VIRATEC-RPAX

D7 – X-band Transmitter System Engineering CDR Milestone Report

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1 Contents

2 Introduction

This document contains technical report describing analysis of constraints and functional requirements (PDR milestone report) of transmitter system developed within collaboration project of establishing X-band uplink and downlink capabilities from RF to IF for the VIRAC 16-m antenna RT-16, "VIRATEC-RPAX". This project is part of the PECS program with ESA.

3 Applicable and reference documents

Table 1. Reference Documents.

RD	Document	Reference
RD-1	D1 Technical Requirement Specifications [X-band]	SAMS-109-36235 Version 0.24
RD-2	VIRAC-RTGS report - D1 Technical Requirement Specifications [S-band]	SAMS-109-31648
RD-3	RPAX_D7_X_band_Transmitter_System_Engineering_Report PDR	RPAX_D7_X_band_Transmitter_System_Engineering_Report_PDR.docx
RD-4	Won Il Chang et al., Compact High-Directivity Contra-Directional Coupler	https://www.mdpi.com/2079-9292/11/24/4115

4 Design of transmitter system

4.1 Overall architecture

The overall architecture of designed X-band transmitter system is shown in Figure 1. The HPA module is based on two commercial of-the-shelf (COTS) Qorvo QPM1017 GaN solid state modules combined using balanced amplifier configuration. The HPA is driven using Alaris KU PA 640720-10 A which is COTS medium power amplifier. The HPA module includes built-in directional coupler for forward and reflected power monitoring. The output interface of HPA module is N-type coaxial cable with transition to WR112 or WR137 waveguide for feed system interfacing.

Transmitter system includes HPA module bias control and monitoring module as well as capability to control and monitor the key parameters via Ethernet connection. The system is powered using COTS switch mode power supply modules.

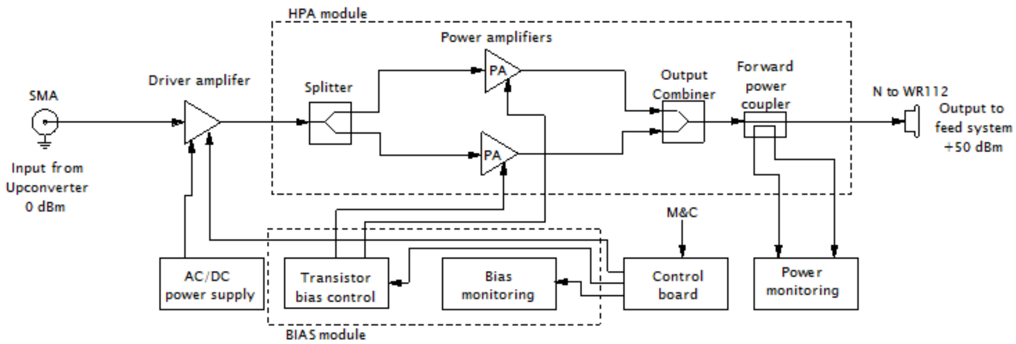

Figure 1. Block diagram of X-band transmitter system prototype.

4.2 Description of HPA module

As already mentioned, the HPA module is based on Qorvo QPM1017. Although this device has advertised frequency range up to 7 GHz, the detailed inspection of performance graphs shows acceptable performance up to 7.5 GHz, thereby including required transmit band of 7.145 to 7.235 GHz. Single HPA module has up to +51 dBm maximum output power with 30…40% power added efficiency at 7.2 GHz. Although theoretically single module output power is within the requirement of +50 dBm, it was decided to combine two QPM1017s which would allow each individual device to operate at half power, thereby improving thermal performance.

4.2.1 Hybrid couplers

Two modules are combined using microstrip quadrature hybrid splitters. The hybrid splitters are optimized for the best amplitude balance and phase shift at center frequency of the TX band. The simulation model of hybrid coupler is shown in Figure 2. The calculated performance of splitter is shown in Figure 3.

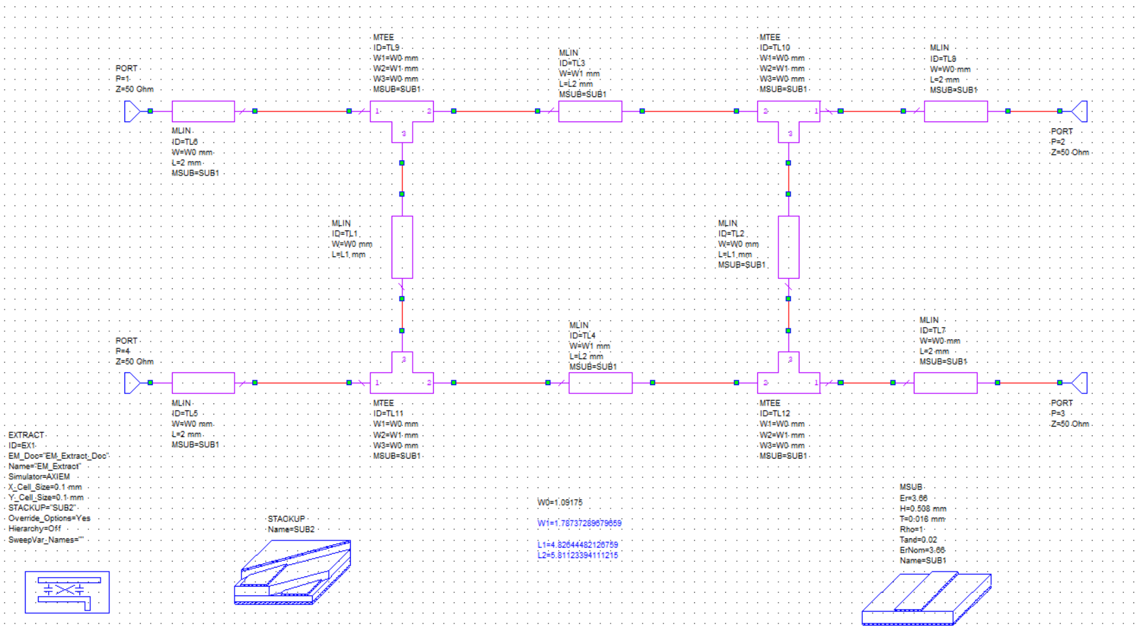

Figure 2. Simulation model of HPA hybrid coupler.

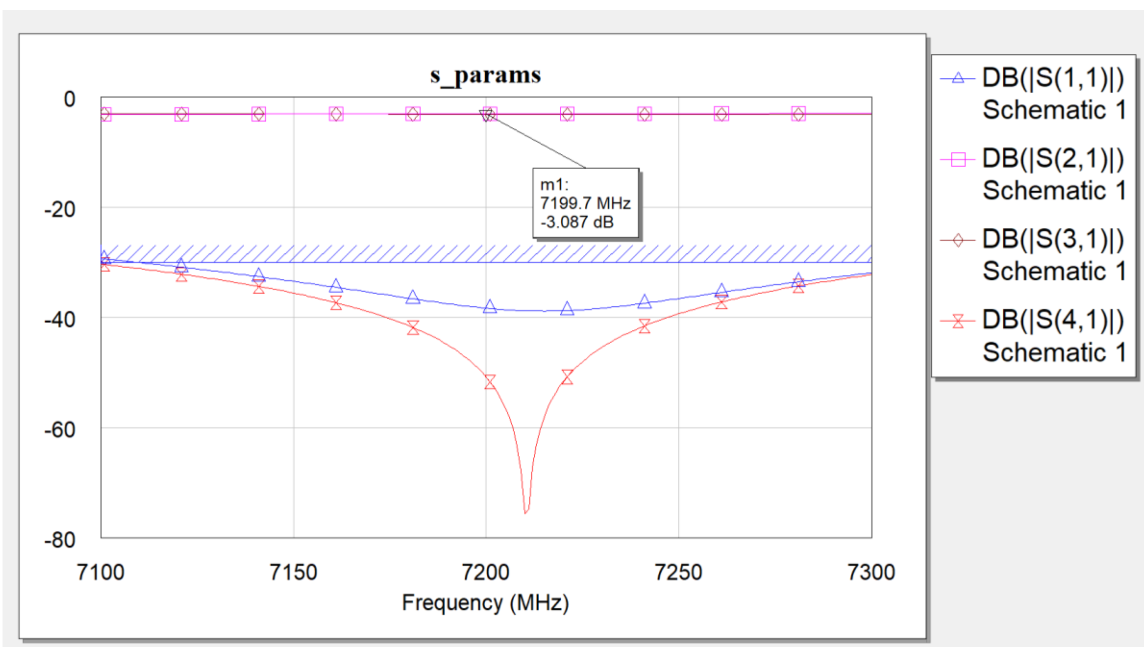

Figure 3. Calculated S-parameters of hybrid coupler.

4.2.2 Balanced amplifier configuration

The simulation circuit of combined amplifier is shown in Figure 4. It employs two hybrid coupler sub-modules and linear S-parameter of QPM1017 measured at 85 degC provided by device manufacturers. The calculated S-parameters are shown in Figure 5. Results show good return loss and linear operation gain of 20 dB at ≈7.2 GHz.

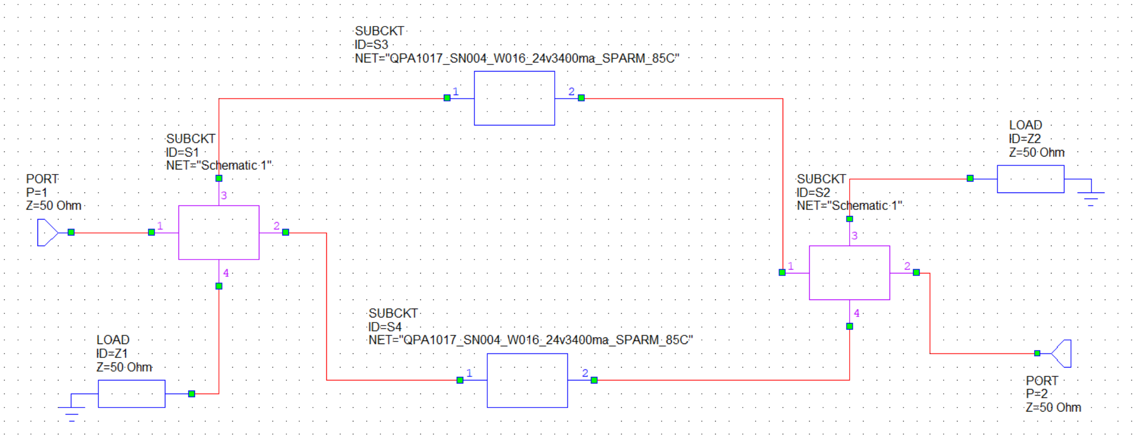

Figure 4. Simulation model of balanced HPA.

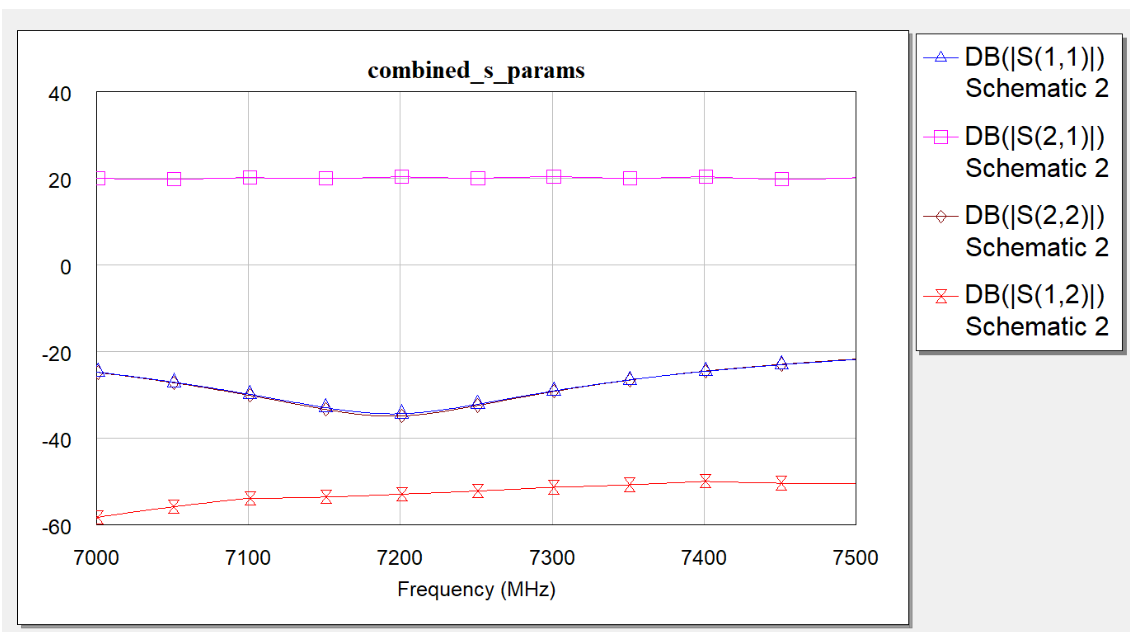

Figure 5. Calculated S-parameters of balanced HPA.

4.2.3 Design of microstrip coupler

The design of monitoring coupler is based on [RD-4] which allows us to achieve high directivity using asymmetric microstrip technology. The simulation model and achieved performance is shown in Figure 6 and Figure 7 respectively. The designed coupling coefficient is 26.7 dB and achieved isolation is >60 dB, which corresponds to directivity of better 30 dB.

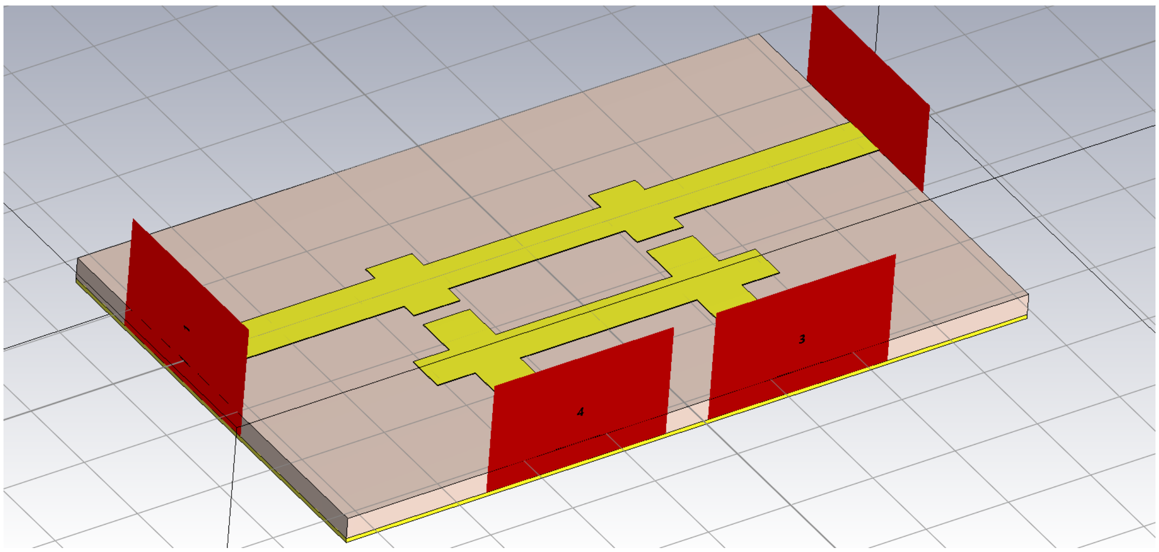

Figure 6. Simulation model of microstrip directional coupler.

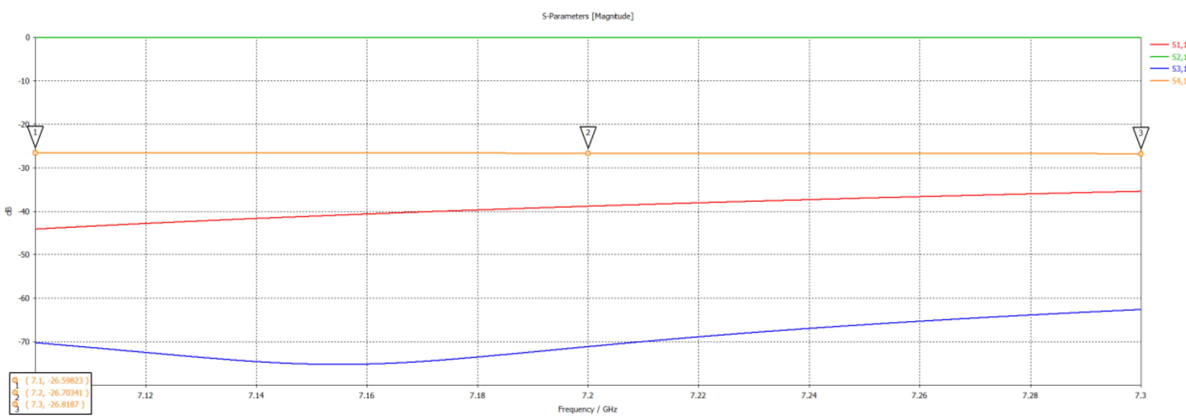

Figure 7. Calculated S-parameters of microstrip directional coupler.

4.2.4 PCB design of HPA module

The final schematic for PCB design is shown in Figure 8 and PCB layout is shown in Figure 9. Chosen PCB dielectric material is Rogers RO4350 with thickness of 0.5 mm. Additional 20 dB attenuation is added in coupled signal path, resulting in overall coupling coefficient of ≈47 dB.

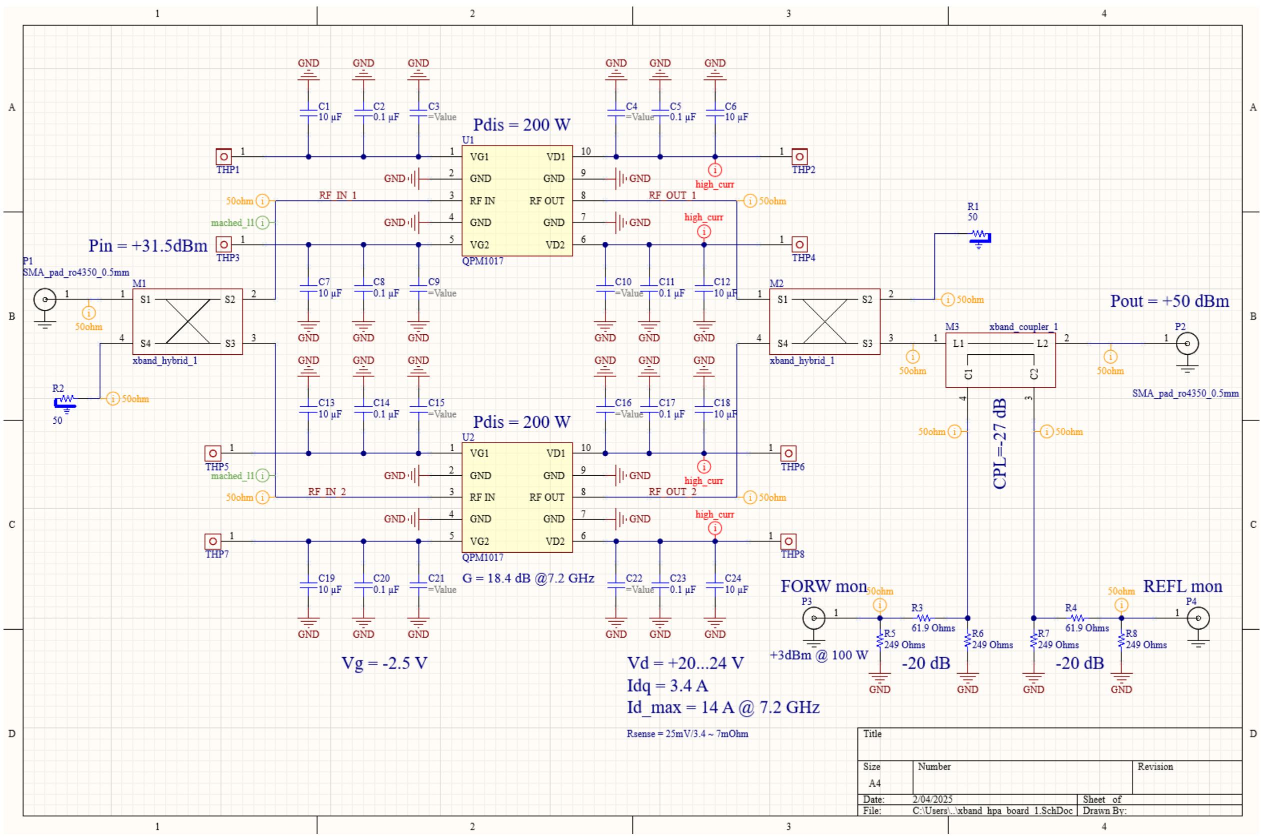

Figure 8. Schematic of HPA module.

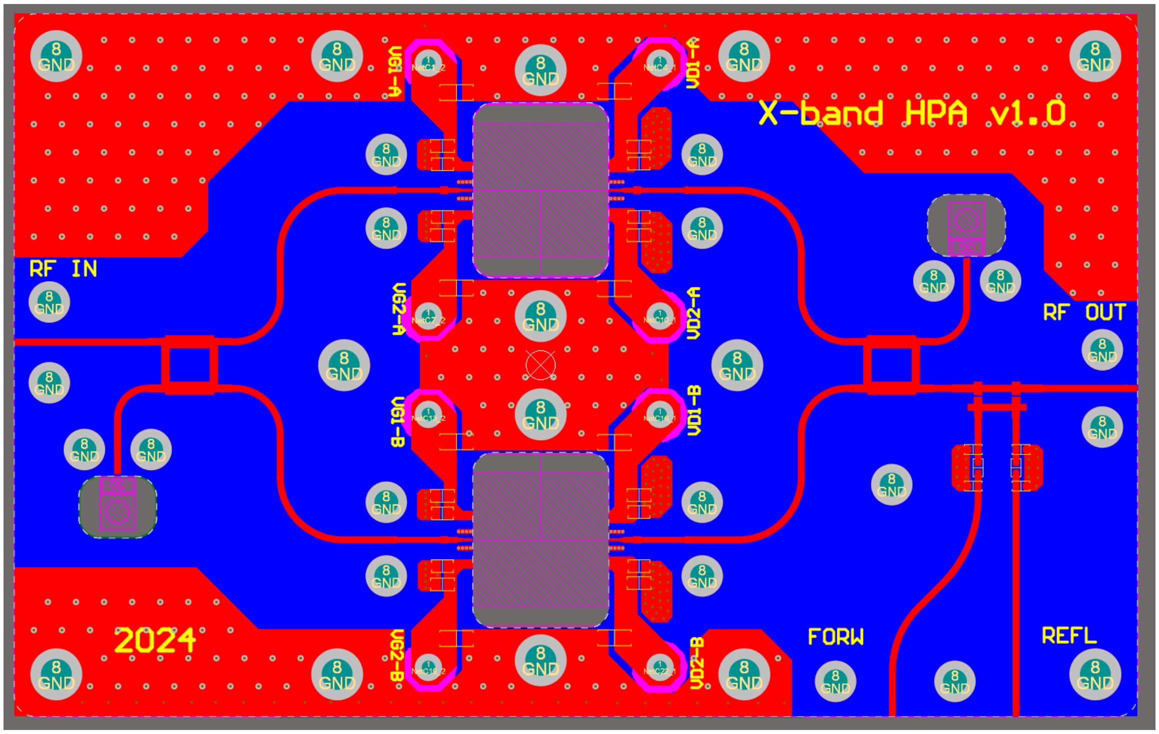

Figure 9. PCB layout of HPA module.

4.2.5 Mechanical and thermal design of HPA module

Exploded view of mechanical CAD assembly is shown in Figure 10. Two power amplifier devices are bolted to heat spreader made from copper which in turn is bolted to aluminum heatsink. Heat spreader contains channels for routing biasing wires below the PCB itself. External enclosure is made from aluminum, which is also bolted to heatsink. The driver amplifier module is bolted to the same heatsink as well. All thermal interfaces contain Arctic Silver 5 thermal paste. Figure 11 shows fabricated and assembled PCB and enclosure.

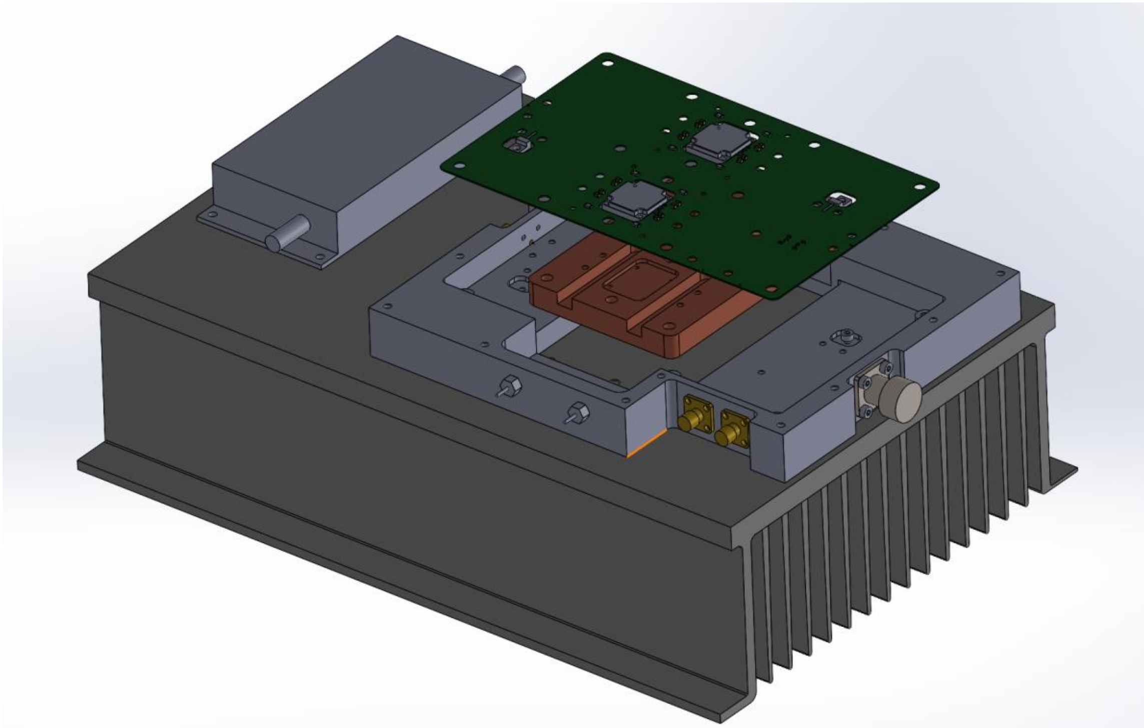

Figure 10. CAD model of HPA module mechanical assembly.

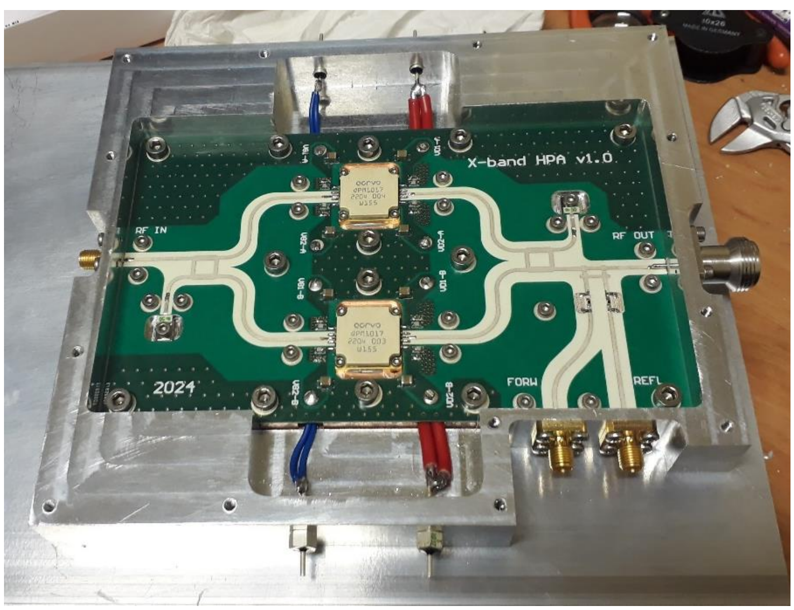

Figure 11. Fabricated and assembled HPA module.

4.2.6 Design of HPA power supply

Due to depletion mode solid state devices employed in power amplifier modules, it is necessary to follow specific biasing sequence procedures. It is also necessary to stabilize the drain current in closed loop mode, but due to class AB operation of output stage, biasing supply must be able to switch operation to open loop mode, to allow average drain current increase in case of large output signal levels. It was decided to use Analog Devices AD7293 bias controller which integrates mentioned functionality in single chip. It also contains various protection and monitoring capabilities. We decided to use evaluation board EVAL-AD7293SDZ during development of this project prototype. To adapt the evaluation board for QPM1017 biasing, an external module was made which contains current sense resistors and high-side PMOS type drain voltage switch. Two independent channels of AD7293 were employed for two balanced amplifier channels respectively. AD7293 is controlled via SPI using W5500-EVB-Pico development board, which also contains Ethernet interface for implementation of remote control and monitoring. The following biasing functionality were implemented:

1. After initial power-on the drains of HPA modules are disconnected from 24V power supply and -4.7V is applied to gates, ensuring that power devices are at off state.
2. After receiving ‘RF ON’ command, drains are connected to 24V voltage and gate voltages gradually increased until drain current of 3A is achieved. At this stage, the drain current is regulated in closed-loop mode regardless of device temperature, drain voltage and signal power.
3. Operation to open-loop mode is initiated with different remote command – in this mode, the gate voltage is fixed at constant level which were last present during closed-loop mode. In the open-loop mode drain current increases up to ≈10A per channel (20 A combined) with increasing RF signal power level.
4. The power-down procedure is reverse of power-up procedure.
5. The open-loop mode is only allowed when closed-loop mode is already operational, to make sure that gate voltage is settled to correct level.

The Table 2 summarizes the commands which were implemented in remote control board. Figure 12 shows an overall X-band transmitter system with various sub-modules identified.

Table 2. Implemented remote commands.

Command	Notes
pon	HPA modules in closed loop biasing mode on/off control. Example: ‘**pon=1**’ to turn biasing on ‘**pon=0**’ to turn biasing off. If operated in open-loop mode, operation is changed to closed-loop at next power up.
olm	Open loop mode control. Example: ‘**olm=1**’ to turn switch operation to open-loop mode. Closed loop mode must be already active. ‘**olm=0**’ to switch back to closed-loop mode.
mon	Query-only command for monitoring of drain voltage, drain current, gate voltage, heatsink temperature and active biasing mode

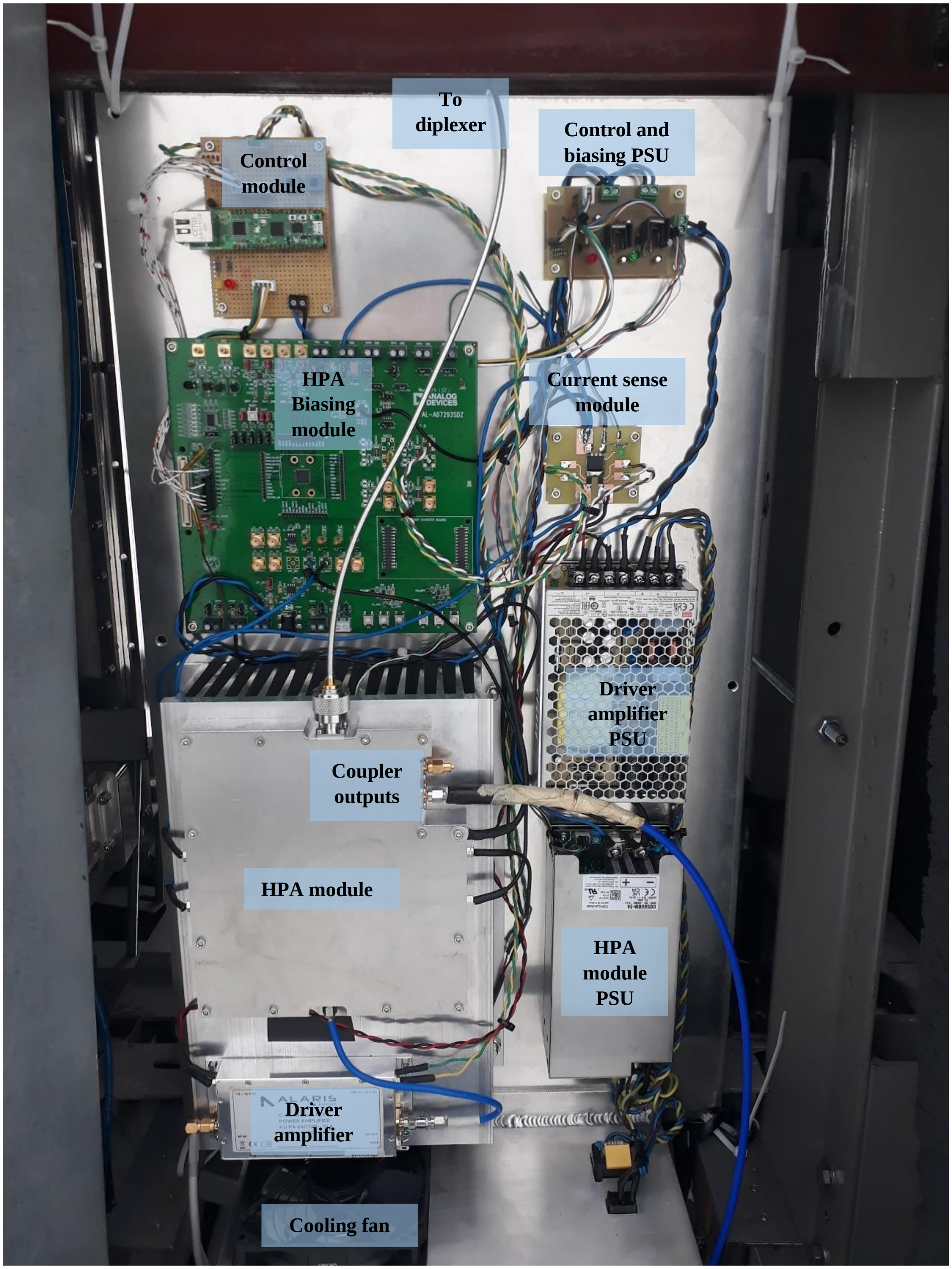

Figure 12. Overall view of transmitter system installed at RT-16 secondary focus vertex room

4.3 Testing results

4.3.1 Output return loss and coupling coefficient.

The measured return loss at HPA module output is shown in Figure 13. No input signal was present at the HPA input during the measurement. Although there is a slight unexpected shift of minimum value, the RL is within -18... -11 dB throughout X-band TX band. The shift may be explained by unmodelled effects of PCB fabrication (shift in hybrid coupler resonance frequency, for example), and/or unmodelled effects of power amplifier case leads transition to PCB or non-optimal transitions from PCB to coaxial connectors. To investigate this issue, more prototyping iterations would be needed.

Figure 14 shows measured monitoring coupler coupling coefficient. Achieved value of -44 dB is relatively close to expected value of combination of coupler itself (theoretical coupling: 27 dB) and additional 20 dB attenuator (see Figure 8).

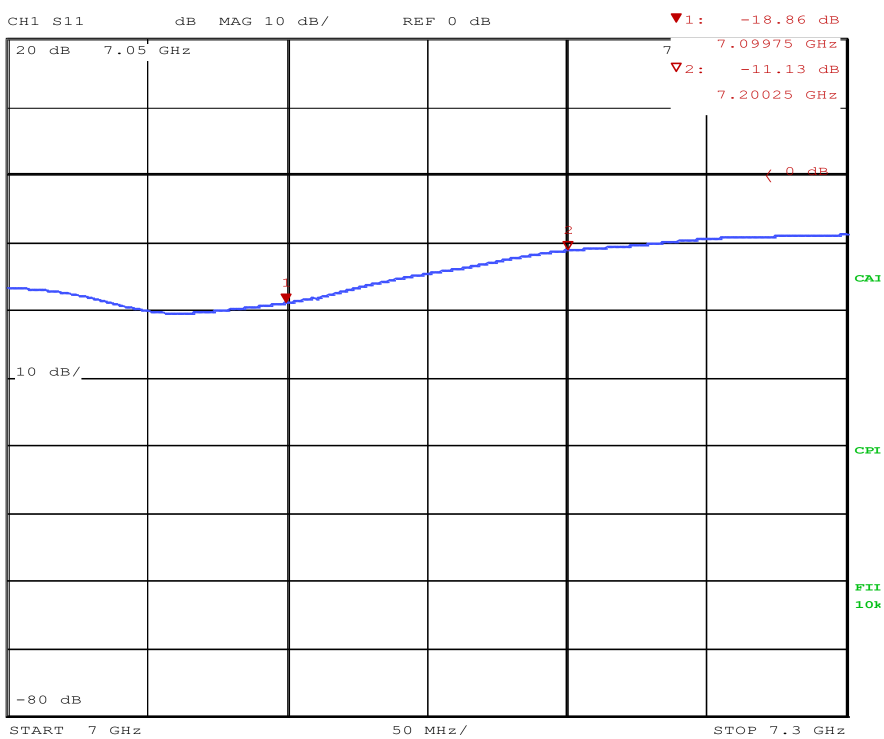

Figure 13. Measured output return loss of HPA module.

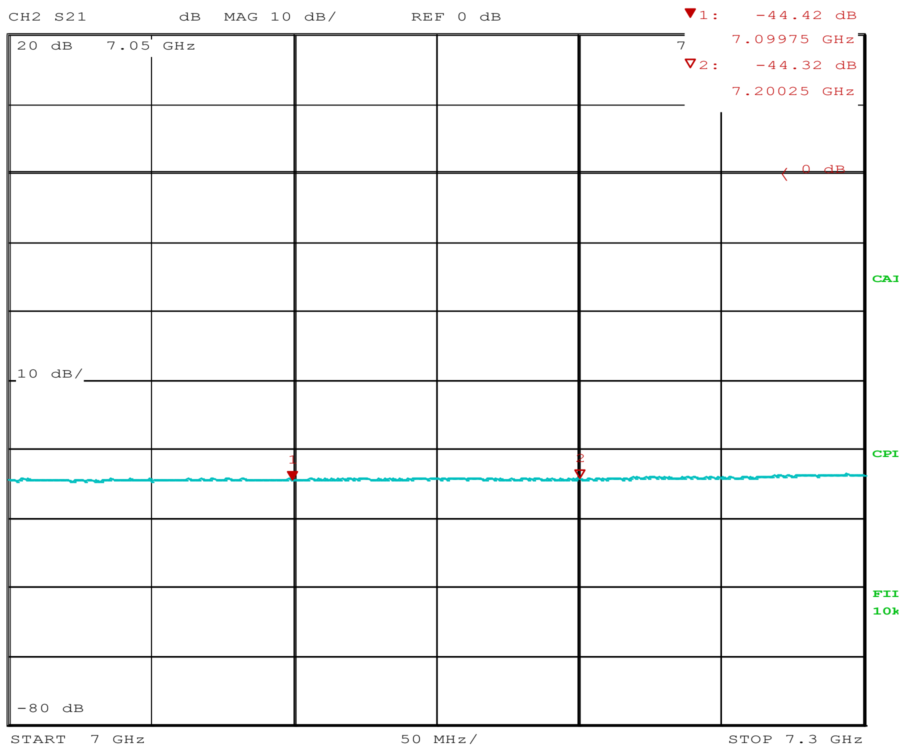

Figure 14. Measured monitoring coupler coupling coefficient.

4.3.2 Coupled power spectrum at maximum output power

Due to proper high-power X-band dummy load availability issues, we used open ended WR112 waveguide placed in front of microwave absorber as radiating dummy load (see Figure 15). Open-loop biasing mode was selected during the measurement.

The input test signal power (CW @ 7.2 GHz) at the transmitter (driver amplifier + HPA cascade) was increased until coupled output power stopped increasing, thereby indicating the saturation. The output spectrum at this power level is shown in Figure 16. The measurement system loss in addition to coupler loss (-44 dB) includes relatively long test cable between coupler and spectrum analyzer with loss of ≈-3 dB @ 7.2 GHz and external 10 dB attenuator due to safety reasons, so actual absolute power level at HPA module output were approximately: -2.6+44+10+3=+54.4 dBm, which is close to expected value of two QPM1017 combined.

Figure 15. HPA measurement setup.

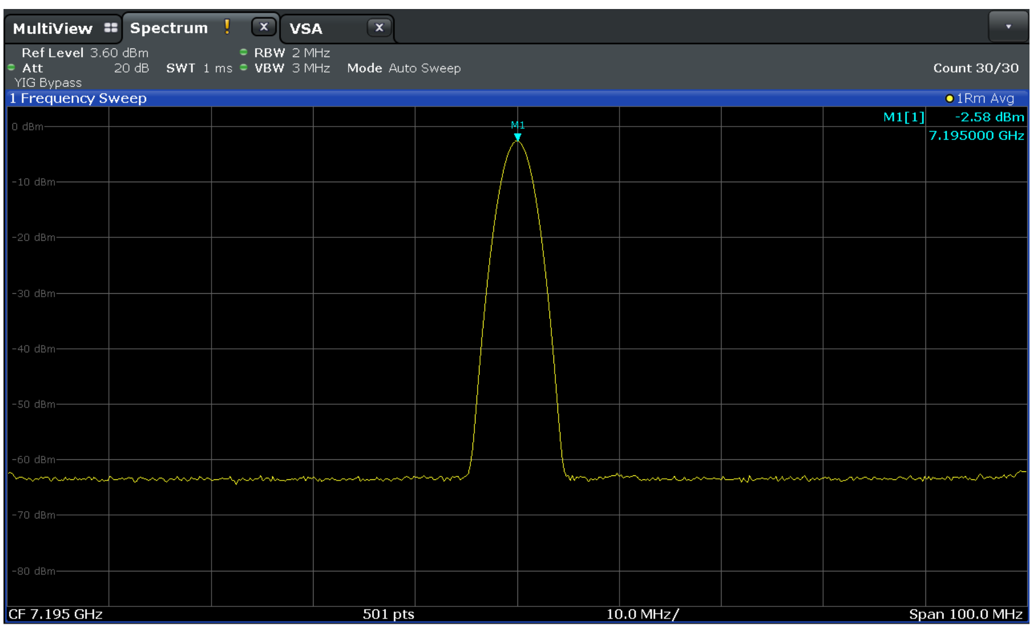

Figure 16. Signal power spectrum at output saturation.

4.3.3 Thermal issue at maximum power

It was found that at maximum power level spot around transition of power amplifier integrated circuit signal lead to microstrip trace as well as nearby ceramic bypass capacitors quickly heated up to ~90…100 degC (see red marker in Figure 17), so it was concluded that it is not safe to operate the amplifier for prolonged periods of time and more investigation and prototyping would be needed to solve this issue. Microstrip traces reach relatively high temperatures as well (see white marker in Figure 17), which may be solved by using dielectric material with lower loss.

It was found that when operating with less power, but still close to specified +50 dBm (so that each balanced amplifier channel would operate at safer +47 dBm level) the heating is more acceptable.

Figure 18 shows the thermal view of absorber heating due to high power radiation from open-ended waveguide, demonstrating the transfer of high-power signal.

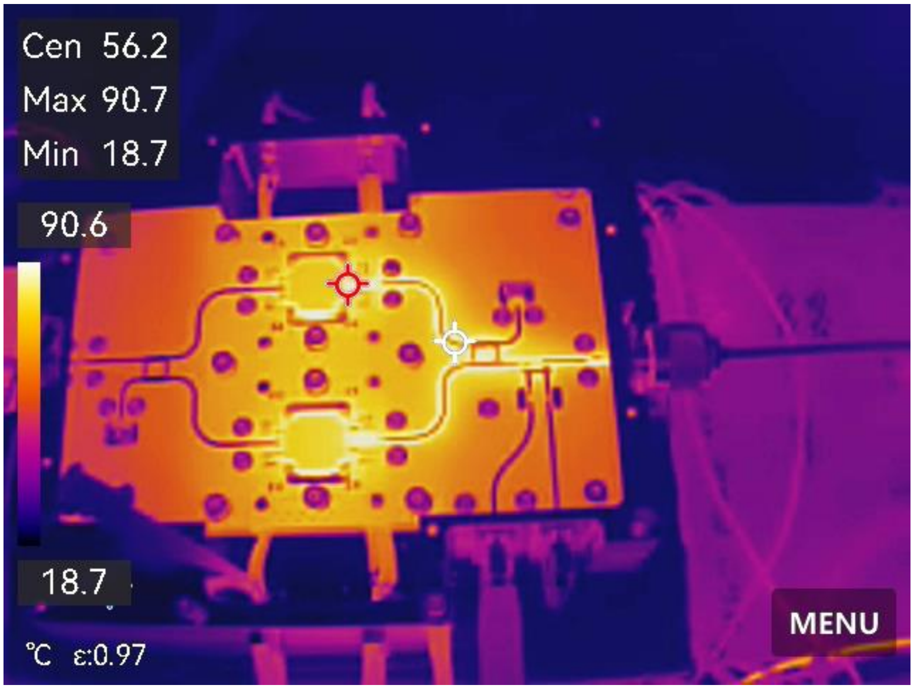

Figure 17. Thermal view of HPA PCB during maximum power operation.

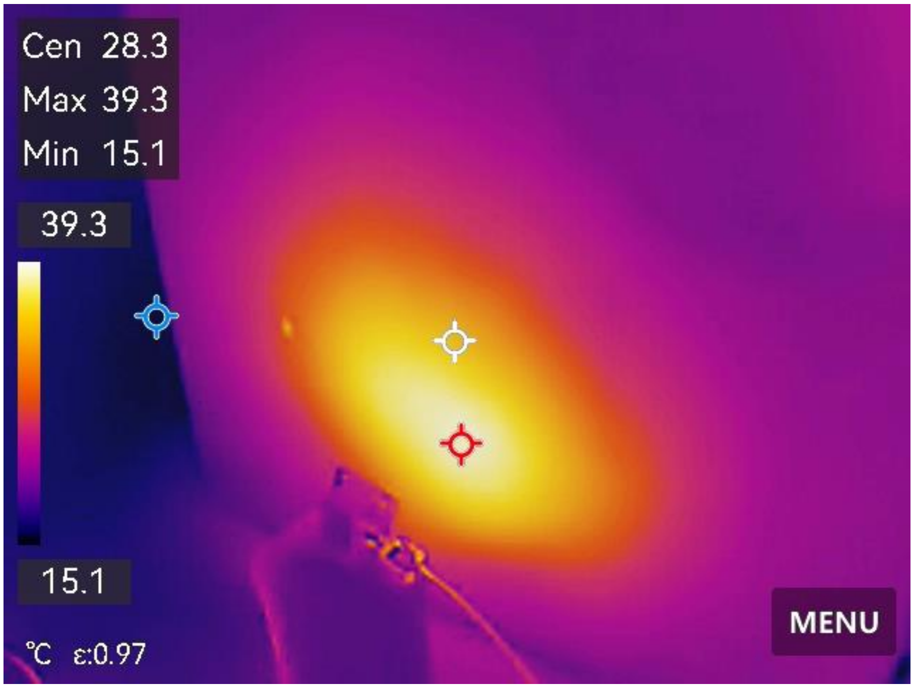

Figure 18. Heating of absorber due to open-ended waveguide radiation.

5 Summary of achieved performance and functionality

Table 3. Summary of achieved performance.

Parameter	Requirement	Achieved
RF Frequency range	7145 – 7235 MHz	7145 – 7235 MHz
Peak output power	100 W (+50 dBm)	Although balanced configuration HPA achieves close to +54 dBm at saturation, thermal issues were found. Operation at lower than maximum expected power still satisfies the +50 dBm specification.
Max gain	50 dB @ P1dB	Combined preamp and HPA gain: 39+20 = 59 dB.
Gain Flatness	Better than +/- 0.5 dB	TBD
Group Delay	- Linear: 0.03ns/MHz - Parabolic: 0.003ns /MHz^2 - Peak-peak value: 1.0 ns	TBD
Harmonics and spurs	<60 dBc	According to QPM1017 datasheet @ 7 GHz: 2nd harmonic: -50 dBc 3rd harmonic: -55 dBc
3rd order IMD	<-29 dBc	According to QPM1017 datasheet @ 7 GHz: <-25 dBc @ 5 MHz tone spacing
AM/PM conversion	<3º/dB	TBD
Noise Figure	<10 dB	Driver amplifier NF: ≈5 dB
Input/output return loss	<-20 dB	Driver amplifier input RL: 10 dB typ HPA output RL: -18…-11 dB
Gain/Attenuation adjustment range	Possibility to reduce gain by >=30 dB with steps of <=0.5 dB from nominal gain values	Separate attenuator not implemented in transmitter system, instead attenuator at IF unit upconverter can be used.
RF input interface	SMA female connector	SMA female connector

RF output interface	WR-137 waveguide	N to WR-137 transition possible
Remote control and monitoring interface	Ethernet, RJ-45 connector	Ethernet, RJ-45 connector
Remote control and monitoring functionality	• Output forward and reflected power monitoring • Bias (Drain/gate voltage and drain current) monitoring of end stage power transistors • Heatsink Temperature monitoring • Gain/attenuator control • PA bias on/off control	Currently implemented: • Bias (Drain/gate voltage and drain current) monitoring of end stage power transistors • Heatsink Temperature monitoring • PA bias on/off control
Protection functionality	• Protection against high reflection at the output • Overheat protection • Bias over-current protection	• Overheat protection • Bias over-current protection
Operating ambient temperature range	0 … +50 ºC	0 … +50 ºC
Power supply	Internal 230V/50 Hz AC-DC power supply	Internal 230V/50 Hz AC-DC power supply
Mechanical constraint	Mechanical design must be suitable for output of HPA interface with feed system/diplexer using maximally compact and simple rectangular waveguide structure.	Mechanical design is optimized for installation at Irbene 16m antenna secondary vertex room close to diplexer.