D12: Executive Summary for ESA project AO 9088

Single chip Ka Band Doherty amplifier

Evolutions page

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Written by UMS	E.RICHARD 2022/03/08				
Checked by UMS	T.HUET 2022/03/15				

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1. INTRODUCTION

This document is the Executive summary of the activity untitled: “Single-chip Ka-band Doherty Amplifier”.
The aim of this activity (AO9088) was to design a single chip Ka-band High Power Amplifier based on Doherty architecture with the best electrical performance, manufactured on one European GaN provider (United Monolithic Semiconductors) and test the part. The targeted specifications requested by ESA for the DPA (Doherty Power Amplifier) was to associate 4W of output power in multicarrier configuration with 35% of PAE (Power Added Efficiency) and 15 dB NPR (Noise Power Ratio). Two iterations have been designed and manufactured to obtain best performances.

2. MARKET ANALYSIS

At the beginning of the project a Ka band GEO/MEO payloads market has been carried out by Thales AVS-MIS. The conclusion was the following: at short/medium term, AFR antenna seems to be the preferred antenna architecture especially in Europe. This is the priority target for SSPA business.

A 20W HPA at saturation (10W at Nominal Operating Point) is required to cover this market, in order to do so two saturation output power have been studied in the framework of this project (10W and 20W versions).
Doherty Power Amplifier topology is mandatory to cope with severe customers efficiency requirements at NOP (Noise Power Ratio of 15dB is the target): (See Table 1 : Ka-band Doherty power amplifier specifications).

3. DESIGN AND TECHNOLOGY ANALYSIS

3.1 GH15-10 PROCESS DESCRIPTION

THALES AVS-MIS made a GaN technology survey in order to select the most appropriate European GaN provider for this project. GH15-10 from UMS was selected for this ESA project for the following reasons:

- This is a GaN European process
- Power density is very good in K band thanks to 0.15µm gate length HEMT technology.
- The thermal performances are very good because this is GaN over SiC (thermally better than Si)
- Models from UMS Design Kit are mature enough to provide good predictions of future results.

The GH15-10 technology is based on AlGaN / GaN high electron mobility transistors with 150 nm gate length and slanted gate-foot profile. Two FET topologies are available. One with source terminated field plates and one without a field plate targeted for switch applications. Two metallization layers are used for interconnects, MIM-capacitors, high frequency lines and inductors. The second metallization layer also provides air bridges to overcome topologies and to cross underlying structures with low parasitic capacitance. Two types of thin film resistors are available. The technology targets the design of monolithic integrated robust low power MMICs and multi-stage high power high efficiency amplifiers up to 35 GHz.
The design and manufacturing of the parts from the first Doherty power amplifier iteration (BARDEEN mask) have used iteration 3 of the UMS GH15-10 technology and the second iteration (WELKER mask) has been done on the last GH15-10 iteration (Iteration 5). This iteration of the GH15 technology,

is space evaluated since December 2021 and part of the European Preferred Part List (EPPL) established by ESA.

3.2 DOHERTY POWER AMPLIFIER ARCHITECTURE

For a space application, efficiency is key. To maintain a high efficiency and linearity when transmitting signals with more complex signal modulations, demands a circuit with good performance at high output power back-off (OPBO). The Doherty power amplifier architecture was considered to be a good candidate, and was therefore the subject of this project.

The Doherty Power Amplifier (DPA) aim is to provide a maximum Power Added Efficiency (PAE) along a wide range of output power. Indeed, classic amplifiers like class AB amplifiers have a maximum efficiency close to their output power saturation, where the linearity is poor. Increasing the range of output power where the efficiency is optimal leads to better linearity performances.

The Doherty Amplifier is implemented by the combination of two actives devices: the main amplifier and the peak amplifier. The main amplifier is typically operated in “class AB” and the peak amplifier is operated in “class C”. The idea is to modulate the load seen by the main to force the amplifier to operate in its maximum efficiency condition for a pre-determined range of output power, called Output Back-Off (OBO). The peak amplifier is biased thru the gate to be off at low input drive levels and begin to turn on when the main amplifier is driven into compression, as shown on Figure 1:

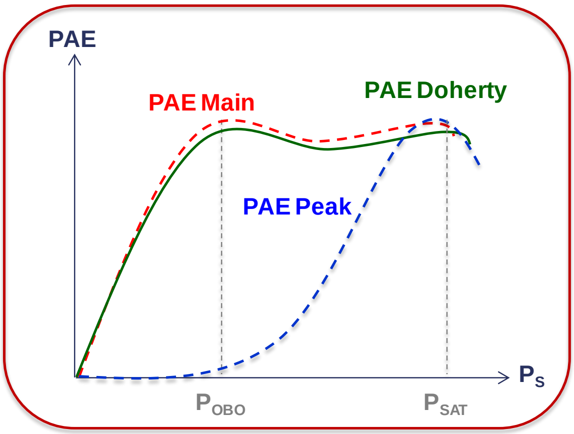


Figure 1 : PAE versus Output Power

On this figure, three regions appear:

A low level region, where only the main amplifier is active and the peak is turned off.
A Doherty region, when both amplifiers are operating.
A saturation region, when both amplifiers are closed to saturation.

4. DESIGN ACTIVITIES

4.1 TARGETED SPECIFICATIONS

The main specifications requested by ESA and THALES AVS-MIS are provided in the next table:

Table 1 : Ka-band Doherty power amplifier specifications

Parameters	ESA specification min. (10W version)	THALES AVS-MIS specification min. (20W version)	Comments
Frequency	17.3-20.3 GHz	17.3-20.3 GHz	Satellite Ka-band downlink
Nominal Operating Output power (NOP)	>36dBm	>39,5dBm	At NPR=15dB (without linearizer)
Small signal gain	>30dB	>30dB	
Power Added Efficiency @NOP	> 35%	> 35%	
Linearity (NPR) @NOP	> 15dB	> 15dB (*)	(*) with 2.9 GHz bandwidth
Input/Output reflection coefficient	> 15dB	> 15dB	
Stability	Unconditionally stable	Unconditionally stable	
Maximum Tj	160°C	160°C	
Operating temperature	-10°C / +75°C	-0°C / +105°C	MMIC backside temperature

4.2 FIRST ITERATION – BARDEEN MASK

4.2.1 Design and measurement activities

BARDEEN design has been done taking into account the space de-rating for both passive and active elements from GH15 technology. To achieve both specifications and secure the results, several versions were designed as shown in Table 2.

Table 2 : Different DPA versions (BARDEEN)

Versions	Drain Voltage	3 stages Doherty Power Amplifier
27481	20 V	Nominal version for high output power configuration
	14 V	Low frequencies shifted version for low output power configuration
27482	20 V	Low frequencies shifted version for high output power configuration
27483	20 V	High frequencies shifted version for high output power configuration
	14 V	Nominal version for low output power configuration
27484	14 V	High frequencies shifted version for low output power configuration

A complete “on-wafer” characterisation has been done on all versions and measurements of Ka-band Doherty are in line with the specifications and show very good agreement with simulation.

Two versions have been selected to be measured in test fixture: 27481 for 10W version and 27482 for 20W version.

4.2.2 Conclusion of the first iteration

Test fixture measurements are not in line with simulations, more ripple and a lack of PAE is observed (-5 points) that we assume is coming from the test fixture RF connectors mismatching.
The development of a specific board without RF connectors, called board OWT will be planned for the second Run in order to better assess MMIC performances. This measurement will be done in pulsed mode leading to a direct comparison with on-wafer measurement. Nevertheless, we intend to keep CW measurements versus temperature measurement in UMS test fixture.

4.3 SECOND ITERATION – WELKER MASK

4.3.1 Design and measurement activities

For this second iteration, the aim was to optimize DPA on the new GH15-10 iteration (iteration 5) that presents better reliability performance; because a shift of frequency bandwidth was observed between iteration 3 and 5 a redesign was needed. Active and passive parts have also been optimized to achieve better performances taking into account both drain biasing (15V ad 20V). Three versions have been designed to mitigate frequency bandwidth risk:

Table 3 : Different DPA versions (WELKER)

Versions	Drain Voltage	3 stages Doherty Power Amplifier
29641	15 V	Nominal version for low output power configuration (10W HPA version)
29642	15 V	Frequency shifted version toward low frequency at the end of the frequency band (10W HPA version)
	20 V	Nominal version for high output power configuration (20W HPA version)
29643	15 V	Frequency shifted version toward high frequency Nominal version for low power configuration (10W HPA version) at high temperature

A complete “on-wafer” characterisation has been done on all versions; these measurements of Ka-band Doherty are in line with the specifications and show very good agreement with simulation.
Two versions have been selected to be measured in test fixture: 29641 for 10W version and 29642 for 20W version. These version have also been measured in board OWT.

4.3.2 Conclusion of the second iteration

Large signal measurements performed on this second Run development show, that test fixture mismatching is impacting the gain ripple and also output power and PAE performances at the end of the frequency band. This was expected, since we experienced it already on the first iteration. Nevertheless, board OWT measurements also show a lack of output power and PAE at the end of the frequency band even though low-level gain is pretty well centered. This lack of performance is highlighting that the load presented to the transistor of the output stage may be not located on the Smith Chart as it was simulated; one hypothesis is that this phenomenon could be related to modelling of the 3 RF wires bondings. Indeed if we compare “on wafer” measurements and “on wafer” simulation we can see a good agreement.

Linearity (Noise to Power Ratio) measurements were done on both DPA and compared with a UMS corporate class AB High Power Amplifier (CHA8252-99F) still on GH15 technology. This class AB HPA presents 10W of saturated output power. The measurements were performed in test fixture in the following configuration:

- Biasing points :
  - 10W Doherty : Vd=15V ; Idq_main=150mA, Idq_peak=5mA

- 20W Doherty : Vd=20V ; Idq_main=150mA, Idq_peak=5mA
- CHA8252-99F : Vd=18V; Idq=250mA

- Frequency : 18.7GHz with Pin : -15 to 15dBm / step 1dB / CW measurement / Tc=105°C
- Four multicarrier signals :
  - Bandwidth : 100MHz - Number of tones : 10 001 with 10kHz spacing – Notch width : 4MHz – PAPR=10dB
  - Bandwidth : 1GHz - Number of tones : 100 001 with 10kHz spacing – Notch width : 44MHz – PAPR=11.5dB
  - Bandwidth : 2GHz - Number of tones : 200 001 with 10kHz spacing – Notch width : 88MHz – PAPR=11dB
  - Bandwidth : 2.9GHz - Number of tones : 290 001 with 10kHz spacing – Notch width : 116MHz – PAPR=11.5dB

The measurement results are presented with two different modulations: 32 APSK (15dB NPR) and SC-FDMA (20dB of NPR). Test fixture losses have been taken into account in the next table below: +0.2dB on Pout and +2% on PAE have been added.

Table 4 : NPR performances comparison

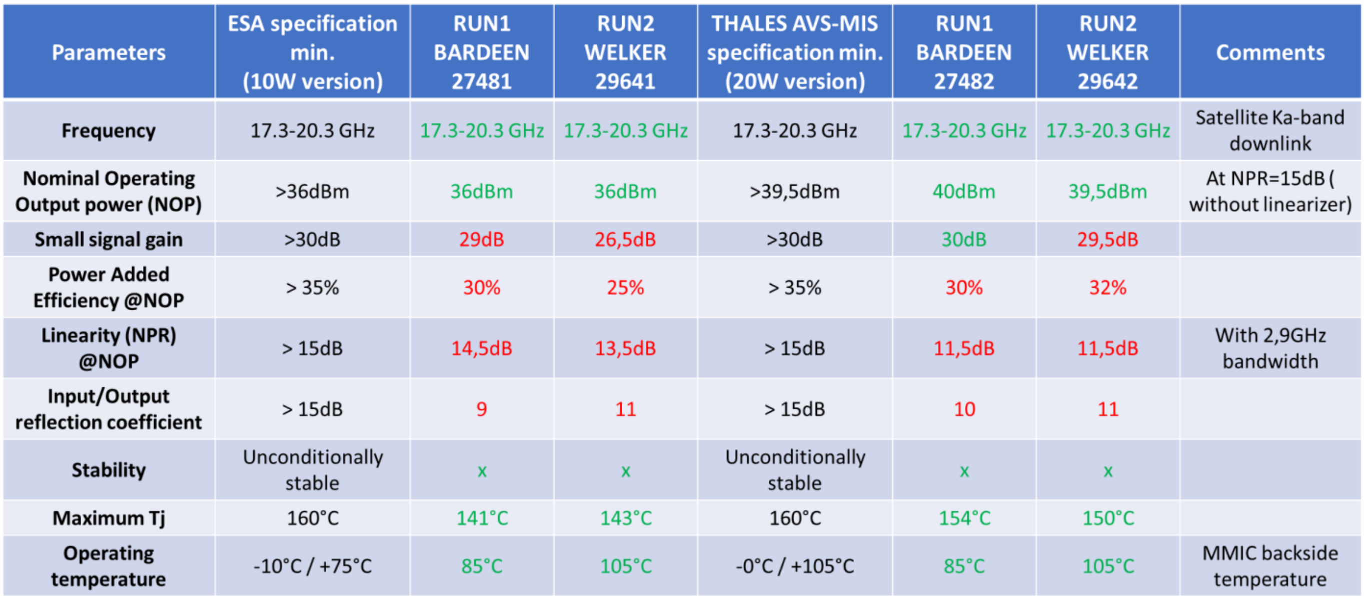
Bandwidth	Modulation	10W Class AB		10W Doherty		20W Doherty	
		PAE	Pout	PAE	Pout	PAE	Pout
100MHz	32 APSK	29%	38.8 dBm	28%	37.7 dBm	33%	39.3 dBm
	SC-FDMA	23%	36 dBm	27%	35.5 dBm	No data	No data
1 GHz	32 APSK	29%	38.7 dBm	27%	37.2 dBm	31%	39.2 dBm
	SC-FDMA	24%	36.5 dBm	25%	35.2 dBm	29%	36.5 dBm
2 GHz	32 APSK	29%	38.2 dBm	25%	36.2 dBm	30%	37.7 dBm
	SC-FDMA	23%	35.7 dBm	23%	33.2 dBm	No data	No data
2.9 GHz	32 APSK	29%	38 dBm	24%	34.7 dBm	28%	36.7dBm
	SC-FDMA	22%	35.5 dBm	19%	31.5 dBm	No data	No data

This measurement comparison is emphasizing that the Doherty power amplifier topology leads to a better efficiency than Class AB power amplifier when a high linearity is required (SC-FDMA): this statement is true only for a bandwidth taken between 0.1 GHz to 2 GHz.

5. CONCLUSION

The summary of both iteration measurement results are presented in Table 5.

Table 5 : Ka-band Doherty compliance matrix



Parameters	ESA specification min. (10W version)	RUN1 BARDEEN 27481	RUN2 WELKER 29641	THALES AVS-MIS specification min. (20W version)	RUN1 BARDEEN 27482	RUN2 WELKER 29642	Comments
Frequency	17.3-20.3 GHz	17.3-20.3 GHz	17.3-20.3 GHz	17.3-20.3 GHz	17.3-20.3 GHz	17.3-20.3 GHz	Satellite Ka-band downlink
Nominal Operating Output power (NOP)	>36dBm	36dBm	36dBm	>39,5dBm	40dBm	39,5dBm	At NPR=15dB (without linearizer)
Small signal gain	>30dB	29dB	26,5dB	>30dB	30dB	29,5dB	
Power Added Efficiency @NOP	> 35%	30%	25%	> 35%	30%	32%	
Linearity (NPR) @NOP	> 15dB	14,5dB	13,5dB	> 15dB	11,5dB	11,5dB	With 2,9GHz bandwidth
Input/Output reflection coefficient	> 15dB	9	11	> 15dB	10	11	
Stability	Unconditionally stable	x	x	Unconditionally stable	x	x	
Maximum Tj	160°C	141°C	143°C	160°C	154°C	150°C	
Operating temperature	-10°C / +75°C	85°C	105°C	-0°C / +105°C	85°C	105°C	MMIC backside temperature

For reminder, between both runs, GH15-10 technology evolved from iteration 3 to iteration 5 for reliability improvement purpose, resulting in a shift of the frequency band towards low frequency. Nevertheless, the second iteration permits to achieve on Doherty 20W version the same performance than on first iteration with a backside of 105°C instead of 85°C. The junction temperature associated is around 150°C with a PAE associated of 32% but the linearity remains below specification.
On 10W Doherty version, NPR measurement results are closer to specifications but PAE level at NOP is not achieved on both iterations and is around 25% for the last iteration at 13.5dB of NPR for a chip backside of 105°C. In any cases, the junction temperature remains below 160°C.

GH15-10 technology was selected at the beginning of the project thanks to a good power density and PAE performance in K-band and a good maturity of model. On wafer performances confirm that GH15-10 technology is effective and model accuracy is also demonstrated. Moreover, in December 2021 GH15-10 has been space evaluated and is now part of EPPL.

This project and results associated have also emphasize a good design methodology for power amplifier in K-band and especially for Doherty power amplifier topology with 16% of frequency bandwidth and high power challenges.

Nevertheless, improvements for future Doherty development could be considered. We assumed that the lack of PAE/Pout performances at the end of the frequency band in test fixture was due to mismatching. A more efficient 3D EM transition of 3 wire bondings would lead to a better correlation between simulation and measurement. Moreover, a more efficient jig test fixture than jig 40 to get rid of the wall effect and have better return losses in the range of 21 GHz would help to have a better overview of DPA performances with temperature variation.

This project highlighted the difficulty to simulate NPR with a good accuracy, especially for high bandwidth such as 2.9 GHz of instantaneous bandwidth. Volti software from ESA remains the baseline as simulation tools for the moment but the validity is for small bandwidth in the range of 100 MHz and no trapping effect in the transistor model is taking into account. New generation of transistor model is requested in order to simulate NPR with good accuracy: activities with Xlim and Keysight are expected in order to make progress on this topic. Another solution could be to find a connection between NPR and two-tone measurements (IMD3 or C/I3) but no direct link was found during measurement analysis.

The last point is related to the Doherty biasing point optimization. We experienced with this amplifier topology that PAE and linearity were difficult to reach with the same biasing point, especially when two biasings are used (main and peak). It's difficult to find rapidly what the best compromise is, especially with temperature variation but this biasing point is key.