Low-mass high-power GaN amplification hybrids for X-band multi-beam active antennas

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INTRODUCTION

This paper presents a description of the Dual Solid State Power Amplifier (DSSPA) modules developed by Airbus for an X-band multi-beam active antenna as part of the ESA's PACIS3 Partnership Project. The project involves collaboration between satellite operator Hisdesat and the European Space Agency (ESA) and is part of Hisdesat's larger SpainSat NG program, which comprises two new generation satellites based on Airbus' new Eurostar Neo product line. Both satellites are scheduled to be launched by 2024 for secure communication applications.

In the context of this project, UMS has designed and manufactured custom HPA & Driver MMICs on GaN GH25-10 process, and Sener Aeroespacial is responsible for the low-mass hybrids design and production, with support from Electrovac, which manufactures hermetic aluminum packages. This concept offers a lightweight, compact, and high-performance hardware solution that meets industrialization objectives and transmit antenna demands.

GaN SSPAs are replacing classical Travelling Wave Tube Amplifiers (TWTAs) and are a key disruptor for multi-beam active antennas due to the increasing demand for flexible payloads that offer high-capacity capabilities for geostationary telecom satellites [1-8]. GaN technology also benefits thermal management, payload capability, and spacecraft sizing, thanks to its higher drain voltage (30-50V) and higher de-rating junction temperature (160°C) compared to GaAs technology [9]. Furthermore, GaN technology aligns with the industry's mass-production ambitions to reduce cost and on time delivery. Lastly, multi-carrier operation mode simplifies the in-orbit performances prediction with expected high PAPR (10-12dB) operation instead of using complex combined modulations during flight hardware screening.

This paper describes the DSSPA design, performances, and qualification results operating in the X-band downlink (i.e., 7.25-7.75 GHz), in which the power stages have been implemented by using UMS GaN MMICs power amplifiers and finally a planar to waveguide transition to the radiating element of the Tx active antenna, also including DC conditioning circuitry to protect and properly bias the GaN MMICs. The DSSPA qualification review and Lot Acceptance Test (LAT) were declared successful after a thorough test campaign, and the flight manufacturing phase is now running [10], with an expected end date of mid-2023.

In addition to the hybrid & MMIC CTA qualification performed according to ECSS-Q-ST-60-05, an additional qualification campaign specific to the Spainsat mission was performed, including all environments that the DSSPA will see over its lifespan. Furthermore, custom GaN MMICs for both satellites were delivered beginning of 2022 and have been fully qualified since mid-2020, confirming excellent stability of the selected space-evaluated process [11].

HYBRID ARCHITECTURE
General overview

The block diagram of the DSSPA is shown in Figure 1. Each channel has two inputs, with a GPO to microstrip transition, that are combined using a Wilkinson combiner prior to entering the driver (first GaN amplifier). Between driver and HPA there are matching networks, and both amplifiers are at different cavities to avoid oscillations. After the HPA (Second GaN Amplifier) there is an isolator to protect the HPA from reflected or incoming power from the output port, an harmonics filter with minimum losses (not to reduce PAE), a coupler for testing and validation purposes, and finally a planar to waveguide transition. The waveguide is a customized design that matches with the next element of the chain (radiating element). Further details of the MMICs are provided in next subsection.

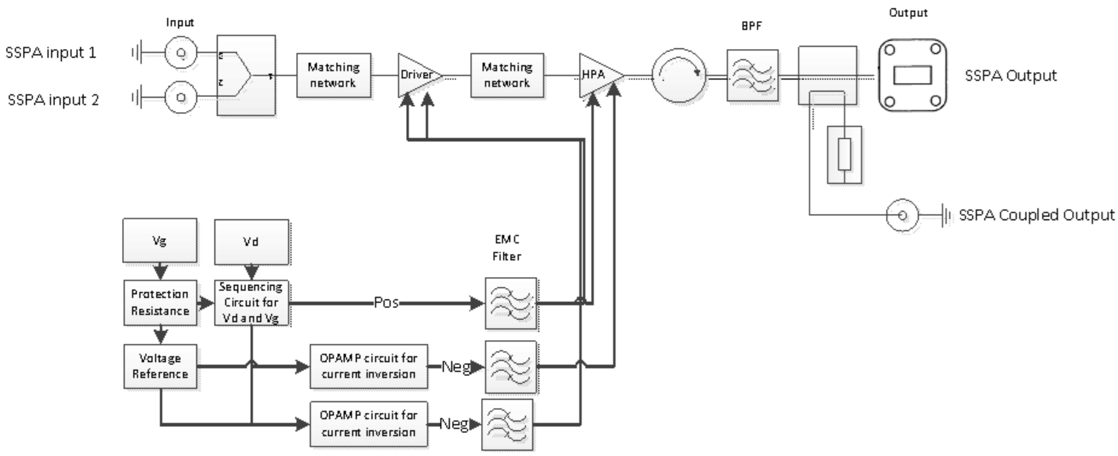


Figure 1 DSSPA block diagram (single path).

From electrical point of view Figure 1 also shows that the gate (Vg) and drain (Vd) voltages in the module are sequenced using a very low Rdson MOSFET for protection purposes minimizing the effects on the PAE, that an operational amplifier is used for gate voltage setting and current inversion of the GaN MMICs in overdrive conditions [7], and the EMC filters, especially the Vd one which is based on capacitors in order to reduce the conducted emissions from the frequency pitch created by a multi-carrier scenario.

From mechanical point of view what is required is a very low mass and low volume equipment since the modules are used in a Tx active antenna with hundreds of elements. For that purpose the technology used is a Microwave Hybrid Integrated Circuit (MHIC) using directly die components inside the module. The material of the package is aluminium to minimize the mass.

From thermal point of view there was a great challenge since the module needs to operate at 85ºC base temperature with physical contact with the heat-pipe. Since the MMICs used are GaN technology there is high margin with derated junction temperature, but the lower the junction temperature, the better the performance in terms of PAE and output power as shown in next subsection. Therefore, the thermal path from the MMIC base temperature to the module base temperature needs to be minimized. For that purpose, and for the first time in an European space mission, very-high silver-doped thermally and electrically conductive adhesive is used to die-attach the MMIC (k=280W/mK) instead of the conventional eutectic soldering (AuSn) of the MMIC (k=80W/mK). A high thermally and electrically conductive stack-up to preserve the CTE difference among materials is used including a specific thermal filler to combine the use of different materials. With all this into consideration, the thermal path from the base of the MHIC to the base of the MMIC is reduced to a delta of 10ºC which is the worst-case scenario in overdrive conditions. Note this stack-up is essential for both mass and heat-transfer, especially the use of aluminium.

From manufacturability point of view, the design has also been optimized for a large production scenario, which is a fundamental requirement in an active antenna.
Finally, and as in any new hybrid and equipment design for space applications, there was the need of qualifying the module according to ECSS-Q-ST-60-05C and to the mission requirements. According to those requirements, a taylored hybrid qualification plan was conceived and executed based on a Circuit Type Approval (CTA) (5 Units), an environmental (ENV) flow (5 units), and a MMIC CTA flow (5 units) due to the use of the very high silver-doped thermally conductive epoxy to die attach the MMIC (see Figure 2). The CTA flow focuses on qualifying the hybrid design with a life test and a final Destructive Part Analysis (DPA) including Residual Gas Analysis (RGA). The ENV flow focuses on qualifying the hybrid for the environment it will see during the mission duration (Vibration, Shock, TVAC, and EMC). During TVAC constant monitoring of the equipment was performed without any glitch appearing in any of the units. Again, the ending of the ENV was a DPA including RGA. The MMIC CTA focuses on qualifying the die attachment method developed for this project, since the MMICs were already qualified as described in the following section.

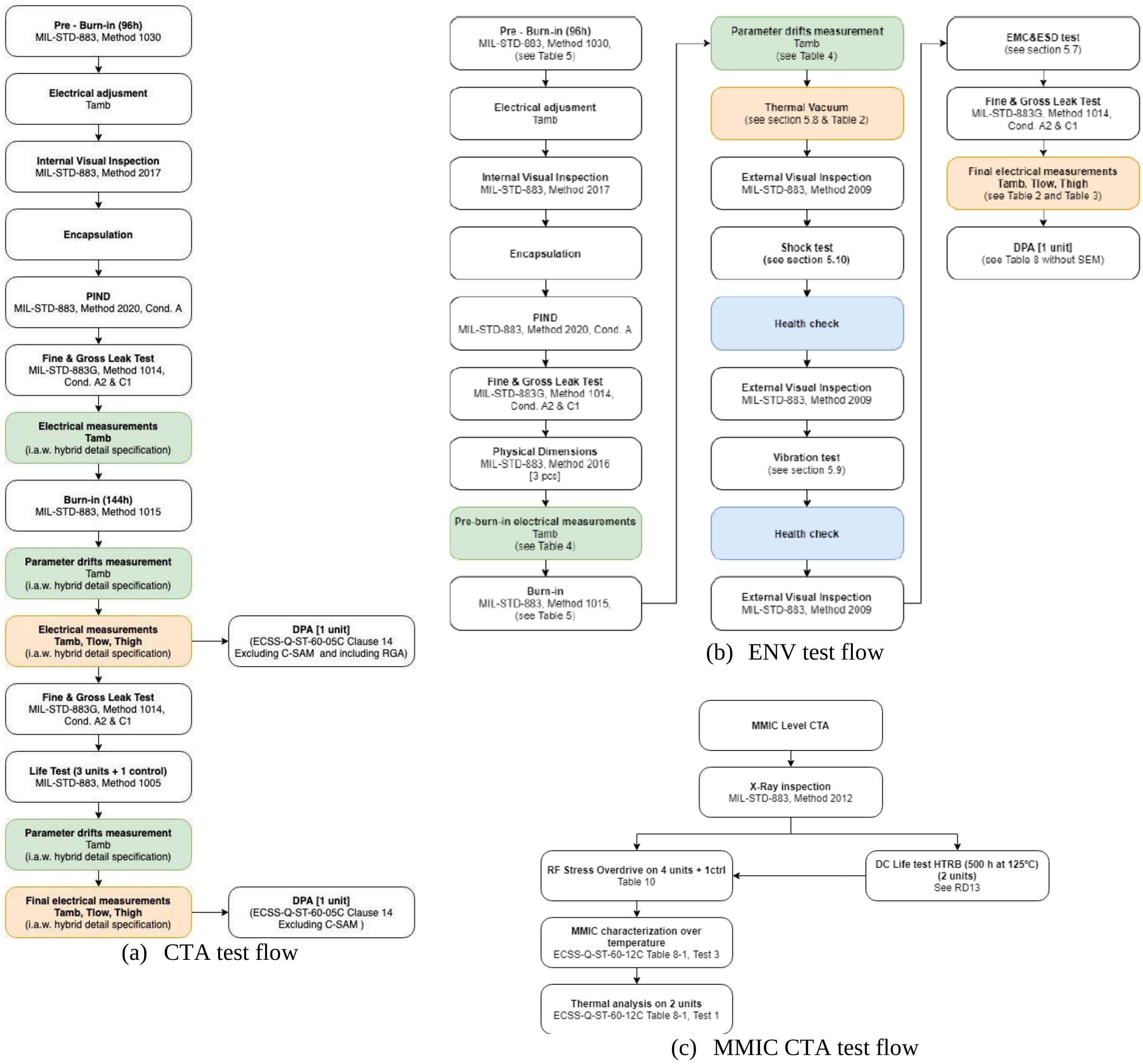


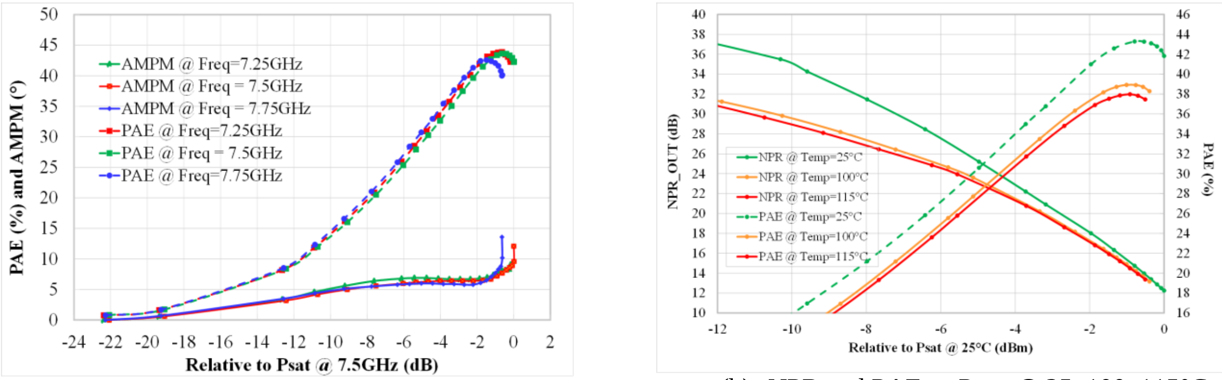
Figure 2 Qualification flows.

GaN MMICs

Both, driver PA and HPA MMICs have been developed on UMS 0.25µm GaN technology (GH25-10), based on AlGaN / GaN epitaxy on SiC substrate. GH25-10 has been qualified on a 4-inches-diameter substrate. This technology targets the development of multi-stage High Power High Efficiency Amplifiers, High Power Switches, Limiters and robust Low Noise Amplifiers up to 20 GHz. It includes MiM capacitors, two types of resistors and a 0.25µm gate length transistors which provide an average power density = 4.5W/mm and a maximum PAE at 9 GHz =71%. It is compatible with space applications constraints; it has been space evaluated and is on the European Prefer Part List (EPPL) since October 2017 [12]. The objectives of the design of the two main elements of the TX chain; the driver and the HPA was to focus on a very high power added efficiency (PAE) at nominal operating point (NOP).

The specification of these DRV and HPA combines high efficiency and high NPR levels for defined operating points. As NPR cannot be efficiently simulated up to now, the architecture was based on Airbus and UMS background to define design rules to be applied to achieve NPR requirements. Several measurements on high efficiency HPA have been performed on 4 different HPA versions as part of the development phase. They had been designed with the same strategy, transistor’s load providing a trade-off between Pout / PAE and a current density between 70 to 80mA/mm and two of them have been measured at several current densities from 25mA/mm to 80mA/mm. The results show that for low current densities, the NPR is slightly improved from saturation to 3dB output back off (OBO). From 3dB OBO to 12dB OBO up to 3 dB NPR improvement can be observed.

The HPA and DRV were 100% tested on wafer. A first selection has been done and the most promising devices were fully characterised in temperature. Figure 3 presents the main results obtained for the HPA in terms of PAE, NPR, and AM/PM as a function of the output power (relative to saturated power). The indicated temperatures are referenced to MMIC backside.

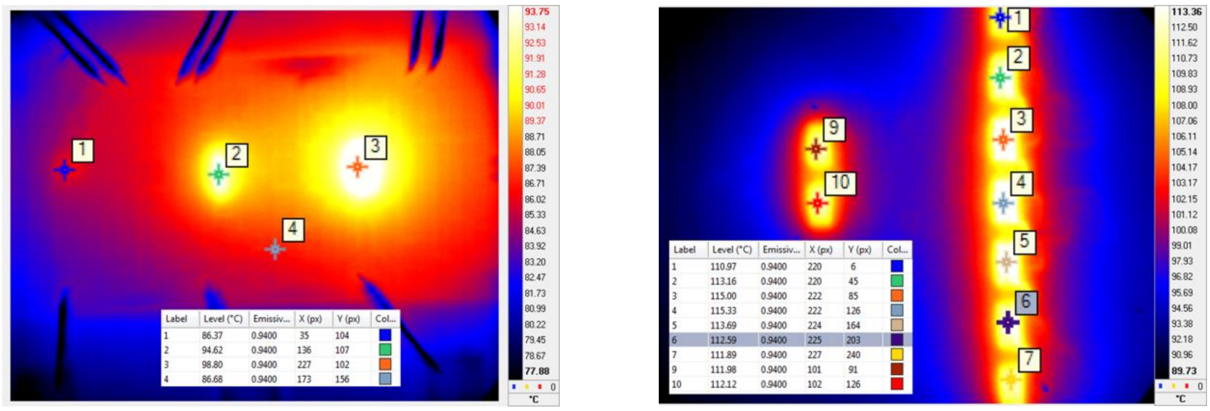


(a) AM/PM & PAE vs Pout @ 100°C.   (b) NPR and PAE vs Pout @ 25, 100, 115°C

Figure 3 Non-linear RF characterization and PAE of the HPA at different temperatures.

In multi-carrier mode, the peak power delivered decreases by 1.2dB and the maximum of PAE by 5 points but at 3-4dB OBO the PAE in the two measurement modes is close. AM/PM is simulated with a good accuracy and its reduction is a major target for MMIC design.

The HPA has been subjected to qualification tests including a DC life test of 1000 hours, a RF life test of 2000 hours at saturation both tests were performed with a Junction Temperature equally to 200°C and finally a RF step stress test. A stabilisation of 10 hours High Temperature Reverse Bias (HTRB) and 10 hours High Temperature Operating Life (HTOL) has been applied to all the circuits before the qualification tests for stabilization purposes. Finally, the MMIC CTA performed by SENER confirmed the qualification of this MMICs with a different die attachment method than the one qualified by UMS. Figure 4 shows the final infrared thermography pictures performed to the MMIC after black-painting which confirms the good thermal conductivity of the assembly and the impressive thermal performance of the very high thermal conductivity silver doped epoxy.



(a) DRV at NOP   (b) HPA in NOP

Figure 4 GaN MMICs infrared thermography.

Hermetic package

The fact of requiring at the same time, light weight and thermal dissipation led to a trade-off between different package material and structures. The housing material chosen was a specific type of aluminium, and the connectors were made of Kovar (NiCo2918). The difference in coefficient of thermal expansion (CTE) between the housing and the connectors had to be considered since the CTE of aluminium is almost 4 times higher than that of Kovar [13]. The flatness of the package after soldering and the robustness of the solder joint itself are affected by this mismatch and had to be considered during material selection, especially for the Micro-D connector, to get consistent results after robustness testing on the soldered package.

Production of the DSSPA package required a series of manufacturing processes starting from the raw material block to reach the hermetic package, which are outlined below.

- Manufacturing of the housing through milling- and die-sinking-EDM-processes.
- Manufacturing of the components, including Micro-D connectors and RF-capable glass-to-metal-seals (GTMS).
- Plating of the housing and components through electrolytic and electroless plating processes.
- Assembly and soldering of Micro-D, SMP and 50Ω-RF connectors into the housing.
- Confirm geometrical tolerances acc. to drawing and robustness acc. to specification requirements.

Figure 5 shows the final package (already sealed) used for the dual channel SSPAs in comparison with one euro coin.

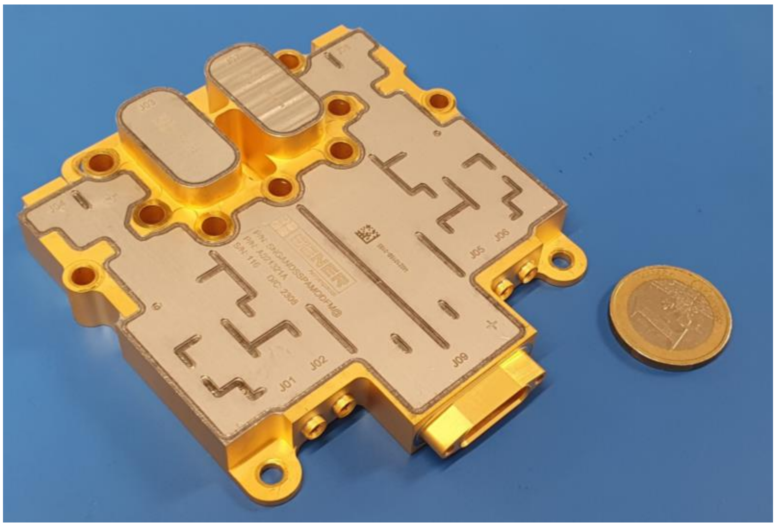


Figure 5 Finished package with fitted lid.

The use of a specific type of aluminium for the housing material was required for this application to provide the desired properties while also offering good machinability for the production process. The cavities of the RF connectors were not possible to be milled due to geometric restrictions, therefore they had to be manufactured through electric-discharge-die-sinking (EDM).

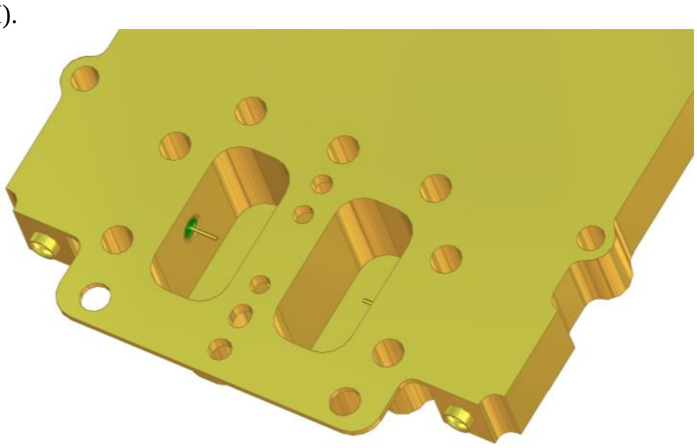


Figure 6 RF-connector (waveguide to microstrip transition) placement in package.

Plating of aluminium was a crucial process for manufacturing of the package to get a robust soldering joint. The industry standard for nickel plating on aluminium is through an electroless nickel-phosphor (NiP) deposition process, for which the mechanism is outlined in [14].

MAIN PERFORMANCES

Apart from the screening sequence defined in ECSS-Q-ST-60-05C, the MMICs undergo a 10h HTRB @125ºC with 50V at Vd and -7V at Vg and a 10h HTOL@115ºC with Vd of 28V and the appropriate Vg to obtain a junction temperature of 200ºC as part of the GaN stabilization process prior to integration. Once integrated there is a pre burn-in of 96h before tuning and sealing. Once sealed, the modules undergo the conventional screening sequence including a burn-in of 144h at 125ºC to age the GaN MMICs and stabilize the DC and RF performance during lifetime of satellite. After that, the performance test of the MHIC is conducted. Figure 7 shows the output Power of the first flight set already delivered to Airbus. Note specially the great similarity among all modules. Figure 7 also shows the NPR and the PAE in multi-carrier scenario for the same flight set.

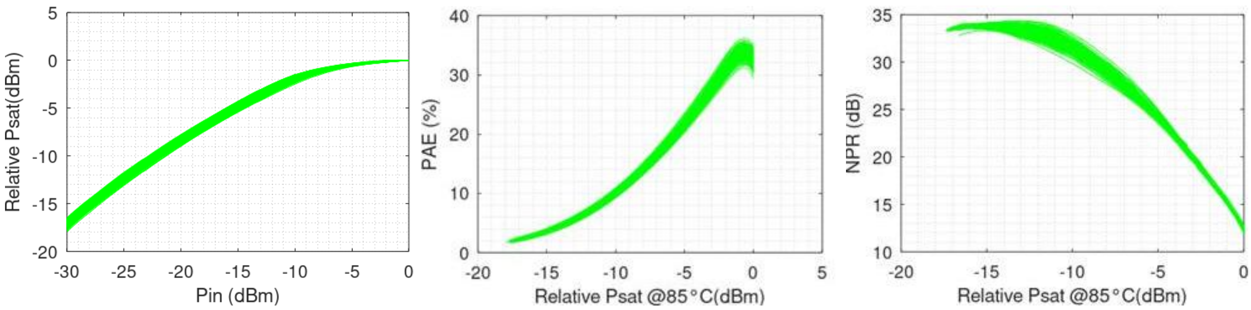


Figure 7 Output Power, NPR and PAE in MC scenario for delivered DSSPAs (Tbase=85ºC).

Finally, Table 1 shows a summary of the life test results from the Lot Acceptance Test (LAT) of the first flight set batch. Note that while there is a degradation in the average linear gain, this does not affect mean gain and mean output power at the operational points, leading to basically less gain compression. Also note that PAE is better at EoL than at beginning of life which indicates that the older the modules, the more efficient. The lower gain compression and same better PAE leads to marginally improve NPR at EoL.

Parameters	*Units*	*Frequency [GHz]*	*Drift LT*
SCS output power average variation	dBm	7.5	-0.07
Linear Gain average variation	dB	7.25-7.75	-0.50
Drain current ageing	A	7.5	+0.03
PAE at saturation	%	7.5	+0.76
PAE at NOP	%	7.25-7.75	+0.65
NPR at NOP	dB	7.25-7.75	-0.08

Table 1 Life test summary results (2000h).

CONCLUSIONS

This article presents the design, performance, and qualification results of a low-mass X-band GaN solid-state power amplifier (SSPA) that is suitable for multi-beam active antennas. The use of an aluminum package has enabled the reduction of the SSPA's mass to 145 g. The performance dispersion of the critical parameters, including output power, gain, and linearity, among delivered modules, aligns with the antenna requirements. Currently, the transmit active antenna is being integrated with excellent results. The launch is scheduled for 2024.

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