# GaN Power stage based on European technology for Navigation SSPA in L-band Contract 4000103322

WE LOOK AFTER THE EARTH BEAT

## Final Review

12/07/2016

Ref.:

THALES ALENIA SPACE SECRET

83230933-DOC-TAS-EN-003

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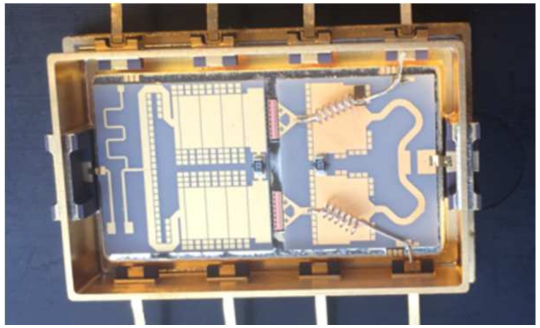
- AGENDA
  - **HPA measurements**
  - Failure Analysis
  - Improvements proposition
  - Possible HPA design with improvement
  - Assessment of performance of SSPAs
  - Development perspectives
  - SOW Compliance Matrix
  - RIDs

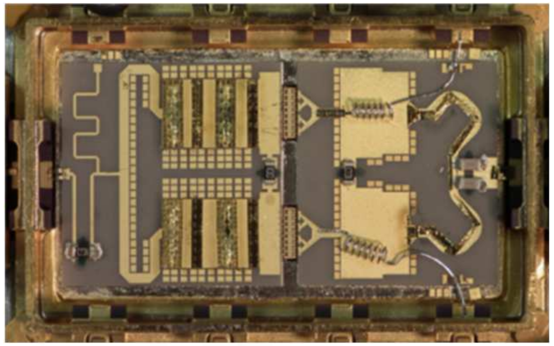
Main message

# HPA measurements

- 10 HPAs manufactured/reworked
  - 5x L-band GaN HPA TREK measured
    - 2 presented HPA N°1 & 4
  - 2x L-band GaN HPA STARDUST manufactured&tested

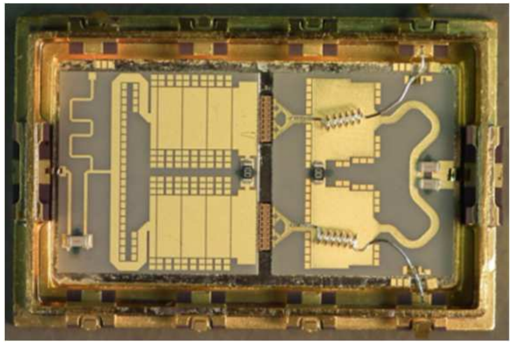


HPA N°1
Reworked

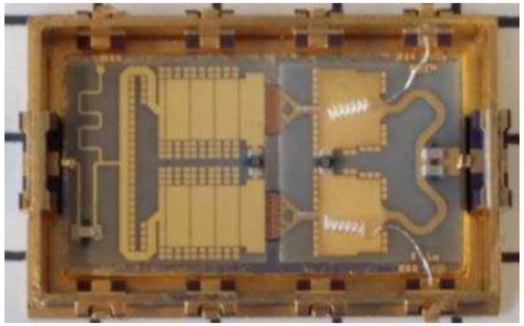


HPA N°4

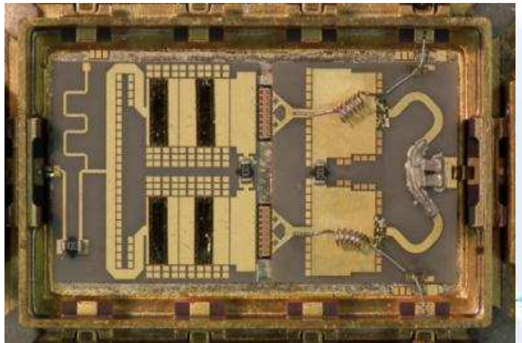
HPA N°2
Reworked



HPA N°3
Reworked

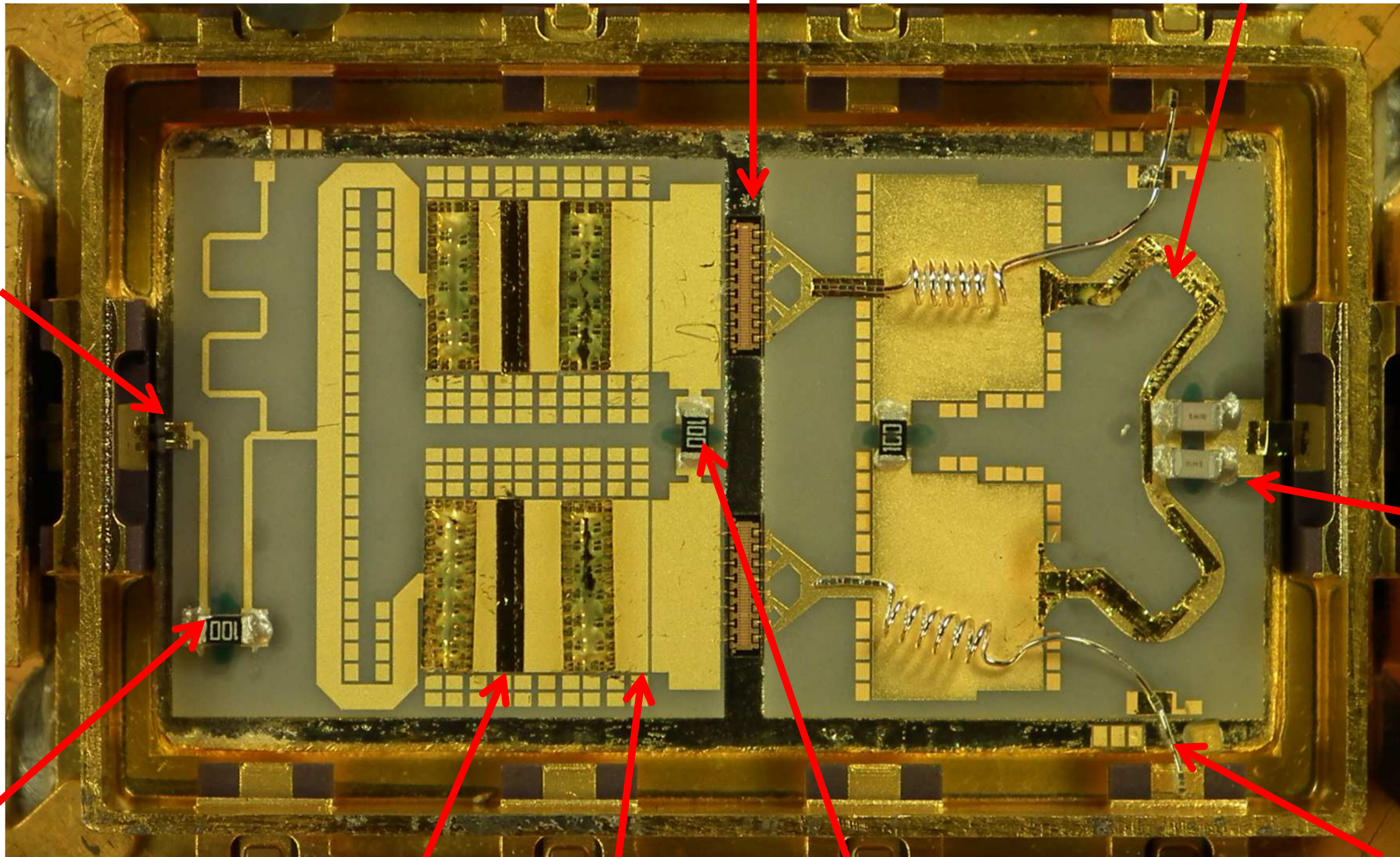


HPA N°5



# HPA design: final configuration

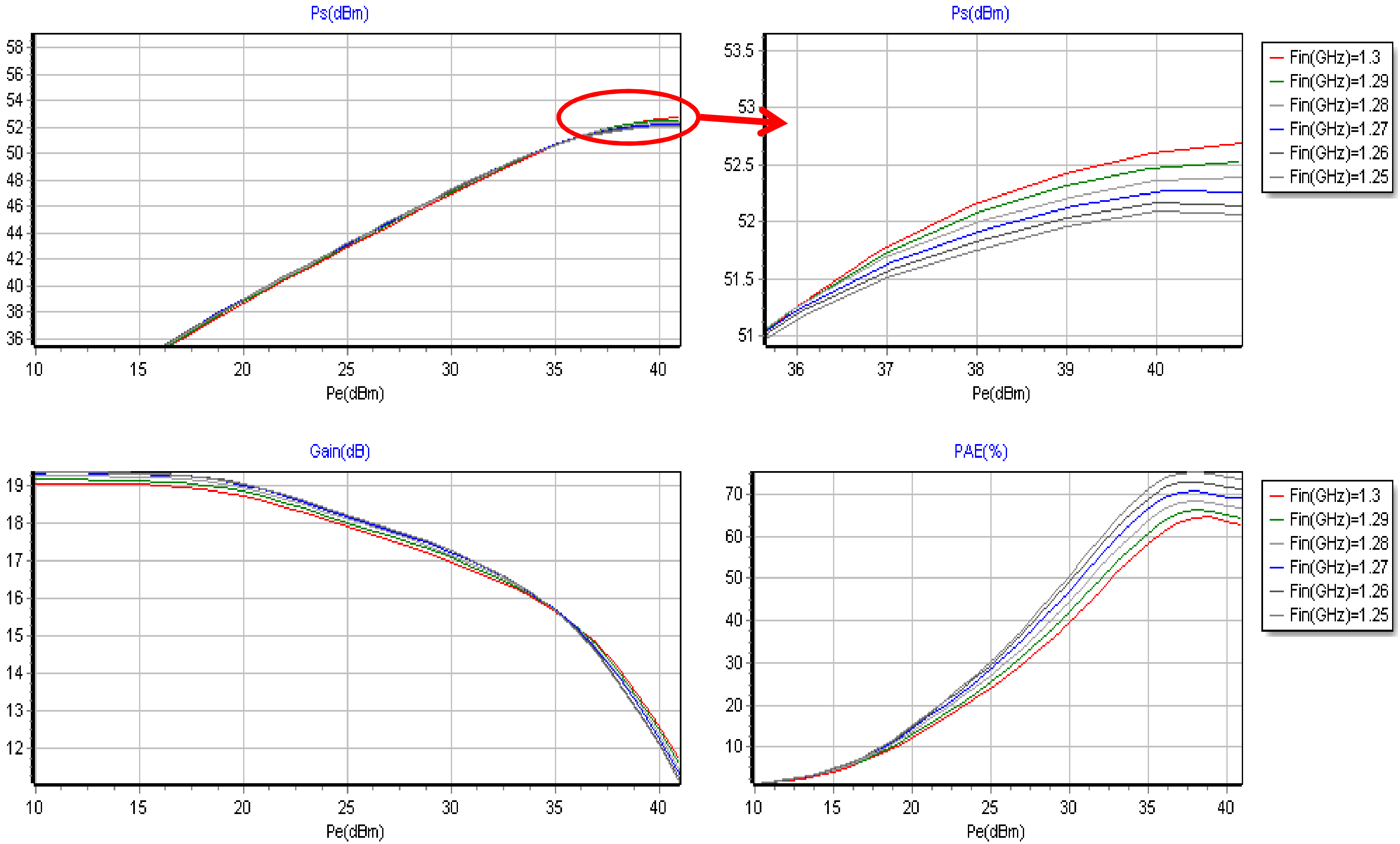




# HPA measurements   HPA N°1  CW

Temp=25°C (Vds=42.5V), Ids= 1400mA, RF=1.25 to 1.3 GHZ.

Pout(dBm), Gain(dB), PAE(%) vs Pin(dBm)





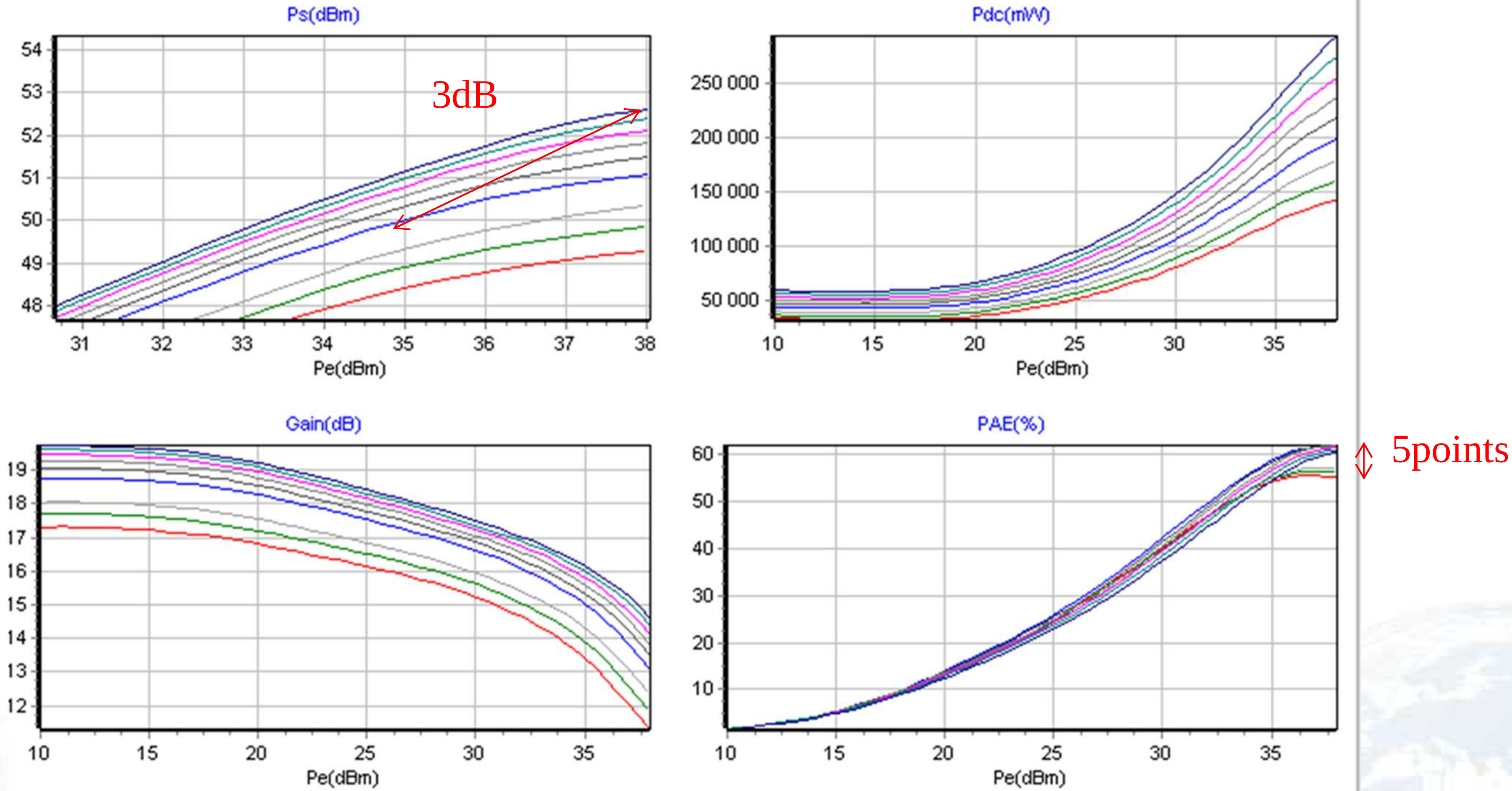

**PROPRIETARY INFORMATION**

# HPA measurements   HPA N°1  CW



Temp=25°C Freq= 1,3 GHz Ids= 1400mA

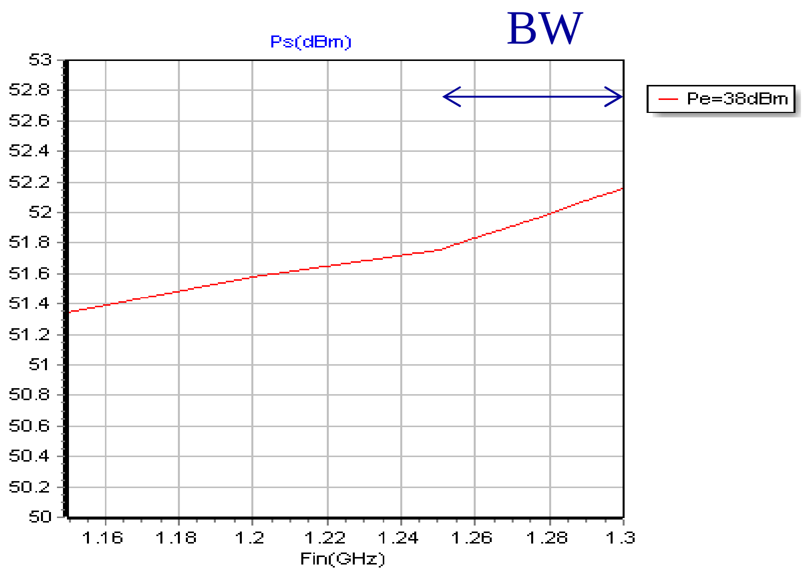
output power flexibility versus drain voltage 25 to 40V

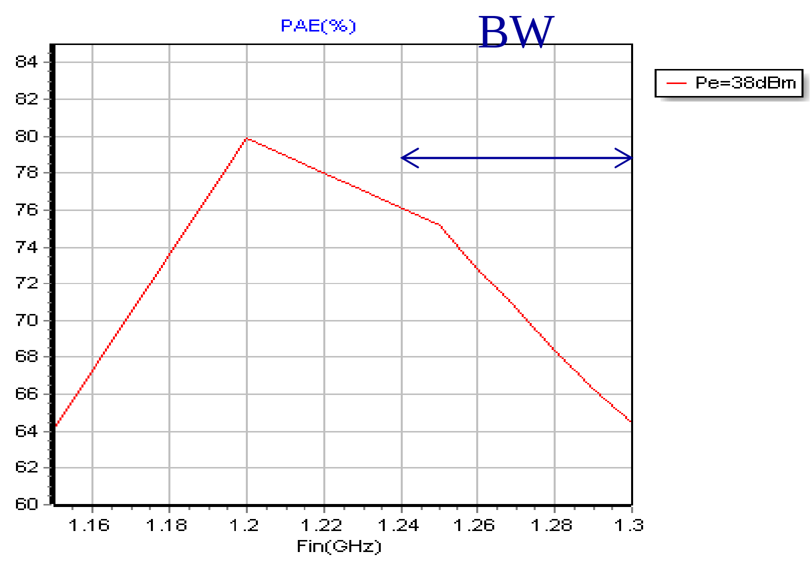


# HPA measurements HPA N°1 CW



HPA#4 Power measurements over frequency Temp=+25°C VDS=+40V Pout (dBm) PAE (%) at Pin =38dBm



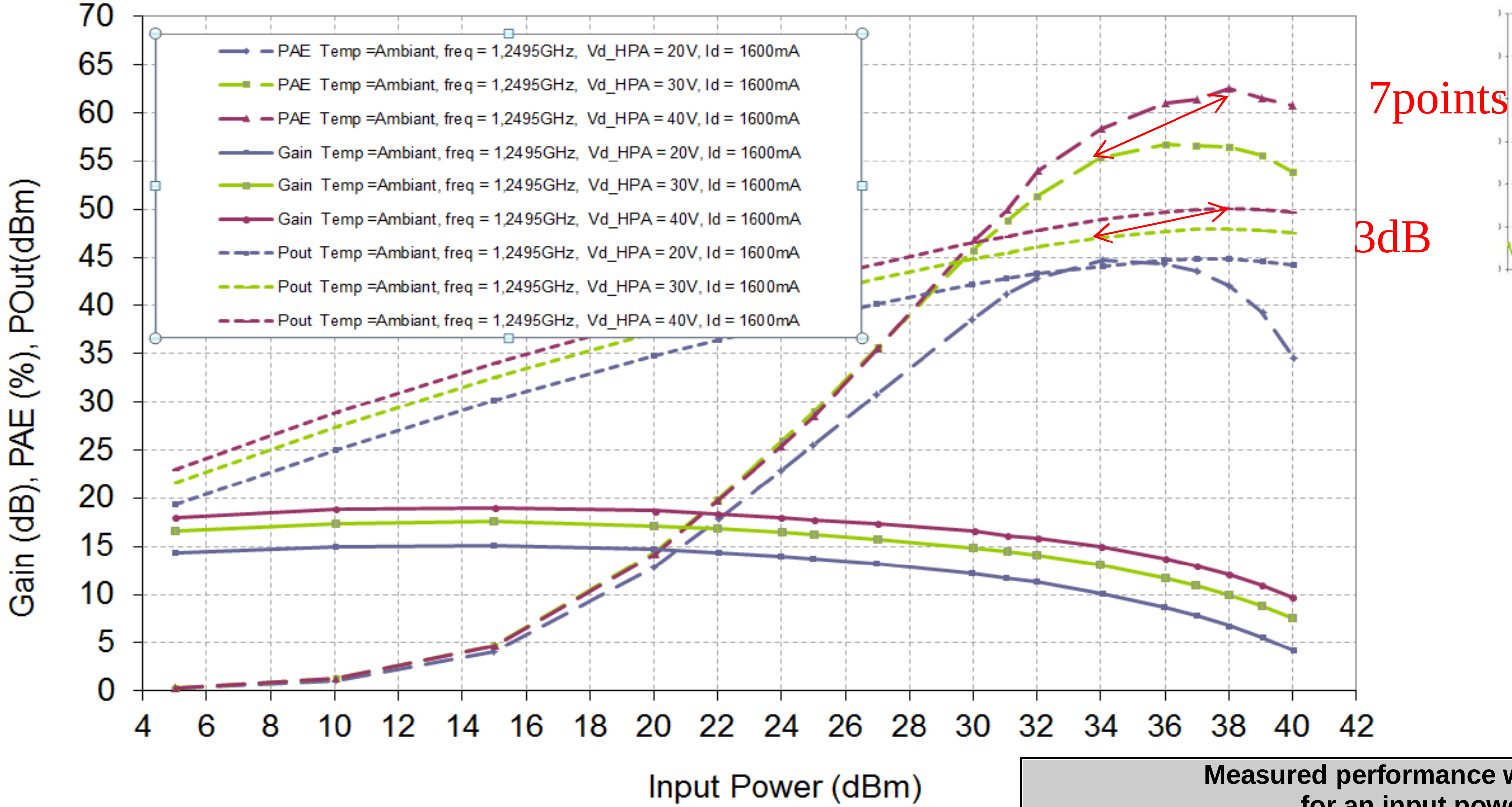



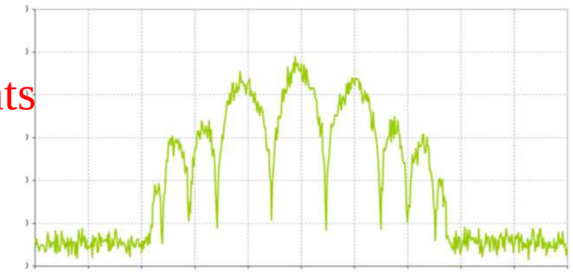

| CW mode : PAE performance for an input power of 38.0dBm | | |
|---|---|---|
| **Parameters** | **Specification** | **Measurement** |
| Output Power | 53dBm | 52 dBm |
| Output Power | 200W | 160W |
| PAE | 61% | > 65% |
| Power gain | 15 dB | 14 dB |
| Gain compression | 5dBcomp | 5dBcomp |

## HPA measurements HPA N°1 E6 Signal



- HPA#1 Power measurements with E6 signal. For Vds=20 30 40V, Ids=1600mA, RF=1,2495GHz,. Gain(dB), PAE(%), vs Pin(dBm)



| Measured performance with E6 Galileo Signal for an input power of 38.0dBm | | |
|---|---|---|
| **Parameters** | **Specification** | **Measurement** |
| Output Power | 51.76 dBm | 50 dBm |
| Output Power | 150W | 100W |
| PAE | 50% | 62% |
| Power gain | 15dB | 13dB |

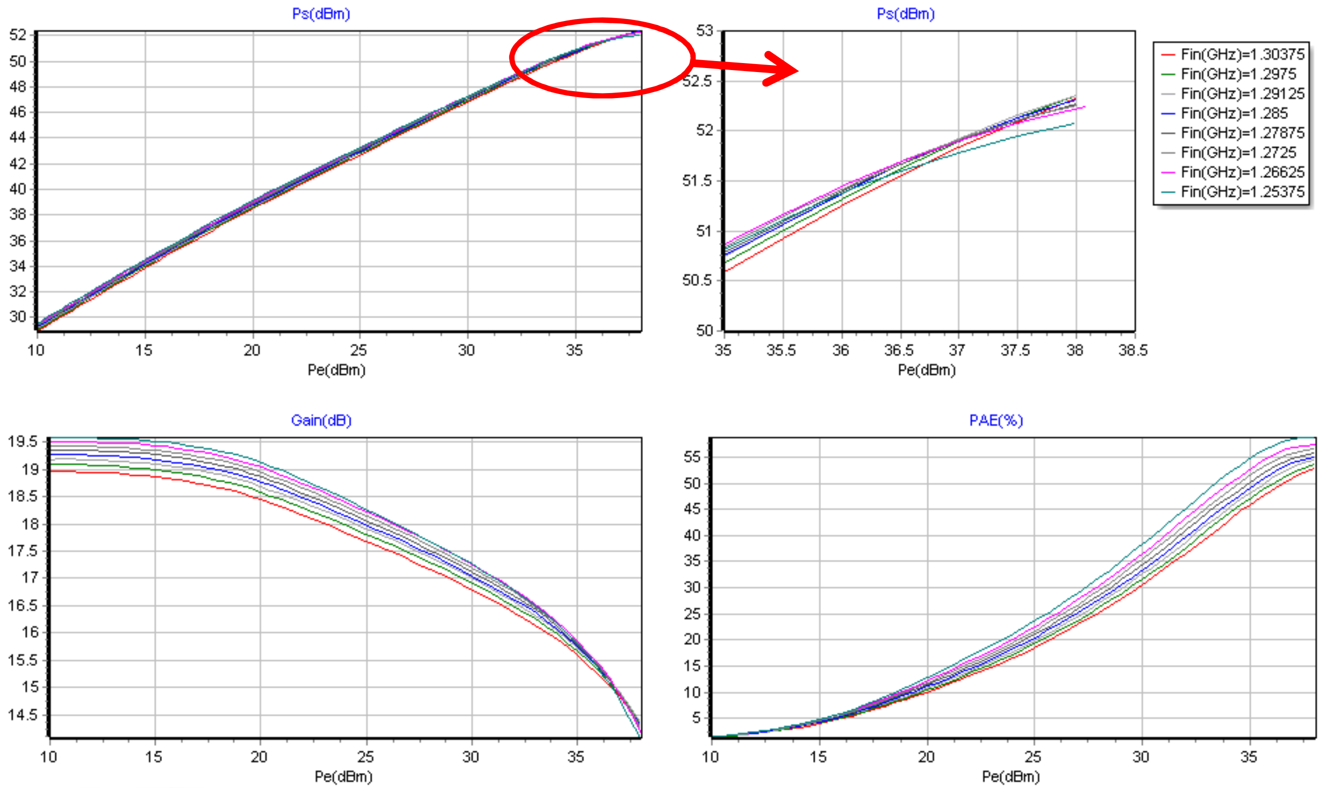
# HPA measurements   HPA N°4  CW

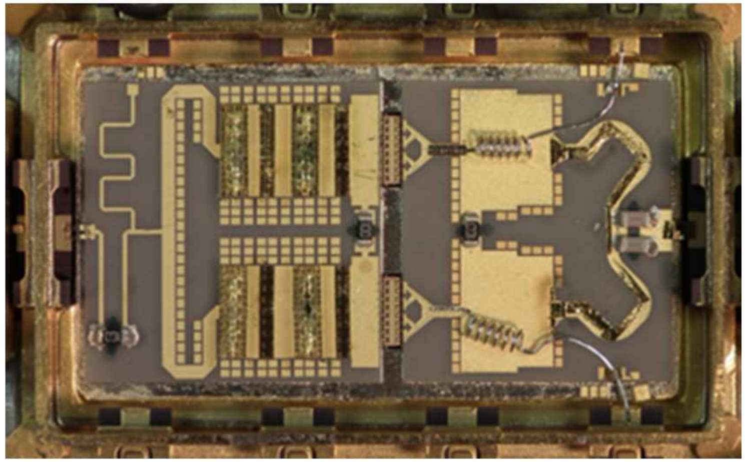


Temp=25°C (Vds=40V), Ids= 1400mA

RF=1.25 to 1.3 GHZ.

Pout(dBm), Gain(dB), PAE(%) vs Pin(dBm)



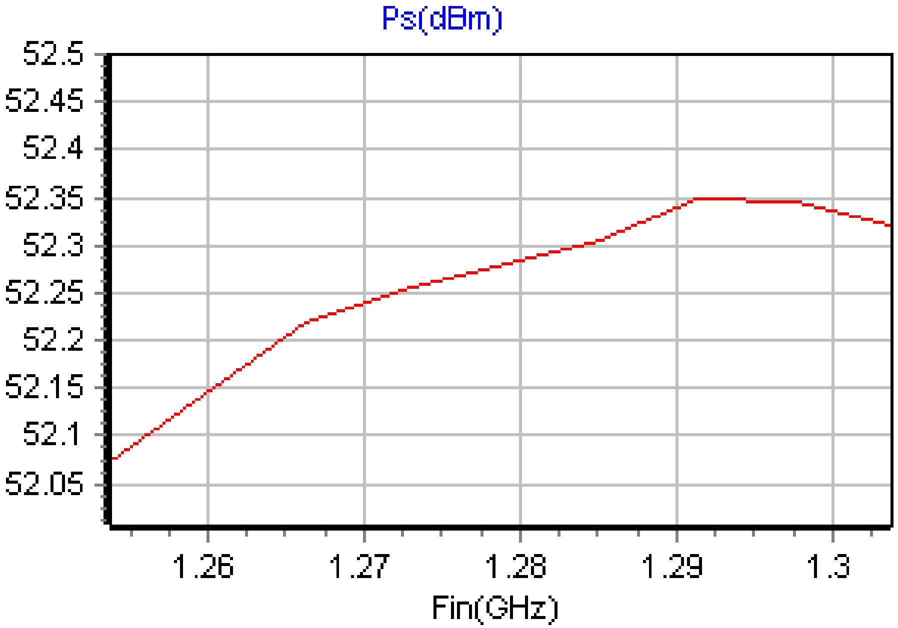


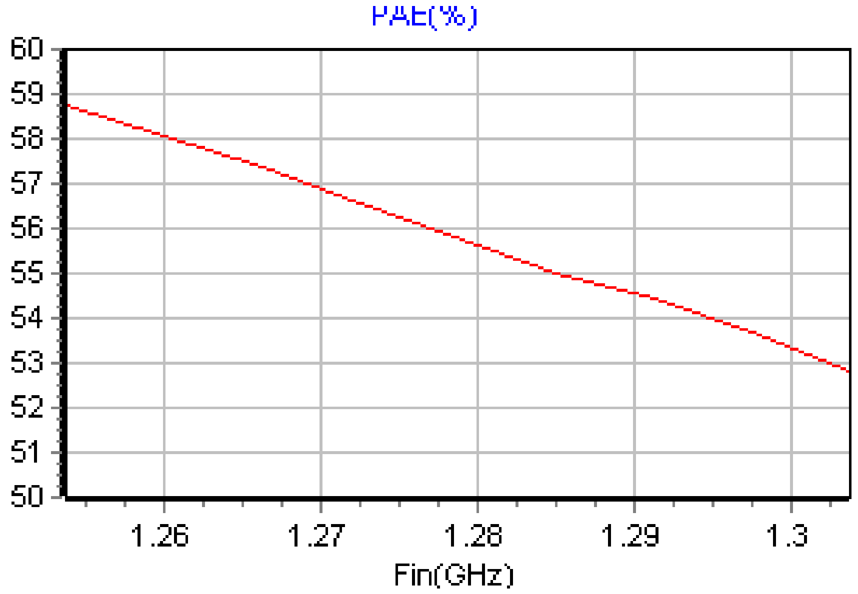
**PROPRIETARY INFORMATION**

# HPA measurements HPA N°4 CW



HPA#4 Power measurements over frequency Temp=+25°C VDS=+40V Pout (dBm) PAE (%) at Pin =38dBm

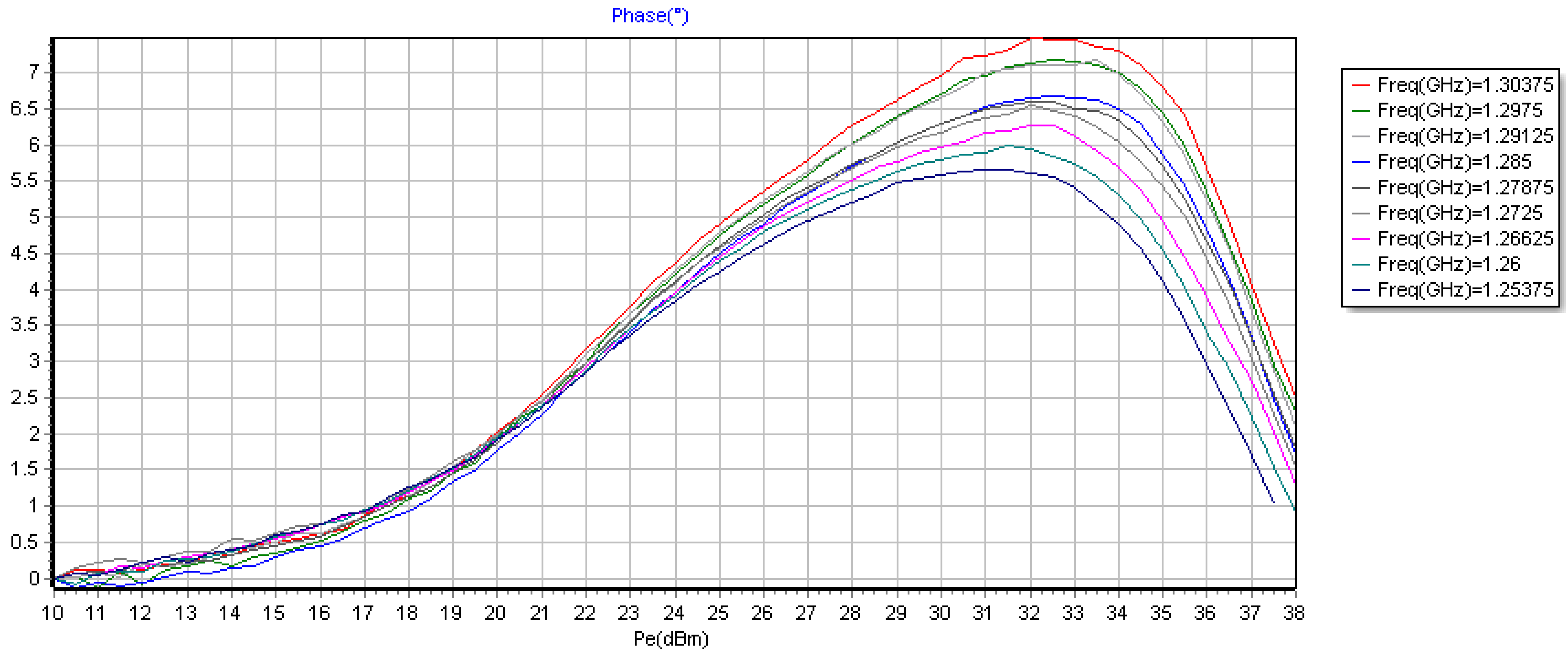



| CW mode : PAE performance for an input power of 38.0dBm | | |
|---|---|---|
| **Parameters** | **Specification** | **Measurement** |
| Output Power | 53dBm | 52.2 dBm |
| Output Power | 200W | 165W |
| PAE | 61% | > 55% |
| Power gain | 15 dB | 15 dB |
| Gain compression | 5dBcomp | 5dBcomp |

Temp=25°C (Vds=40V), Ids= 1400mA, RF=1.25 to 1.3 GHZ.

Phase shift (°) vs Pin(dBm)





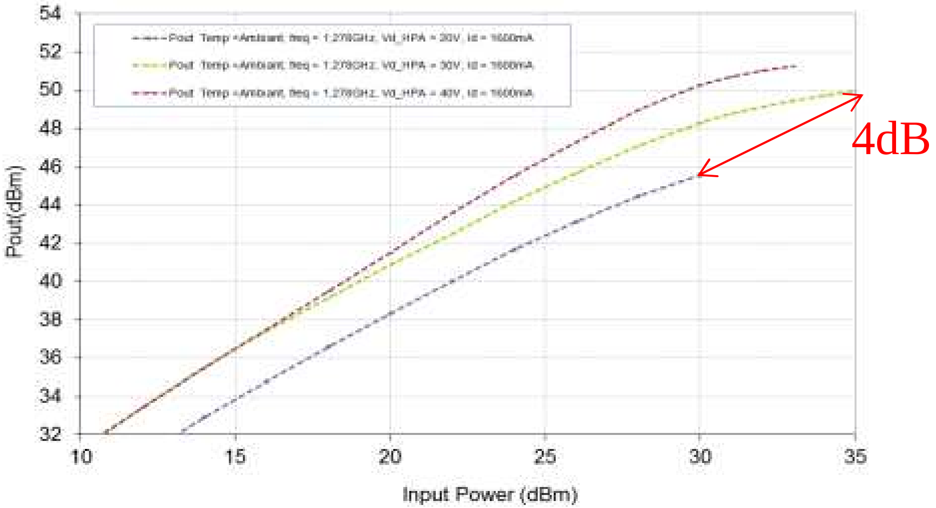


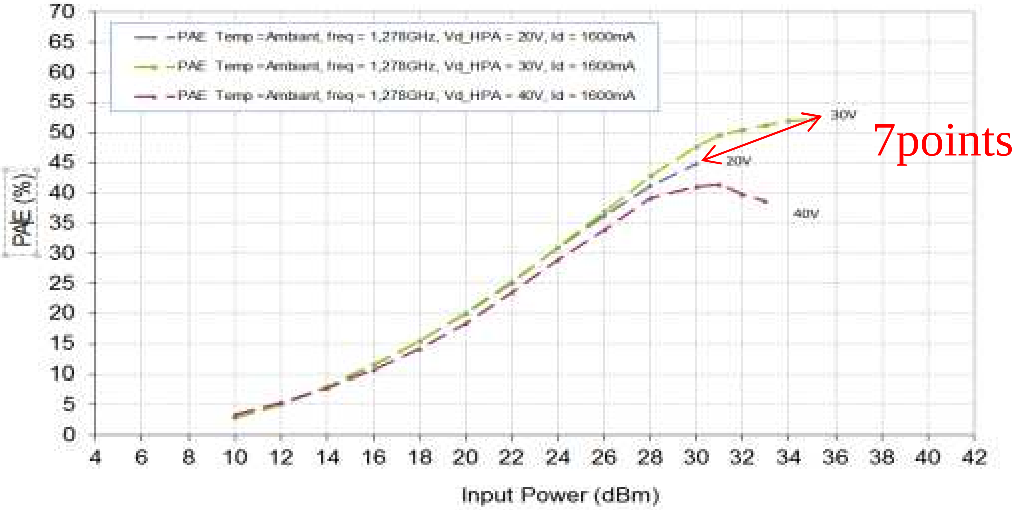

**PROPRIETARY INFORMATION**

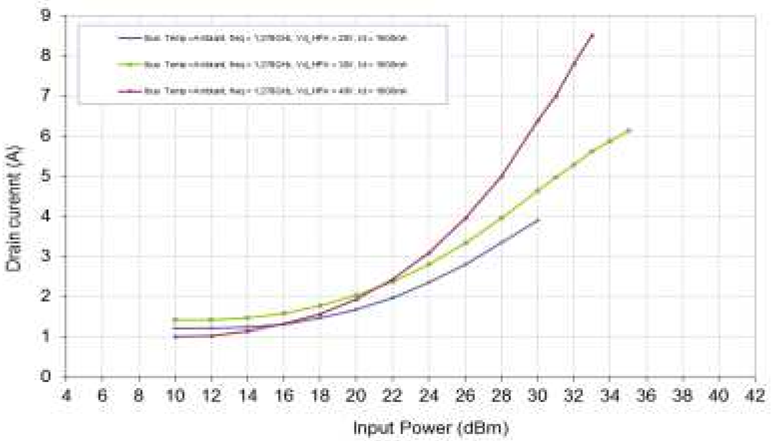
# HPA measurements HPA N°4 E6 Signal



- HPA#4 Power measurements with E6 signal. For Vds=20V 30V 40V, Ids=1500mA, RF=1,278GHz,. Pout (dB), PAE(%) I drain (A) vs Pin(dBm)








**PROPRIETARY INFORMATION**



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# CW mode Performance Compliance Matrix



| CW mode : Measured performance for an input power of 38.0dBm | | | | |
|---|---|---|---|---|
| **Parameters** | **Specification** | **Measurement** | **Compliance** | **Comments** |
| Output Power | > 190 W | 160 W (1)<br>170 W (4) | N/A | At center frequency |
| PAE | 55% | 68% (1)<br>56% (4) | N/A | At center frequency |
| Power Flexibility<br>3dB back off | 4 % efficiency degradation | 5 % (1) | C<br>PAE >55% | |
| Center frequency | 1278.75 MHz | 1278.75 MHz | C | |
| Power gain | 15 dB | 14 dB (1) (4) | NC | |
| Gain compression | 2dBcomp | 5dBcomp (1) (4) | NC | |
| BW | >50MHz | 50MHz | C | |
| Phase shift | 3 deg max -20<IBO<-10dB<br>6 deg max -10<IBO<-5dB<br>15 deg max -5<IBO<-0dB<br>20 deg max 0<IBO<+3dB | 6 deg (4)<br>7 deg (4)<br>7 deg (4)<br>N/A (4) | PC<br>7 deg max of phase shift | |
| Phase Linearity v.s. frequency | 2.5 deg peak-peak | Not measured | NC | |
| Input Reflexion coefficient | <-15dB | <-15dB (1)<br><-8dB (4) | PC | Over frequency range |
| 2nd harmonic rejection | >30 dBc | Not measured | NC | |
| Main DC voltage supply | >40V | 40V | C | |
| Temperature | -10/ +80 degrees<br>All performance met<br>junction temperature below<br>150 deg. C | measured only at 25°C | PC | For 100W of dissipation at 85°C junction temperature is around 110°C see (5) |

(1) HPA N°1
(4) HPA N°4
(5) D3b 0.5µm Transistors an Power Bar thermal analysis

# E6 Signal Performance Compliance Matrix



| E6 Signal : Measured performance | | | | |
|---|---|---|---|---|
| **Parameters** | **Specification** | **Measurement** | **Compliance** | **Comments** |
| Output Power | > 150W | 100W (1)<br>100W (4) | NC | (1) at VDS 40V<br>(4) at VDS 30V |
| PAE | 50% | 62%(1)<br>52%(4) | C | At center frequency |
| Power Flexibility 3dB back off | 4 % efficiency degradation | 7 % (1) (4) | PC | |
| Center frequency | 1278.75 MHz | 1278.75 MHz | C | |
| Power gain | 15 dB | 14 dB (1)<br>15 dB (4) | PC | |
| Gain compression | 2dBcomp | 5dBcomp (1) (4) | NC | |
| Input Reflexion coefficient | <-15dB | Not measured | NC | |
| 2nd harmonic rejection | >30 dBc | Not measured | NC | |
| Main DC voltage supply | >40V | 40V | C | |
| Temperature | -10/ +80 degrees<br>All performance met.<br>junction temperature below 150 deg. C | measured only at 25°C | PC | For 100W of dissipation at 85°C junction temperature is around 110°C see (5) |

(1) HPA N°1
(4) HPA N°4
(5) D3b 0.5µm Transistors an Power Bar thermal analysis

# AGENDA

- HPA measurements
- **Failure Analysis**
- Improvements proposition
- HPA design with improvement
- Assessment of performance of SSPAs
- Development perspectives
- SOW Compliance Matrix
- RIDs

Main message

# Failure due to a lack of Soldering

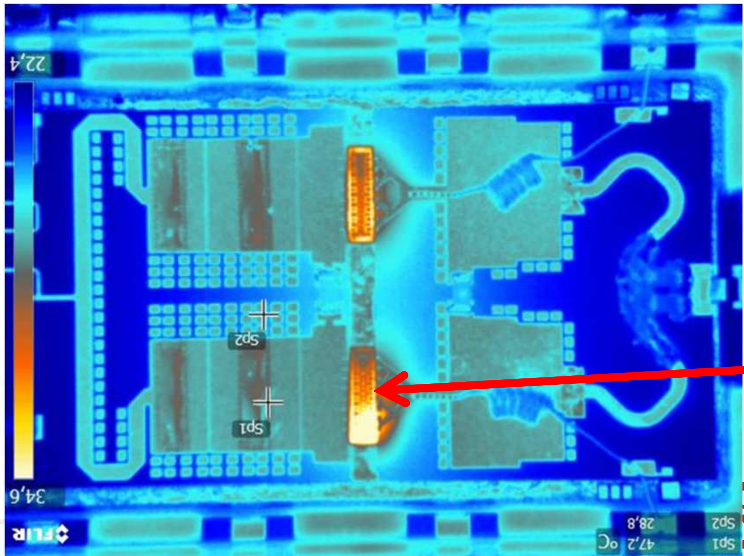


We have used housing Silver diamond carriers that are very good heatsink (thermal conductivity ~ 800 W /m. K) cf [RD2] :

- poses problems of irregular solder
- Due to the Silver diamond material, the X-rays are very difficult to be performed and the results are not so conclusive.

These carriers are now obsolete. For the next HPAs we will use copper diamond carriers:

- Very good heatsink ~ 400 W /m. K.
- Facility to perform X-rays analysis and to control soldering quality under the power bar

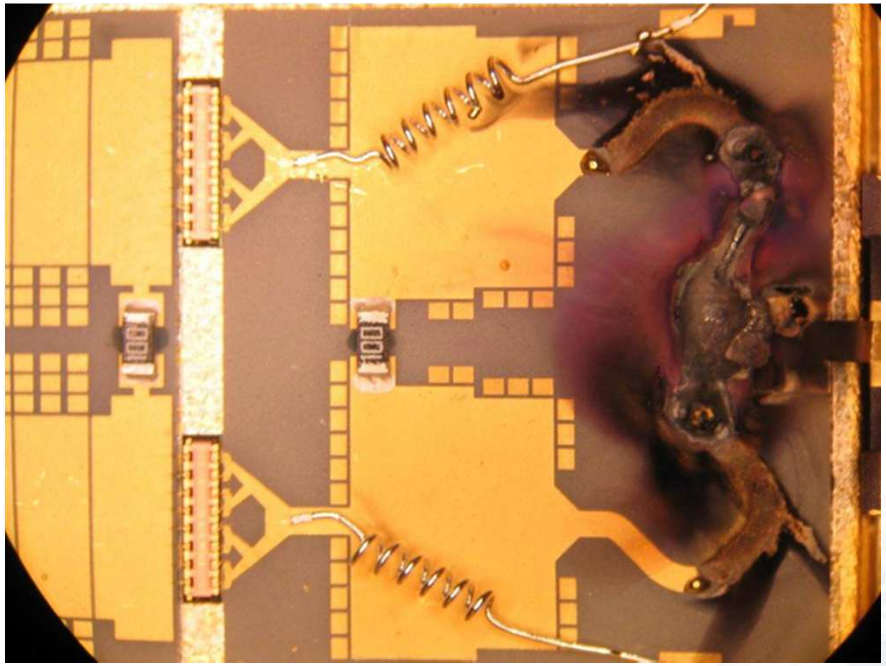


Overheating due to a lack of soldering below the transistor

# Output capacitor DC black Failure



In the design, we decide to put ATC600s Capacitor with low Electrical Serial Resistance [RD3]. But the selected report processes on MIC was gluing (84 LMI). This conductive glue has unfortunately significant RF losses, which led to a break of the output circuit matching linked to the high level of dissipation. By adding glue we managed to reduce overheating.



# Failure due to low frequency oscillations

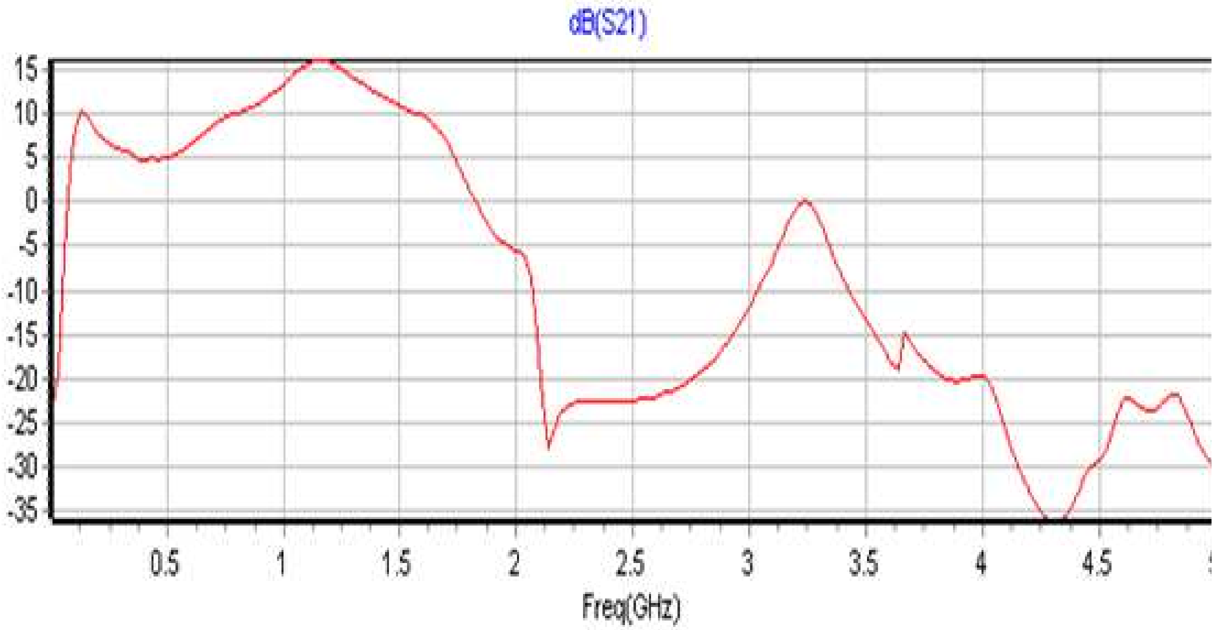


Compared to the simulations, all the measured HPA present  more gain at low frequencies:

- K<1 for Freq<100MHz
- Low frequencies oscillations
- Several HPAs destroyed

The reduction of gain at low frequencies has been managed by adding a RC network in serial at the input.

- Improvement of the stability with few margin
- Trade-off between stability vs perfomance




Gain response vs frequency with RC network

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Main message

# Improvements proposition



- Use copper diamond carriers instead of Silver diamond
  - Better Soldering and controling

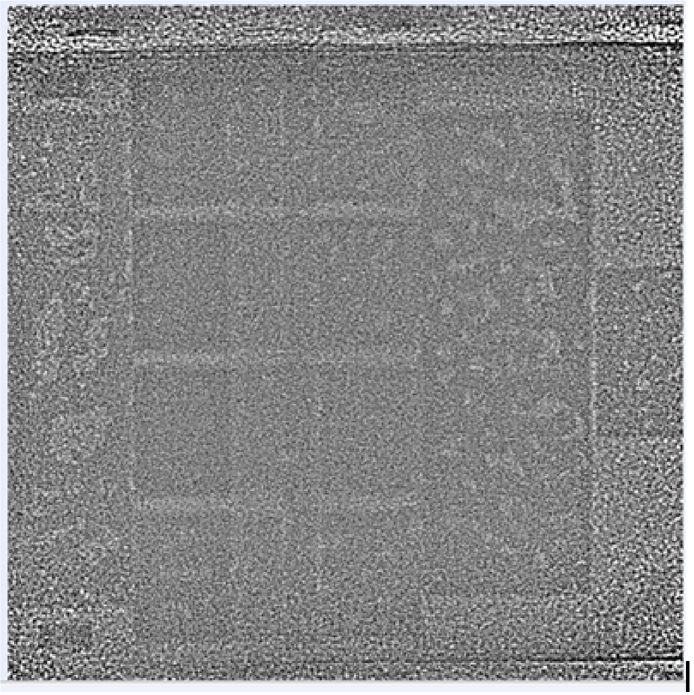


Figure 3 : C-Band HPA X rays with Diamond Silver

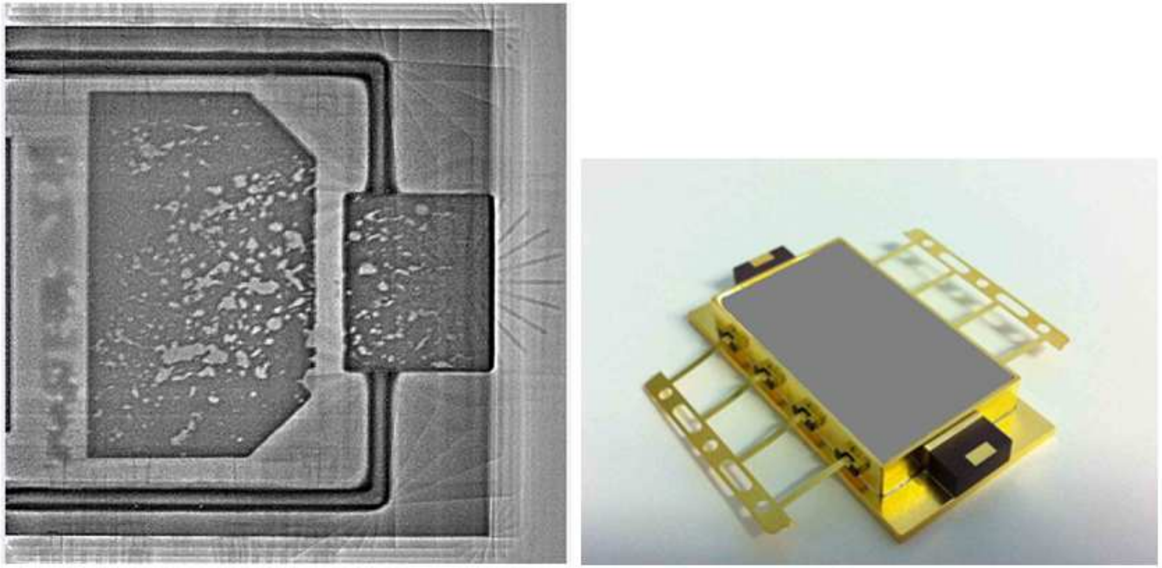


Figure 4 : X rays with Diamond cooper Egide vehicle test

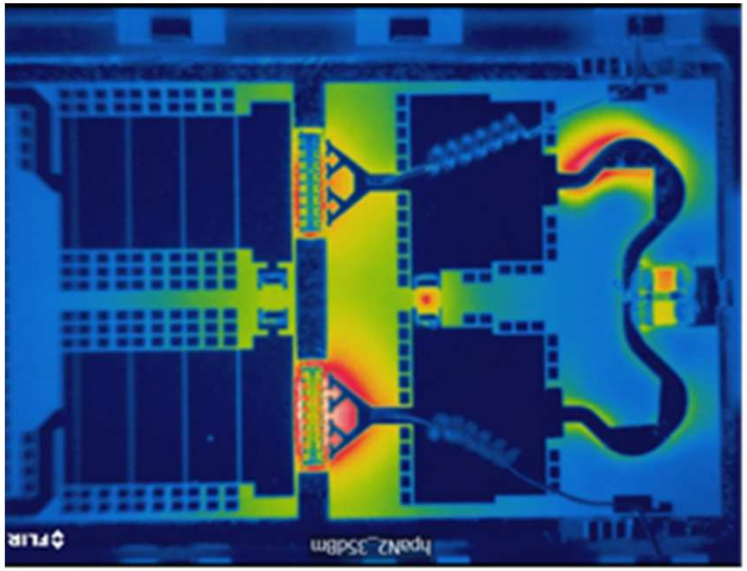
# Improvements proposition



## Transistor Sorting

The transistors must be paired as well in voltage pinch than current IDSS. In order to have the same DC current and the same behavior with the RF power

| N° Mesure | X | Y | VG100 (V) | IDSS (mA) |
|---|---|---|---|---|
| 110614967 | V | 42 | -2.140625 | 7684 |
| 110614535 | R | 42 | -1.909375 | 6404 |
| 110614103 | N | 42 | -2.253125 | 8468 |
| 110613671 | J | 42 | -2.2125 | 8526 |
| 110613683 | J | 53 | -2.2375 | 8565 |
| 110614115 | N | 53 | -2.21875 | 8189 |
| 110614088 | N | 29 | -2.23125 | 8609 |
| 110614520 | R | 29 | -2.234375 | 8533 |
| 110614952 | V | 29 | -2.203125 | 8427 |
| 110614954 | V | 30 | -2.225 | 8424 |
| 110613670 | J | 41 | -2.203125 | 8521 |
| 110614102 | N | 41 | -2.25625 | 8535 |



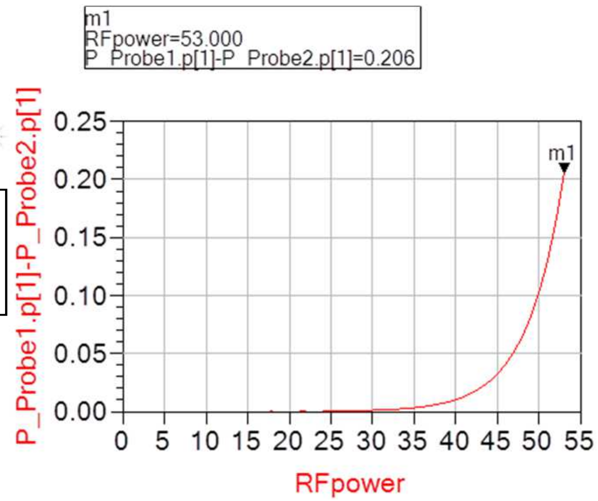
Example of DC +RF unbalanced

# Improvements : Output capacitor



- ATC 116 DA 11pF 0.889x0.889mm
- + soldering

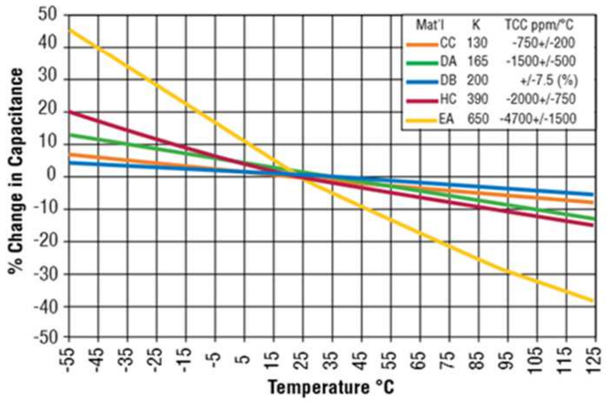
Q=500@1,8GHz
Rp= Q/C.ω
Rp=4kΩ

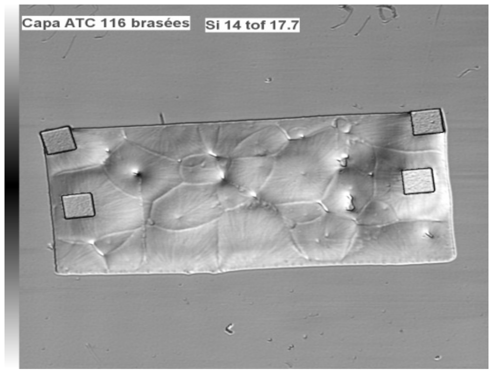



Dissipation estimation for 2 capacitors in //

**Mid-K Dielectrics**

| Dielectric Code | Dielectric Const. (K) | TCC (–55°C to +125°C) | Cap. Range (pF) | Max. DF (%)* @ 1 MHz | Max. DF (%)* @ 1 KHz | Q |
|---|---|---|---|---|---|---|
| CC | 130 | –750 ±200 PPM/°C | 0.3 to 56 | 0.15 | – | 2310 @ 5 GHz |
| DA | 165 | –1500 ±500 PPM/°C | 0.4 to 68 | 0.25 | – | 500 @ 1.8 GHz |
| DB | 200 | ±7.5% max. change (non-linear) | 0.5 to 82 | 0.25 | – | 29 @ 5 GHz |
| HC | 420 | –2000 ±500 PPM/°C | 1.1 to 180 | 0.7 | 0.3 | – |
| EA | 650 | –4700 ±1500 PPM/°C | 1.5 to 270 | 0.3 | 0.3 | – |




SAM (Scanning Acoustic Microscopy) of ATC116 soldering MIC test jig



**PROPRIETARY INFORMATION**

# Improvements : quasi-MMIC approach



The input matching circuits are based on the use of the technology UMS ULRC-10.

This GaAs technology enables the use of lumped elements (R, L, C):

Enhance the complexity, accuracy and integration of matching networks

- Consolidating stability function
- Perform DC / RF decoupling efficient
- Enable broadband matching
- Minimize production tunings
- Second harmonic matching

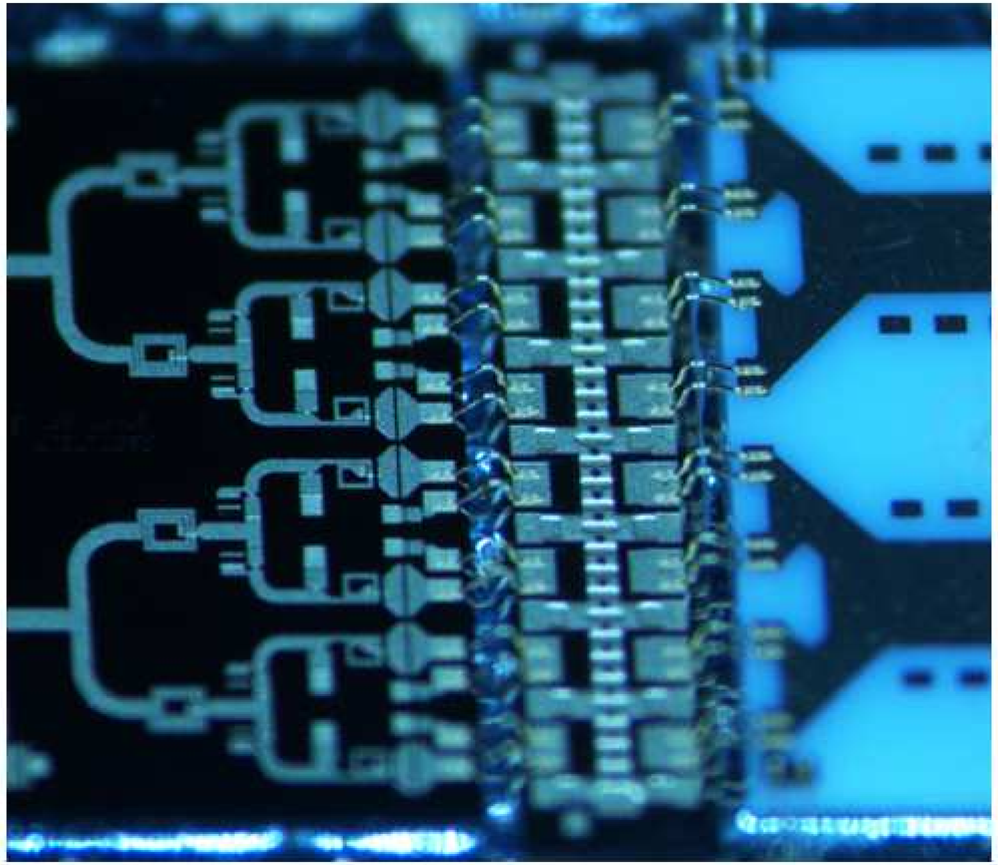


Figure 12 : Photo of C- BAND HPA with quasi MMIC approach

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- HPA measurements
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Main message

# Possible HPA design with improvement



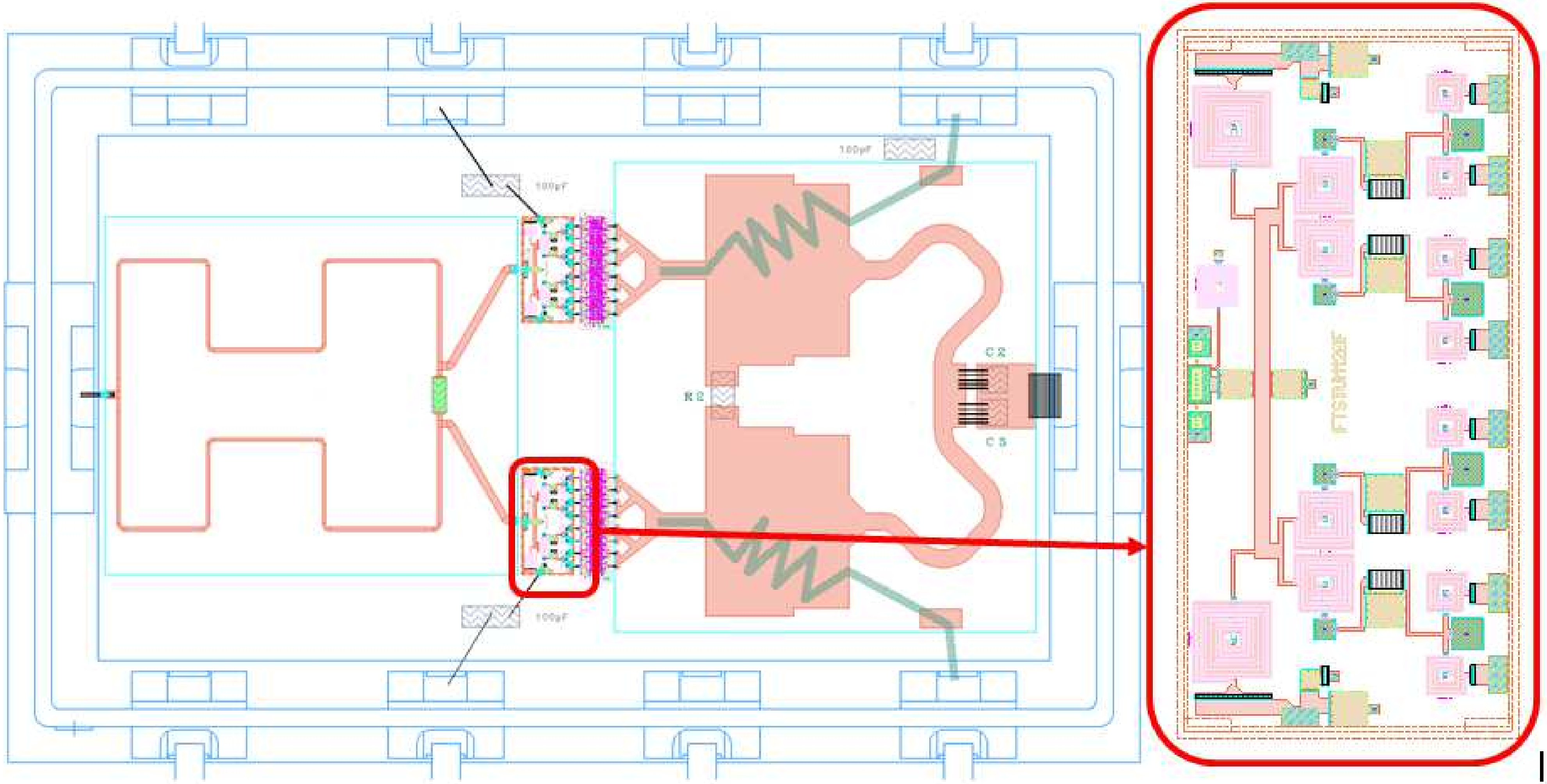


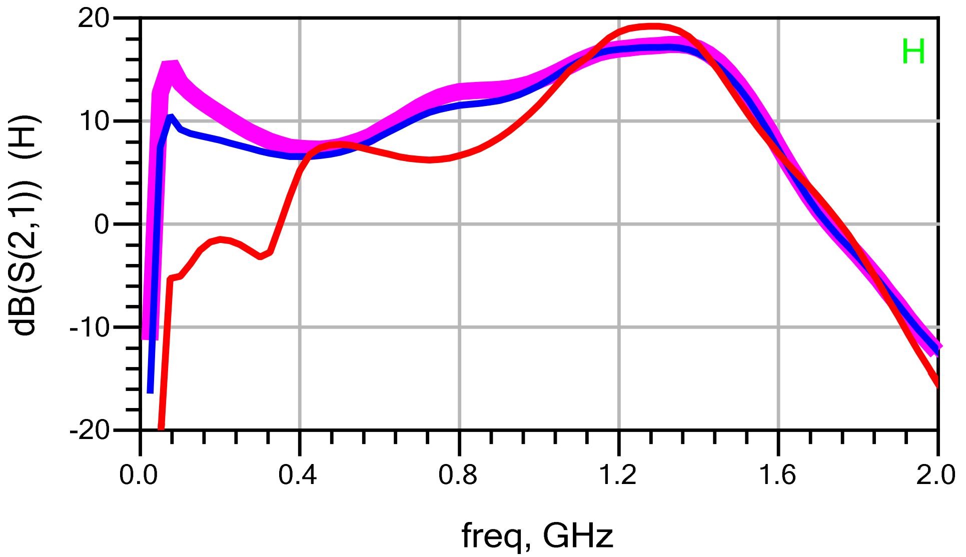
Figure 17 : Layout of HPA with Quasi MMIC approach

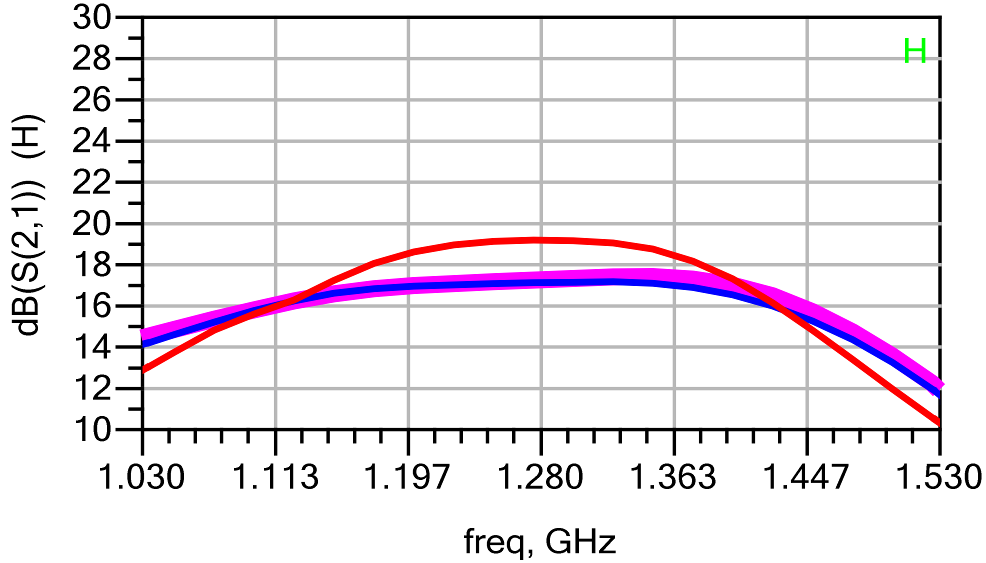


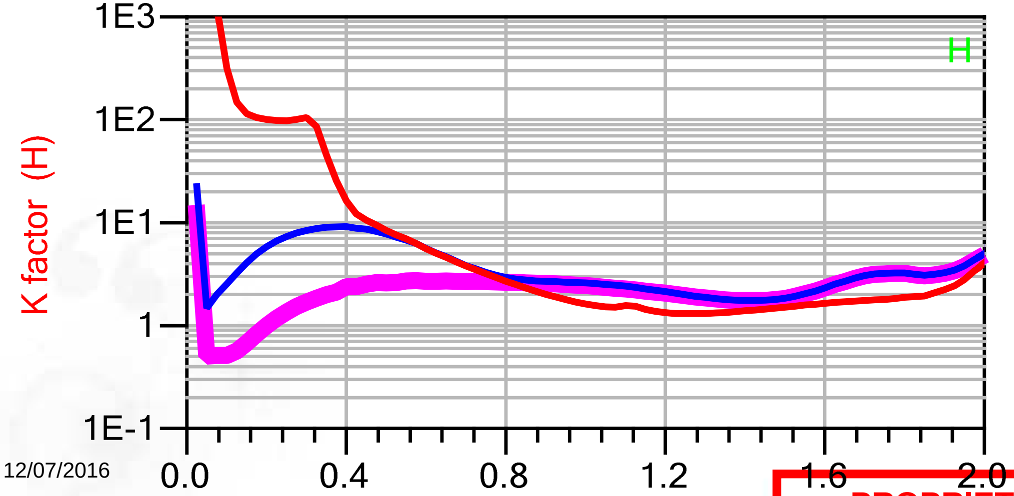
**PROPRIETARY INFORMATION**

# HPA simulated performances with improvement

## S parameters



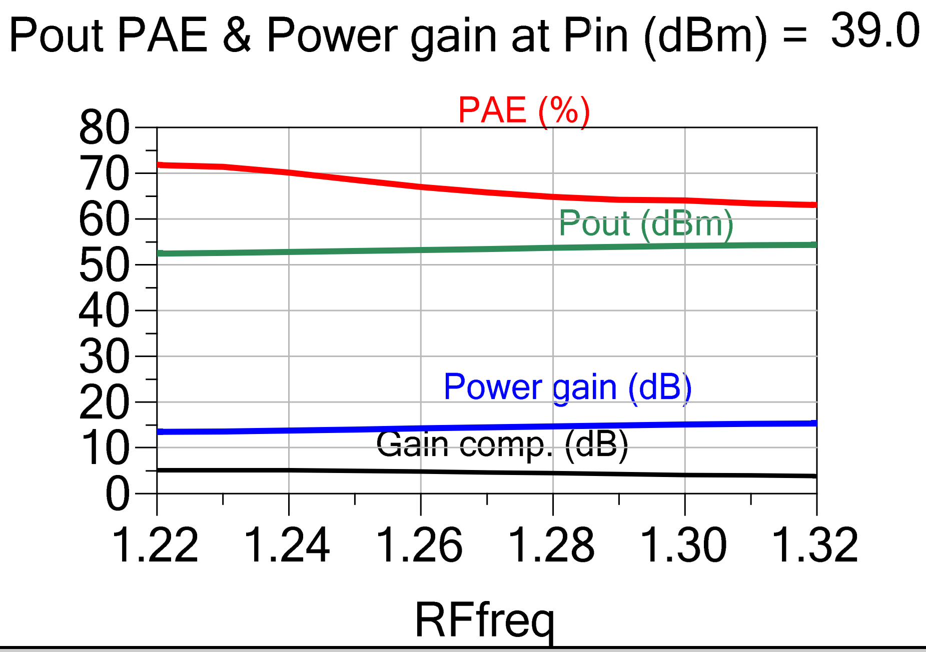




- Initial simulation (W/O Serial Resistance)
- RC Added simulation (W/O Serial Resistance)
- Quasi-MMIC Simulation

# HPA simulated performances with improvement



- CW power simulation




| CW mode : PAE performance for an input power of 39 dBm | |
|---|---|
| **Parameters** | **Simulation** |
| Output Power | 53.7dBm |
| PAE | >69% |
| Power gain | 15 dB |
| Gain compression | 5dBcomp |

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# Preliminary market trend: SSPA for navigation applications



For Galileo G2G, 3 types of SSPA with different level of Pout are required in the payload:

- **E1 band (fc=1,575 GHz, Δf= 40MHz) : 220W up to 300W (max), CW mode**
- E5 band (fc=1,17 GHz, Δf= 90MHz) : 130W, CW mode
- E6 band (fc=1,28 GHz, Δf= 40MHz): 130W CW mode

For EGNOS or SBAS services, the maximum output power required for future SSPA will be:

- E1, SSPA with Pout<150W in CW mode
- E5, SSPA with Pout<170W in CW mode

# Preliminary specifications of a L-band 300W GaN SSPA for navigation applications



| Parameter | Value |
|---|---|
| Frequency | E1 (fc=1,575 GHz) |
| Bandwidth | 40 MHz |
| Pout | Maximum of 300W at saturation level (CW mode) |
| Associated efficiency | >53% |
| Gain max | 75dB |
| Control Mode for Gain | Fixed Gain Mode |
| Primary Bus | 50 or 100V |
| CAN protocol | Yes |
| Mass | <3,1 kg |
| Temperature | [-20°C,+65°C] qualification |
| Size (Lxlxh) | 300x140x125mm |

Table 1 : Preliminary specifications of a L-band 300W GaN SSPA for navigation (G2G, E1 signal)





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# 300W SSPA block-diagram



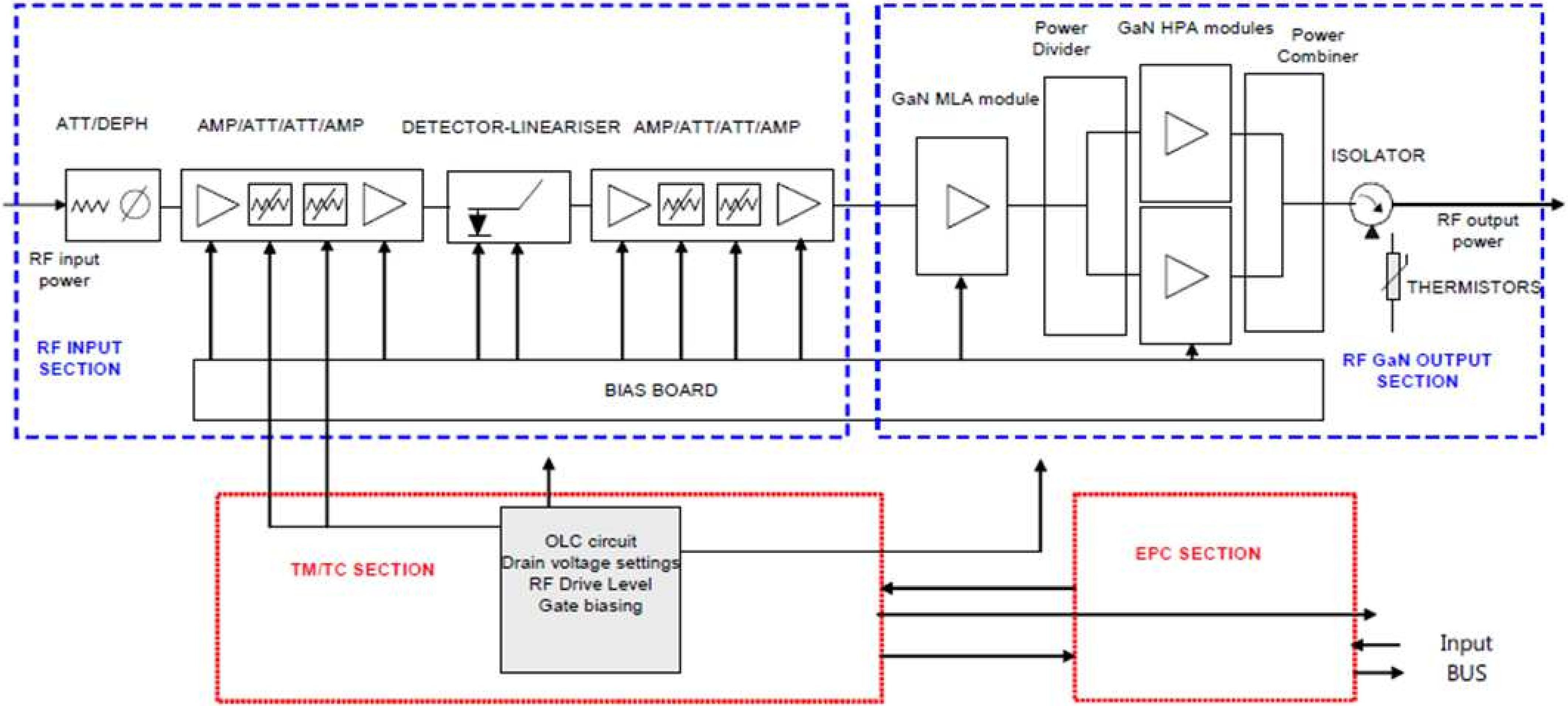



Figure 18: 300W SSPA schematic using GaN HPA modules

# Electrical budget in CW mode of the 300W L-band GH50 SSPA



| | RF SECTION | Gain | Cumul Gain | NF | Cumul NF | Signal Level | Signal level | Intermod | Pdc | Pdiss | PAE | EPC | Gain Comp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N° | Elements | dB | dB | dB | dB | dBm | W | dB | W | W | % | N° | dB |
| | INPUT | | | | | -10,00 | 1,00E-04 | | | | | | |
| 1 | ATT_PHASE_SHIFTER | -6,00 | -6,00 | 6,00 | 6,00 | -16,00 | 0,0000 | N/A | 0,00 | 0,00 | 0,00 | 2 | 0,00 |
| 2 | LLA_GaAs | 17,30 | 11,30 | 5,00 | 11,00 | 1,30 | 0,0013 | N/A | 0,33 | 0,33 | 0,40 | 2 | 0,00 |
| 3 | ATT1 | -27,00 | -15,70 | 27,00 | 16,96 | -25,70 | 0,0000 | N/A | 0,00 | 0,00 | 0,00 | | 0,00 |
| 4 | 1XCHA3801 | 28,67 | 12,97 | | 16,96 | 2,97 | 0,0020 | N/A | 0,32 | 0,32 | 0,62 | 2 | 0,01 |
| 5 | COUPLER+ATT | -5,00 | 7,97 | 5,00 | 16,97 | -2,03 | 0,0006 | N/A | 0,00 | 0,00 | 0,00 | | 0,00 |
| 6 | LIN_GaN | -9,51 | -1,54 | 10,00 | 17,09 | -11,54 | 0,0001 | N/A | 0,10 | 0,10 | -0,56 | 3 | -6,10 |
| 7 | LLA_GaAs | 17,30 | 15,76 | 5,00 | 17,35 | 5,76 | 0,0038 | N/A | 0,33 | 0,33 | 1,12 | 2 | 0,00 |
| 8 | ATT2 | -28,00 | -12,24 | 28,00 | 18,51 | -22,24 | 0,0000 | N/A | 0,00 | 0,00 | 0,00 | | 0,00 |
| 9 | 1XCHA3801 | 28,64 | 16,41 | | 18,51 | 6,41 | 0,0044 | N/A | 0,32 | 0,32 | 1,35 | 2 | 0,04 |
| 10 | MLA_GaN_2stages_25W | 34,88 | 51,29 | | 18,51 | 41,29 | 13,4488 | N/A | 31,84 | 18,40 | 42,22 | 1 | 2,77 |
| 11 | Diviseur_IN | -3,31 | 47,98 | 0,30 | 18,51 | 37,98 | 6,2756 | N/A | 0,00 | 0,90 | 0,00 | | 0,00 |
| 12 | HPA_200W_ESA_TRP | 14,42 | 62,40 | | 18,51 | 52,40 | 173,7057 | N/A | 267,81 | 100,38 | 62,52 | 1 | 5,01 |
| 13 | HPA_200W_ESA_TRP | 14,42 | 62,40 | | 18,51 | 52,40 | 173,7057 | N/A | 267,81 | 100,38 | 62,52 | 1 | 5,01 |
| 14 | Combineur_OUT | 2,71 | 65,11 | 0,30 | 18,51 | 55,11 | 324,2233 | N/A | 0,00 | 23,19 | 0,00 | | 0,00 |
| 15 | Isolator | -0,15 | 64,96 | 0,15 | 18,51 | 54,96 | 313,2162 | N/A | 0,00 | 11,01 | 0,00 | | 0,00 |
| | Total RF Section | | 64,96 | | 18,51 | 54,96 | 313,22 | N/A | 568,87 | 255,65 | 55,06 | | 1,73 |

| TM/TC Board | |
|---|---|
| Connected To EPC Output N° | Pc W |
| 1 | 1,00 |
| 2 | 0,50 |
| 3 | 1,00 |

| EPC | Overall Efficiency (%) : | | 93 |
|---|---|---|---|
| Output | Voltage | Current | Power |
| N° | V | A | W |
| 1 | 42,00 | 13,53 | 568,46 |
| 2 | 5,00 | 0,36 | 1,80 |
| 3 | -5,00 | 0,22 | 1,10 |

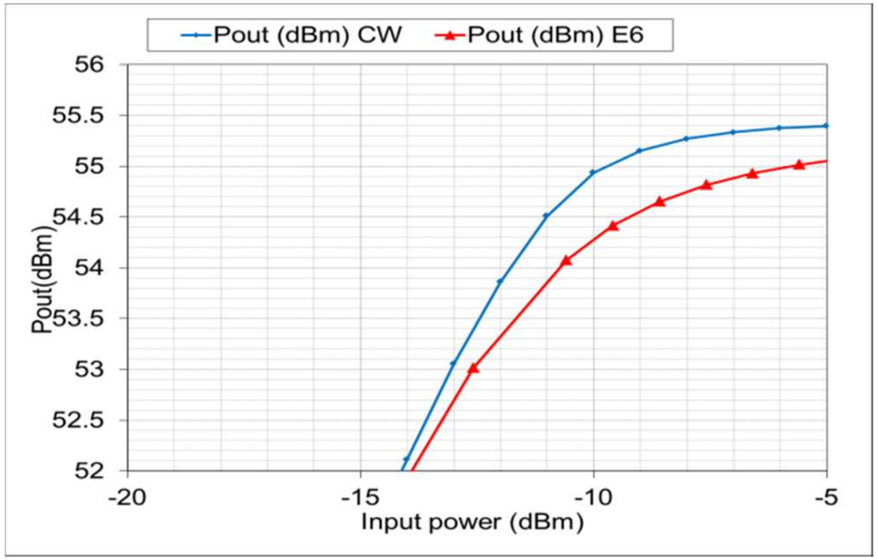
| EQUIPMENT | | | | |
|---|---|---|---|---|
| Primary DC Voltage | Primary DC Current | Primary DC Power | PAE | Pdiss |
| V | A | W | % | W |
| 100,00 | 6,14 | 614,37 | 50,98 | 301,16 |

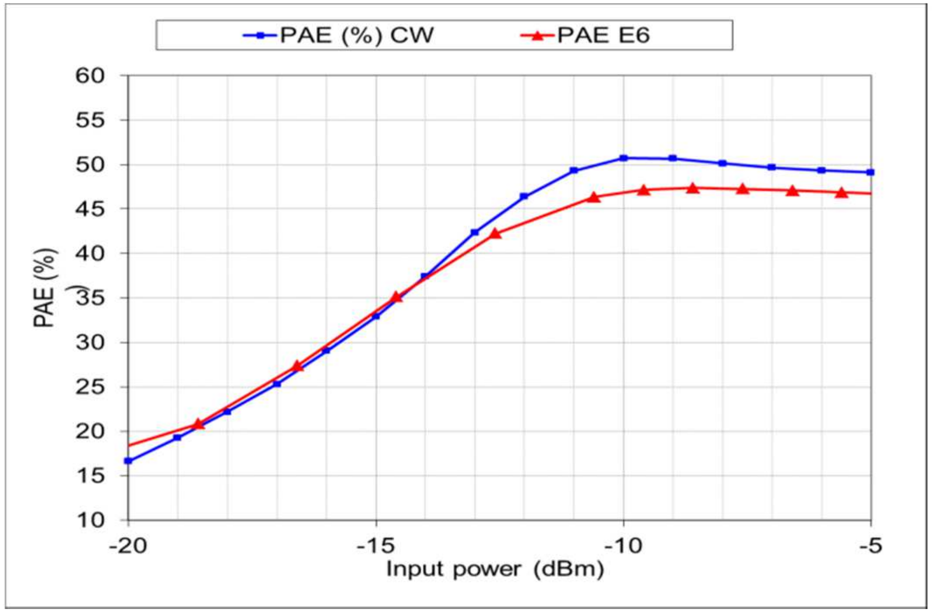
Table 6: Electrical budget in CW mode of the 300W L-band GH50 SSPA

Measured data

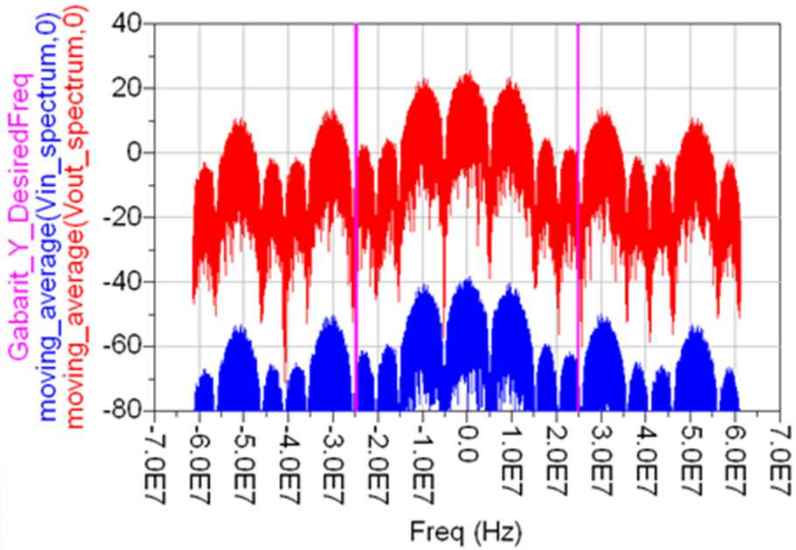
# Simulation with E6 GALILEO SIGNAL at SSPA Level






Spectra at the Input and Output of the SSPA




| Parameter | Value |
|---|---|
| Signal | E6 Signal |
| Pout(W) | ≥ 250W |
| PAE(%) | >45% |
| Compression | 2 dB |
| Gain at compression | 64dB |

Table 8 : SSPA main electrical performances with a E6 signal

# AGENDA

- HPA measurements
- Failure Analysis
- Improvements proposition
- HPA design with improvement
- Assessment of performance of SSPAs
- Development perspectives
- SOW Compliance Matrix
- RIDs

Main message

# Development perspectives



- The HPA module designed, manufactured and tested in the frame of this study has proven its ability to deliver very high output power at L band (up to 180W) with efficiency above 65%. These excellent performances made it a perfect candidate to the high power SSPA at L band, as well as at S band the derived HPA module, with a straightforward adaptation to the new frequency.

- This module will be the heritage power building block for the High Power L/S SSPA product that will make use of a single HPA, and also for the Very High Power L/S SSPA which power section will be built around two HPA modules in parallel.

- One major program target for these products at L band is the Galileo program, with several tens of units. But several other prospects have been already identified : digital radio satellite payloads at S band where overall emission power is over 3 kW and is achieved on current programs with several 250W class TWTA, communications channels and GNSS augmentations systems where 50~100W SSPA are commonly used.

# AGENDA

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# SOW Compliance Matrix



## Deliverable compliance matrix

| Items | Compliance | Comments |
|---|---|---|
| HW1: Mask reticule for foundry run (GDS2 file) | **C** | |
| HW2: GaN wafer and diced transistors | C | |
| SW1: Electrical transistor & passive circuit models for usage in ADS circuit simulation tool | C | |
| HW4: HPA modules including test jigs, 2 units [(1)] | PC | 1st HPA Performance are closed to the target<br>2nd HPA is not working |
| HW5: Delivery of Multipactor / Corona test jig equipped with power micropackage | C | |

(1) 03_AO6505 TAS-F_Proposal_Management_Volume 2.pdf
Table 8: Compliance to the SoW

# SOW Compliance Matrix



## Interface and Environmental compliance matrix

| Interface Requirements | |
|---|---|
| **Specification** | Compliance |
| RF accesses shall have coaxial connectors in 50hm.<br>DC accesses shall be separated from RF accesses via a dedicated connector.<br>These connectors shall be provided by the test jig . | C |
| The HPA RF accesses shall be DC blocked and the DC accesses shall be RF free. | C |
| The test jig shall have a sufficient surface in order to provide the capability to transfer efficiently the<br>heat produced by the HPA when connected to a heat sink. | C |
| The test jig shall be delivered with the HPA. | C |

| Environmental Requirements | | | | |
|---|---|---|---|---|
| **Parameter** | **Value** | **Specification** | Compliance | **Comments** |
| Pressure | Ambient and 10e-6 mbar | The HPA shall be able to operate in vacuum Multipactor free with margin as per | C | More than 6dB margin |
| Temperature | -10 / +80 degrees | Defined as the temperature of the surface where the HPA package shall be mounted<br><br>All performance met and junction temperature below 150 deg. C for GaN | PC | measured only at 25°C<br><br>For 100W of dissipation at 85°C<br>junction temperature is around 110°C see (5) |

(5) D3b 0.5µm Transistors an Power Bar thermal analysis

# Discussion



- Partially compliant to the specification and to deliverables
- In order to improve stability, reliability and performance, TAS-F has identified corrections and solutions to be implemented on future L-band GaN HPA module design
- Less than 20x  32mm Trek Dies available from UMS at  the beginning of the study (already noticed identify during negotiation meeting)
- Total of 10x HPAs manufactured/reworked
  - 2x HPA modules manufactured and tested with STARDUST dies
- Preliminary HPA re-design with ULRC-10 MMIC

# AGENDA

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Main message





ThalesAlenia Space