNA is characterized on-wafer for S-parameters and noise figure (NF) performance, in order to compare with the simulations. Moreover, several samples are assembled in a module with waveguide input and output RF interfaces in order to optimize the noise performance versus dc bias as well as to characterize the LNA survivability. S-parameters and NF before and after high input power stress are measured in the module.

A. S-parameters and noise performance

The on-wafer S-parameters and NF compared to simulation results with bias V_D = 8 V and I_D = 110 mA/mm are shown in Fig. 3. The LNA exhibits a small-signal gain between 30 and 35.8 dB over the whole Ku-band, with average NF of 1.57 dB. Within the band of interest (13.25-13.75 GHz) the measured noise is 1.42 dB with an associated gain of 35 dB, input return loss better than 11 dB and output return loss better than 20 dB.

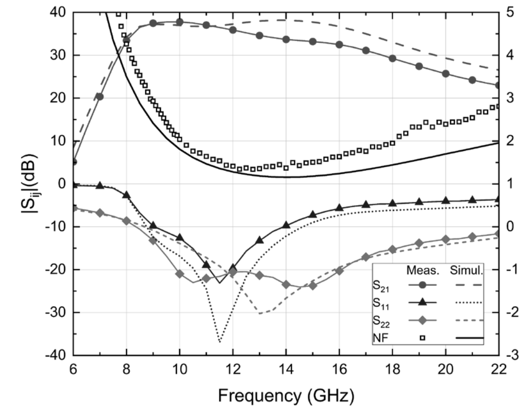

Fig. 3. S-parameters and NF simulations and on-wafer measurements of the 4-stages Ku-Band MMIC LNA. The bias for optimum performance is V_D = 8 V and I_D = 110 mA/mm.

In order to integrate the LNA MMIC, a custom-made module with WR-62 waveguide interfaces is fabricated. The input microstrip-to-WR-62 transition contributes to the LNA's noise figure due to its insertion loss, which is approximately 0.12 dB. A representative unit of the LNA in the module is fully characterized under different bias conditions. Small-signal gain and noise figure at 13.5 GHz versus bias drain-source voltage and drain current density in each LNA transistor are shown in Fig. 4. The ranges of applied drain-source voltage and drain current density are 3 - 8 V and 100 – 160 mA/mm per stage, respectively. The minimum noise figure measured is 1.47 dB with 32.3 dB associated gain for dc bias 6.5 V and 130 mA/mm. For drain voltages above 5.5 V and current densities exceeding 110 mA/mm, the NF remains below 1.53 dB.

B. Large-signal characterization

The large-signal characterization of the LNA is performed at 13.5 GHz, measuring the gain compression and the output power 1-dB compression point (OP_{1dB}) in the waveguide module. A variation in the bias conditions is applied to assess the performance. The results are shown in Fig. 5. The LNA provides an OP_{1dB} of 13.5 dBm for V_D = 5 V and I_D = 150 mA/mm. For a fixed current density, the OP_{1dB} increases whereas the drain voltage increases. Moreover, for a fixed drain voltage (5 V), the higher the current density, the higher the OP_{1dB}.

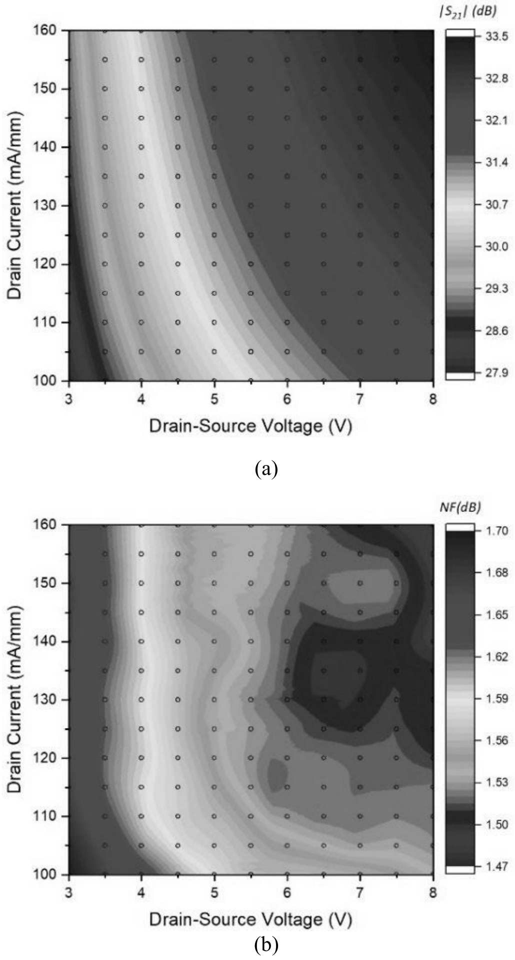

Fig. 4. Contour plots of measured (a) Small-signal gain and (b) Noise figure (NF) versus dc bias (drain-source voltage and drain current density) of the assembled MMIC LNA at 13.5 GHz. The circles denote the bias point where the corresponding S-parameters and NF have been measured.

C. Power handling

The robustness of the LNA is demonstrated by stressing the LNA module using a CW input signal for 5 minutes. A 13.5 GHz CW signal is generated by a signal generator to provide high-level input power. The input and output power levels are monitored through directional couplers and power meters. CW powers ranging from linear regime up to 31 dBm, in 1 dB steps, are applied for 5 minutes each, which corresponds to the maximum available power of the test-bench used. The LNA performance is measured prior and post stress. No significant S-parameters and noise figure degradation is observed as shown in Fig. 6. Further measurements are intended to be made in order to verify the highest input power overdrive level until the LNA degradation.

D. State-of-the-art comparison

A detailed summary of the LNA measured results, assembled on the waveguide chassis, and a comparison to state-of-the-art GaN LNAs at Ku-Band are given in Table 1. To the best of the authors' knowledge, this work demonstrates the lowest noise reported to date for a GaN LNA in this frequency band. Furthermore, this work achieves higher gain than the other designs found on literature with one of the lowest dc power consumptions within Ku-band.

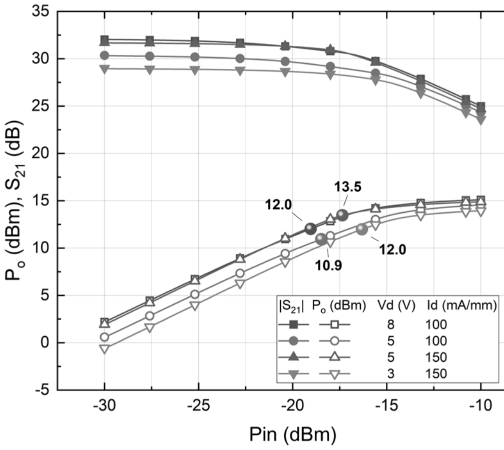

Fig. 5. Output power and gain versus input power of the assembled MMIC LNA at 13.5 GHz for different bias conditions. OP1dB for each bias point is also displayed.

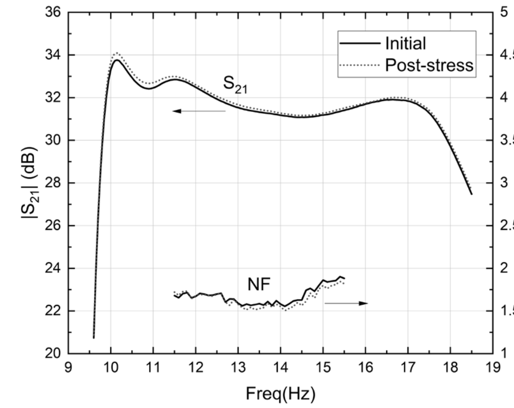

Fig. 6. Gain and noise figure of the module LNA before and after being stressed with a RF CW stepped input power of 31 dBm, for 5 min. DC bias VD = 5 V and ID = 150 mA/mm.

IV. Conclusion

A Ku-band LNA MMIC in 150 nm HEMT GaN technology on SiC substrate is described. The LNA on-wafer exhibits an average noise of 1.57 dB in the whole Ku-band with a small-signal gain between 30 and 35.8 dB. The minimum noise figure is 1.34 dB, with associated gain of 35 dB at 12.25 GHz. The Ku-band LNA exhibits excellent noise performance, both on-wafer and assembled in a module. The assembled LNA over a wide range of dc biasing conditions maintains noise figures below 1.53 dB at 13.5 GHz for V_D from 5 to 8 V and I_D in the range from 110 to 160 mA/mm, respectively. The minimum noise figure measured at 13.5 GHz is 1.47 dB, with associated gain of 32.3 dB and a dc power consumption of 720 mW. Moreover, the assembled LNA withstands 31 dBm CW input overdrive without any damage. Therefore, this robust GaN-based LNA MMIC is especially suitable for radar or radiometer receivers which may be exposed to undesired signals with excessive powers.

Table 1. State-of-the-art GaN HEMT technologies LNA at Ku-band.

Ref.	Techn.	Freq. (GHz)	Gain (dB)	NF (dB)	OP_{1dB} (dBm)	P_{DC} (W)
[9]	Si 100 nm	2-18	18	< 3.5	18	-
[10]	SiC 250 nm	14	>19.8	1.9	28	1.02
[11]	SiC 250 nm	12.8-14.8	20	< 1.85	25	0.84
[12]	SiC 250 nm	12.8-14.8	22	<1.8	>23	0.7
[13]	Si 200 nm	15-16	21.3 22.6	1.7-1.8	27.6-33.3	1.68
[14]	SiC 250 nm	8-15	25	2.8-3.6	26	0.98
[15]	SiC 250 nm	14-18	>18	2.4	-	0.73
[16]	SiC 250 nm	4-18	15.9	2.3-3.7	-	-
This Work	SiC 150 nm	11.5-15.5	32.7	1.6	-	0.72
		13.5	32.3	1.47	12.9	

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