I.FAST

Innovation Fostering in Accelerator Science and Technology

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DELIVERABLE REPORT

GaN RF Amplifier Module at kW level

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ABSTRACT

A new solid-state power amplifier in Gallium Nitride (GaN) semiconductor technology was developed in the I.FAST project and is reported here to deliver 1-kW with 82.45% power added efficiency at 750 MHz. This is the first demonstration of operation with high efficiency and nominal power of the first GaN power amplifier above 1-kW power level at 750 MHz.

I.FAST Consortium, 2023

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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Executive summary

This report outlines the design and implementation of a 1 kW Gallium Nitride (GaN) RF solid-state power amplifier operating at 750 MHz. It builds upon the earlier description of a 200 W solid-state amplifier, including input and output isolators for enhanced protection. Six such amplifiers are combined to achieve a 1 kW output, requiring a low loss combiner.

The designs of a binary 6:1 power combiner and a 1:6 power splitter are also presented in this report. Power losses of the combiner and splitter are thoroughly examined, revealing a remarkable 0.15 dB insertion loss for each component, indicating exceptional efficiency in RF power distribution.

A comprehensive testing setup is introduced to assess the 1-kW RF power amplifier's performance, revealing a maximum gain of 19.14 dB, and 82.45% power efficiency at 44.53 dBm input power, and 1148 W output power.

This work contributes to improve the state-of-the-art for kilowatt level amplifiers at 750 MHz and has direct industrial applications as the RF power source of the RFQ that was developed at CERN.

1 Introduction

In the previous report, the design and implementation of a detailed 200-watt solid-state amplifier based on GaN technology are described. Figure 1 below illustrates this amplifier, which includes both input and output isolators. These isolators not only protect the transistor against reflected power but also provide a possibility of using a combiner with low port to port isolation specifications. To achieve a power output exceeding 1-kW, six of these amplifiers must be combined, taking into account the potential losses in the combiner.

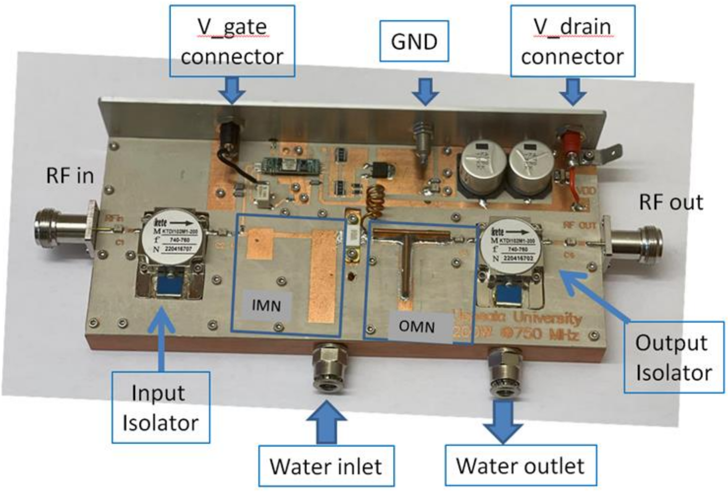

Figure 1: Implemented 200-W GaN RF solid-state power amplifier.

1.1 DESIGN, IMPLEMENTATION, AND TESTING OF THE COMBINER

Various methods, including binary, Wilkinson, hybrid, and cavity combiners, have been introduced for designing a combiner, each with its own advantages and disadvantages. For example, binary combiners typically offer suitable bandwidth but tend to have higher power losses due to the number of transmission lines involved, whereas cavity combiners have lower power losses but significantly narrower bandwidth. In this project, given that the amplifiers have both input and output isolators, a binary combiner is employed to combine their output signals. To compensate high power losses, three input ports of the combiner are placed in parallel. Figure 2 depicts the schematic of a 6:1 RF high-power combiner.

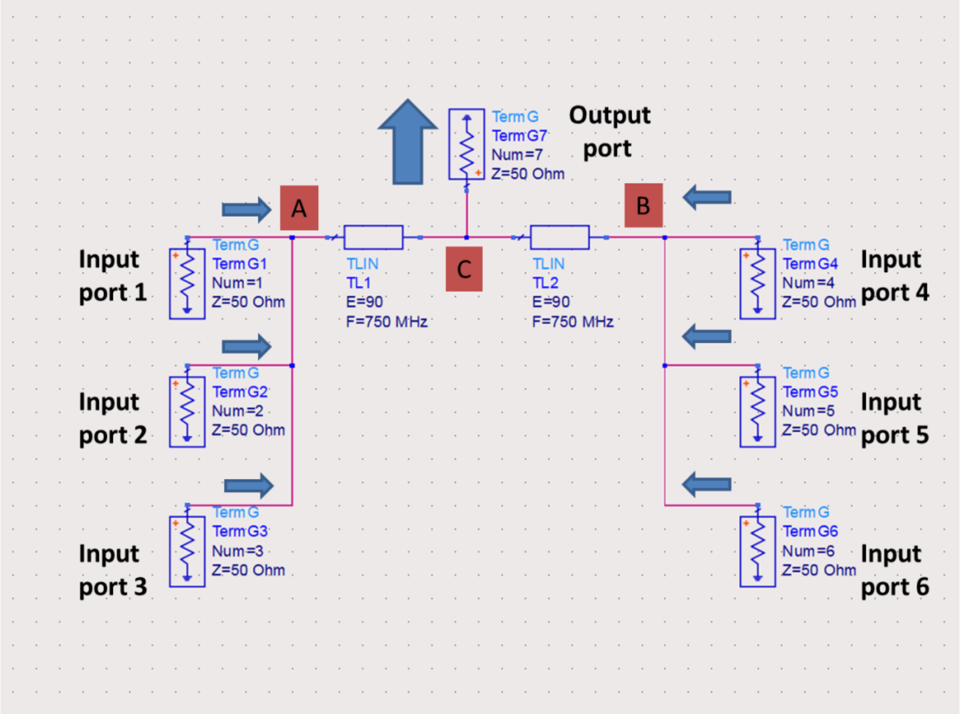

Figure 2: Schematic of 6:1 RF high-power combiner.

As a result of the three input ports in parallel, the combiner impedance at point A becomes 50/3 (16.6) ohms. Furthermore, since the combiner's output impedance must be 50 ohms, the impedance at point C must be considered 100 ohms for every transmission line, TL1 or TL2. Consequently, the impedance of TL1 and TL2 must be 41.2 ohms to achieve full matching between the combiner's input and output. This is calculation of λ/4 impedance transformation.

Furthermore, for the input signal to be uniformly distributed among the six amplifiers, a 1:6 power splitter is introduced into the system. This splitter divides the incoming signal into six equal parts, each sent to a 200-W RF power amplifier. To maintain a streamlined design approach and simplify the development process, the 1:6 signal splitter closely resembles the 6:1 signal combiner. This design consistency ensures that the signal is both effectively distributed and evenly combined, contributing to the overall efficiency and performance of the RF power amplifier system. The visual representation of this design can be found in Fig. 3 for reference.

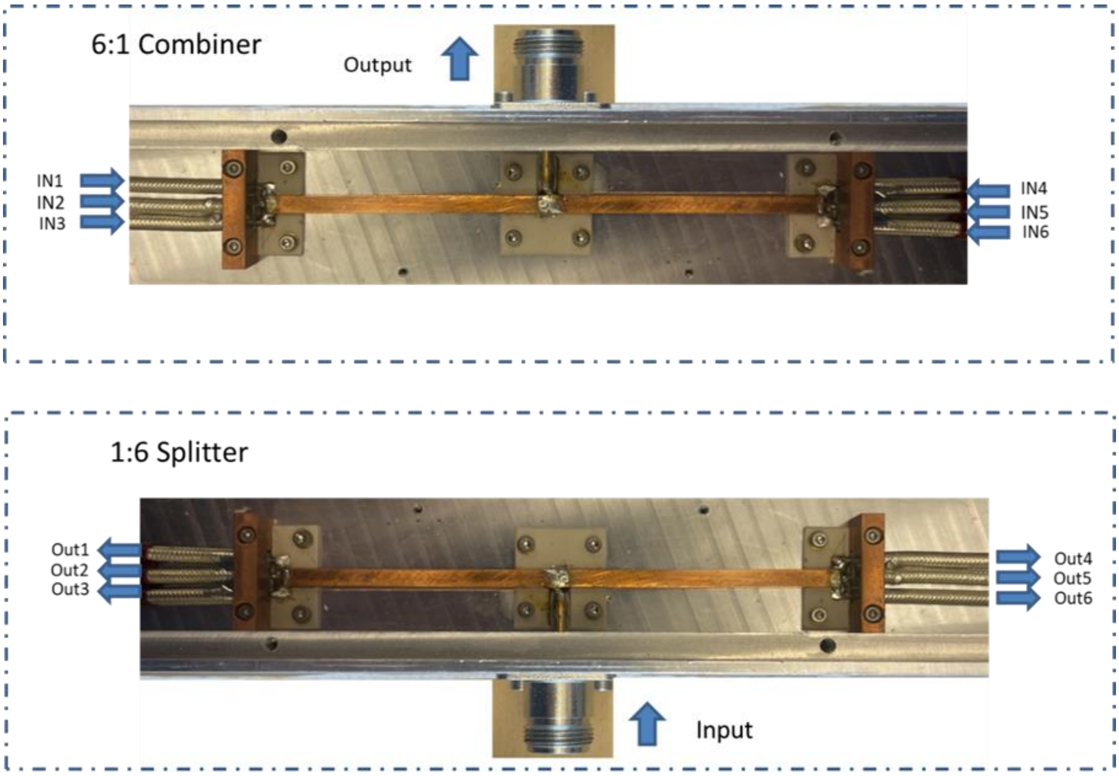

Figure 3: Implemented high power 1:6:1 splitter/combiner at 750 MHz.

1.2 TEST AND MEASUREMENT OF SPLITTER AND COMBINER

To test the power combiner/splitter, they are connected in back to back state using coaxial cables. Then, power losses at 750 MHz are measured. Since the measured losses pertain to the combiner and splitter, half of this value is attributed to the power losses of each. The connection in addition with power loss measurement method exhibits in Fig. 4. To calibrate cable and connector, signal generator is connected to the spectrum analyzer via the coaxial cables directly while DUT is not employed. The blue curve represents the results obtained from the direct connection of the signal generator to the spectrum analyzer in absent of DUT. The yellow curve represents the results of measuring power losses in the presence of the combiner/splitter. The measurement results are shown in Fig. 5.

The power losses for the combiner and splitter are determined by calculating the difference between the blue and yellow curves, as observed in Fig. 5. This difference amounts to 0.3 dB, which translates to 0.15 dB power losses for both the combiner and the splitter. Achieving a power loss of 0.15 dB for both the combiner and splitter is an excellent result, particularly for a high-power combiner/splitter. It indicates that the combiner and splitter efficiently combine and split the RF power with minimal losses, a crucial factor in maintaining the overall efficiency of the RF system.

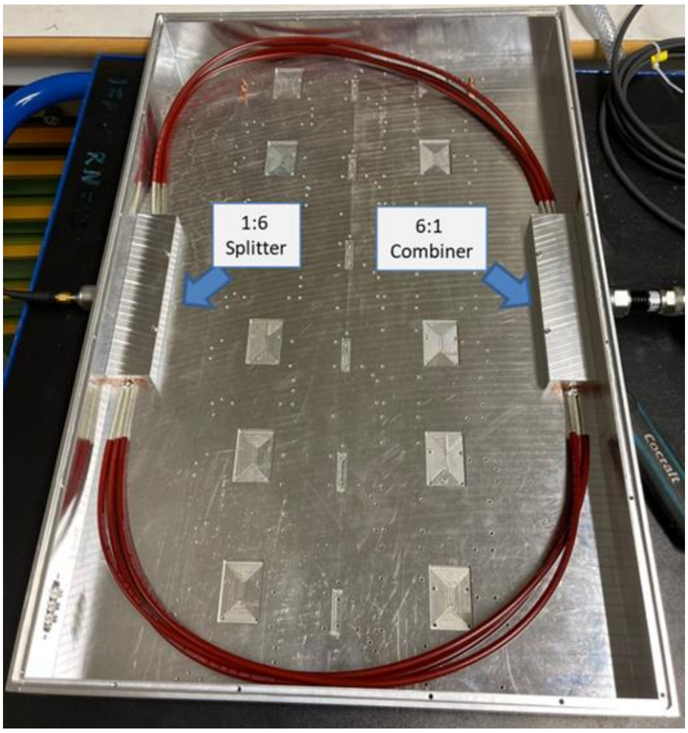

Figure 4: Connection and power loss measurement method of 1:6 splitter and 6:1 combiner.

(a) marker on blue curve *(b)market on yellow curve*

Fig. 5. Measurement results in (a) absent and (b) present of splitter/combiner circuits.

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1.3 DC BIAS CIRCUIT

After verifying the performance of the power combiner/splitter, six bias DC circuits are installed on the aluminum heat sink plate. In this step, coaxial cables connected to the combiner and to the splitter are tuned with equal length. These coaxial cabled are used to connect the combiner and the splitter to the amplifier's input and output, as shown in Fig. 6.

To build this amplifier, CGHV40180F transistors based on GaN technology has been used, requiring DC bias circuit sequencer. The MABC-001000 modules from MACOM are employed for the bias circuits. Additionally, to supply transistor drain current, P-channel MOSFETs with the part number of IRFR5410PBFCT are used. The schematic of the transistor bias circuit is depicted in Fig. 7.

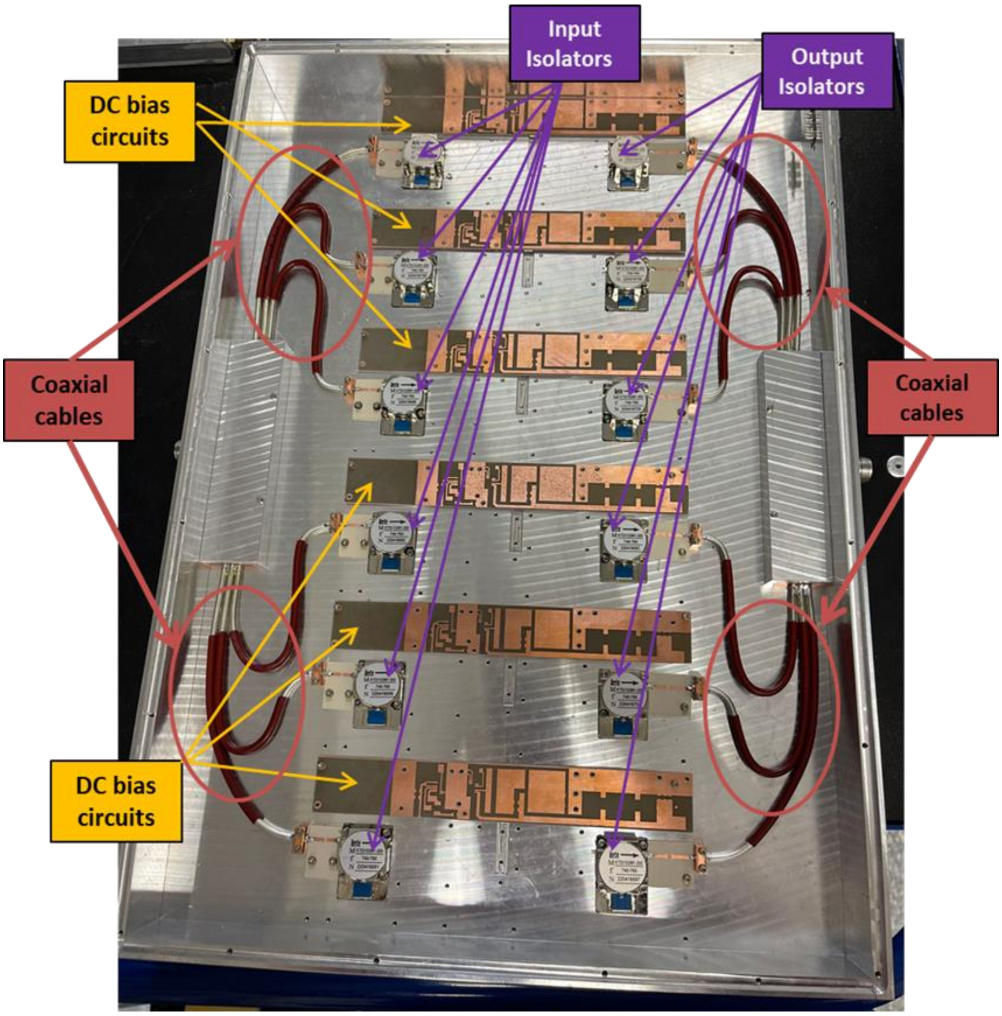

Fig. 6. Implemented DC bias circuits, coaxial cables, and input/output isolators on heat sink plate.

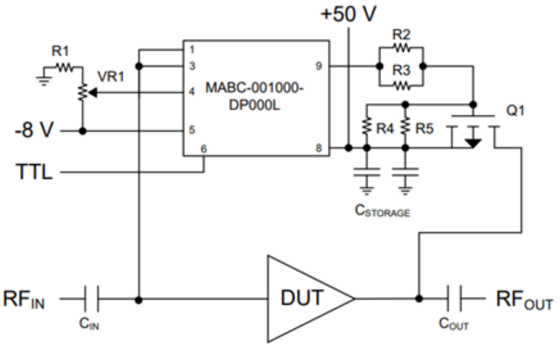

Fig. 7. Schematic of DC bias circuit showing P-channel MOSFET integrated with MABC-001000 module (Ref. MABC-001000 datasheet)

1.4 IMPLEMENTATION AND TEST OF 1KW RF POWER AMPLIFIER

As Fig. 7 demonstrates, a voltage source of -8 volts for the gate and +50 volts for the drain are required to bias the transistors. Therefore, the voltage for all amplifiers is provided through an only 50-volt source, and the gate voltage for all amplifiers is supplied through an only -8 volt source. Figure 8 displays the implemented 1-kW solid-state RF power amplifier, including six 200 W amplifiers, six bias DC circuits, connections, and the RF combiner and splitter. To test and measure the 1-kW solid-state RF power amplifier, a test bench is set up, which includes a signal generator, a driver, power supplies, a high-power attenuator, a coupler, a power meter, and a spectrum analyzer, as depicted in Fig. 9.

The results of testing and measuring the 1-kW power amplifier, including signal gain, drain efficiency, output power in watts and dBm, power-added efficiency (PAE), and drain current, are presented in Table 1. Furthermore, Fig. 10 shows a graphical representation of the measurement results of the amplifier.

As the measurement results indicate, the maximum gain of the amplifier is 19.14 dB. The maximum output power is 1148 watts, and the maximum power efficiency is 82.45% at an input power of 44.53 dBm. The amplifier's gain at this point is 16.07 dB.

The reported power efficiency of 82.45% for the 1-kW RF solid-state power amplifier at 750 MHz is indeed quite high and represents very efficient design in comparison with the state of art exhibited in Table 2. It indicates that the amplifier is effectively converting input power into output power while minimizing losses.

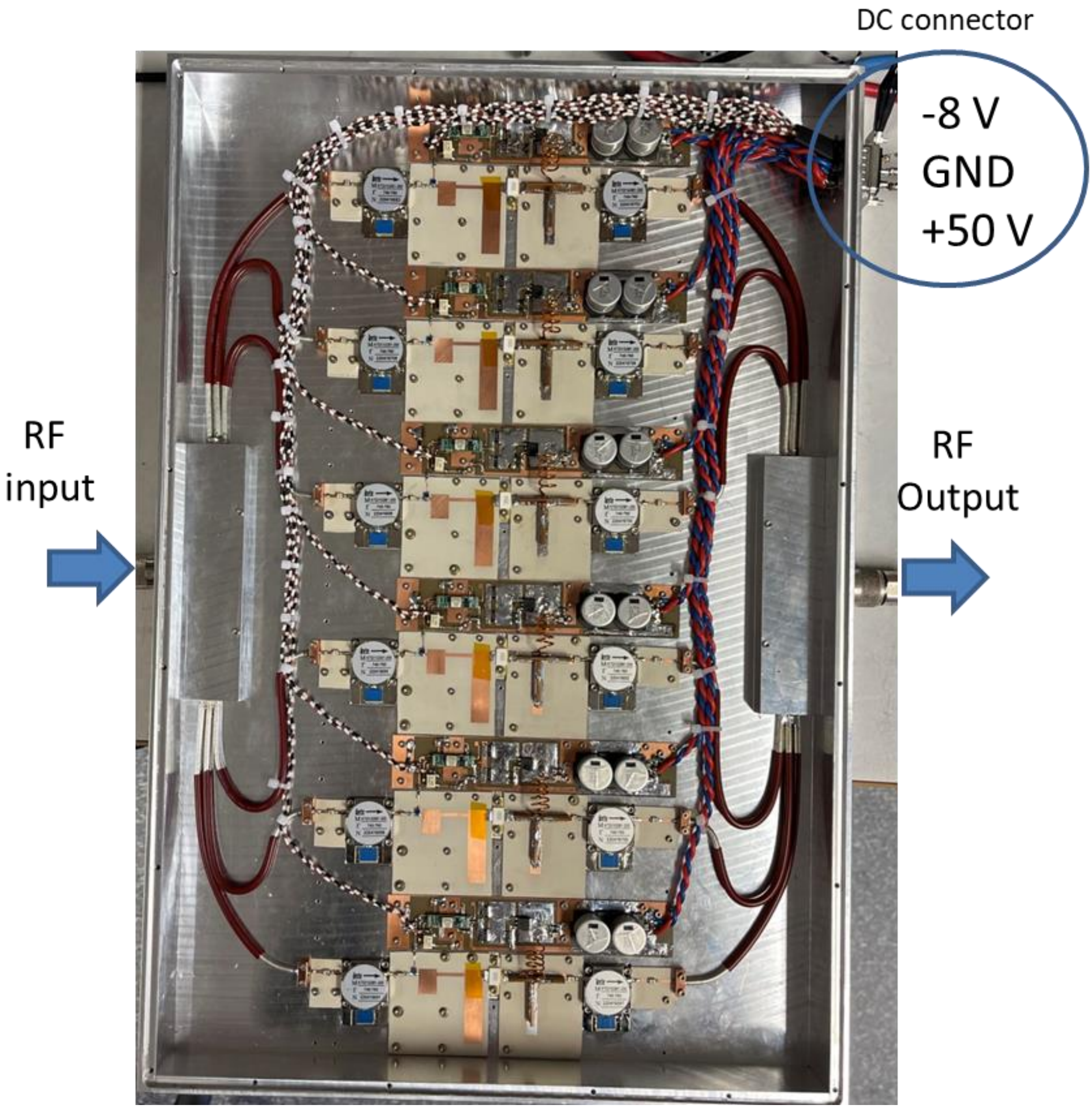

Fig. 8. Implemented 1kW RF high power amplifier including DC bias circuits, 6 200-w RF power amplifier, coaxial connections, and RF combiner and splitter.

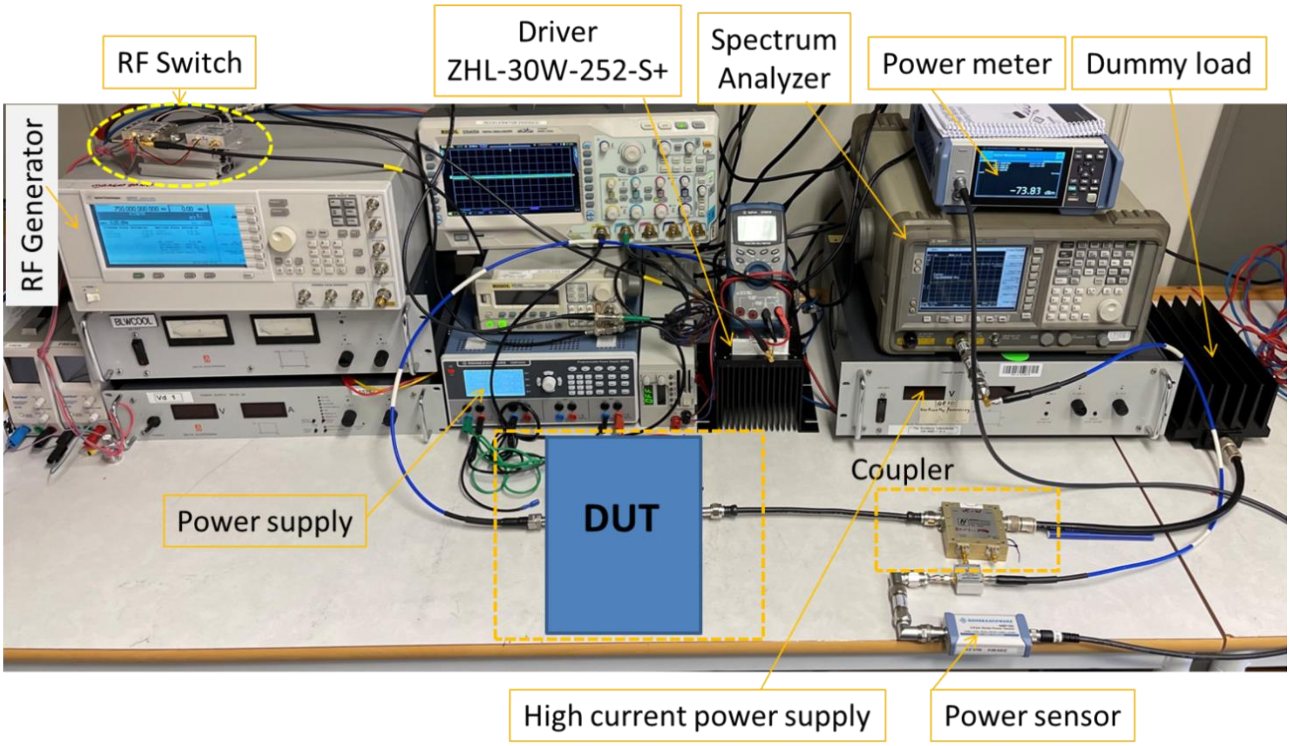

Figure 9: Test bench for testing and measuring the RF power amplifier.

Table 1: Measurement results of 1 kW RF power amplifier at 750 MHz.

$P_{in(dBm)}$ Driver	$P_{in(dBm)HPA}$ $=P_{outDriver}$	HPA Pout(dBm)	HPA Pout (W)	I_Drain (A)	Power added _Efficiency(%)	Drain_Efficiency (%)	Gain (dB)
-25	23.3	36.36	4.33	1.87	4.63	5.19	13.06
-24	24.3	38.5	7.08	2.4	5.90	6.62	14.20
-23	25.3	40.6	11.48	3.1	7.41	8.31	15.30
-22	26.3	42.4	17.38	3.9	8.91	10.00	16.10
-21	27.4	44	25.12	4.8	10.47	11.74	16.60
-20	28.4	45.6	36.31	5.8	12.52	14.05	17.20
-19	29.47	47.13	51.64	7	14.75	16.56	17.66
-18	30.52	48.5	70.79	8.2	17.27	19.37	17.98
-17	31.57	49.9	97.72	9.7	20.15	22.61	18.33
-16	32.62	51.2	131.83	11.4	23.13	25.95	18.58
-15	33.68	52.46	176.2	13.1	26.90	30.18	18.78
-14	34.74	53.7	234.42	15.2	30.85	34.61	18.96
-13	35.8	54.9	309.03	17.4	35.52	39.85	19.10
-12	36.86	56	398.11	19.7	40.42	45.35	19.14
-11	37.9	57	501.19	22	45.56	51.12	19.10
-10	38.92	58	630.96	24.6	51.30	57.56	19.08
-9	39.92	58.77	753.36	26.8	56.22	63.08	18.85
-8	40.83	59.4	870.96	28.4	61.34	68.82	18.57
-7	41.62	59.8	954.99	29.7	64.31	72.16	18.18
-6	42.32	60.07	1016.25	30.3	67.08	75.26	17.75
-5	43.02	60.17	1039.92	31	67.09	75.28	17.15
-4	43.66	60.35	1083.93	31.1	69.71	78.21	16.69
-3	44.16	60.46	1111.73	31.2	71.26	79.96	16.30
-2	44.53	60.60	1148.15	31.25	73.48	82.45	16.07

Table 2. State of art for UHF power amplifier.

Reference	**Operating class**	**F_{min} (MHz)**	**F_{max} (MHz)**	**P_{out} (dBm)**	**Gain (dB)**	**PAE_{min} (%)**	**Package/Die**	**Technology**	**Institution**
2023 [This work]	**Class B**	**750**	**-**	**60.60**	**16.07**	**73.48**	**packaged**	**GaN**	**FREIA – Uppsala U.**
2020[1]	Push pull	24.5	27	59.8	25	83	packaged	LDMOS	FREIA – Uppsala U.
2019[2]	Class AB	400	450	60	15	-	Packaged	GaN	SSPL - Delhi
2018[3]	Class AB	UHF	-	67.2	-	55	Packaged	GaN	CETC - Nanjing
2017[4]	Class AB	1200	1400	64	16.7	55	packaged	LDMOS	USTB - Beijing
2016[5]	Class AB	352	-	60.9	20.5	71	Packaged	LDMOS	FREIA – Uppsala U.
2016[6]	Class AB	200	500	40	18	71	packaged	GaN	CESAT - Islamabad
2016[7]	Class B	420	450	60	25	73	3 chip Packaged	GaN	Integra Tech. - CA
2020[8]	Class E	400.8	-	63.6	22	70	Die	GaN	Integra Tech. - CA
2018[9]	Class E	680	750	47	-	80	packaged	GaN	U. of Cantabria
2018[10]	Class E	100	-	60.8	-	82	packaged	LDMOS	FREIA – Uppsala U.
2017[11]	Harmonic tuned	420	450	60	40	75	Packaged	GaN	Integra Tech. - CA
2017[12]	Class E	670	900	44.7	-	70	packaged	GaN	U. of Cantabria
2016[13]	Class F	704	-	58	-	79	packaged	GaN	Green Mountain Radio Research
2016[14]	Class F	550	950	40	15	75	packaged	GaN	U. of Calgary
2011[15]	Class F	550	1100	40	10	74	packaged	GaN	Cardiff U.

*Blue for linear classes, Orange for nonlinear classes.

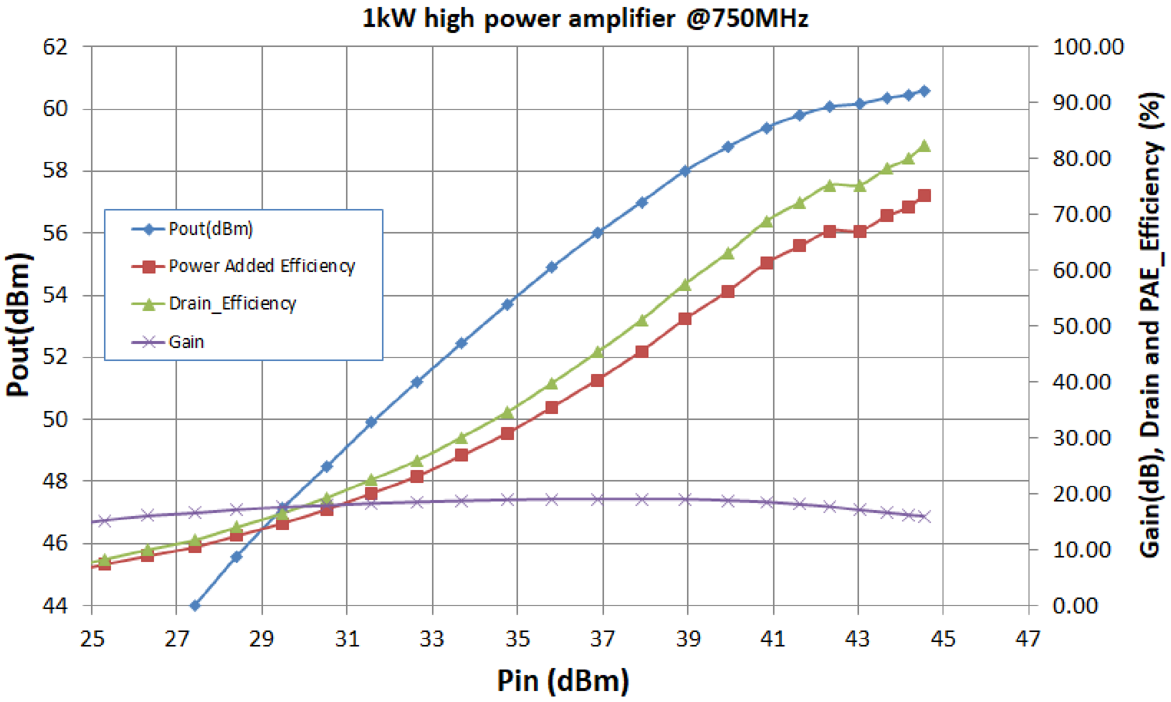

Figure 10: Measurement Results of RF Power Amplifier Including Signal Gain, Output Power, Drain Efficiency, and Power Added Efficiency at 750MHz.

In the context of RF (Radio Frequency) power amplifiers, power efficiency is a critical factor, especially for high-power applications. The fact that this amplifier can deliver over 1 kW of output power while maintaining a power efficiency of over 80% is a certificate to the quality of the design and implementation. It means that a large portion of the input power is being efficiently amplified without dissipating as heat, which is desirable for minimizing power consumption and reducing heat generation in RF systems.

However, whether it is the best power efficiency depends on the specific requirements and goals of the application, as well as the state of the art in RF amplifier design. Achieving high power efficiency is often a trade-off with other parameters such as bandwidth, linearity, and cost. Nonetheless, an 82.45% power efficiency for a 1-kW RF solid-state power amplifier is a commendable achievement and demonstrates a well-designed and efficient amplifier. The cost of implementing a 1-kW RF power amplifier at 750 MHz in GaN semiconductor is about 7€ per watt.

2 Future plans / Conclusion / relation to other IFAST work

This amplifier will be used as a driver amplifier for the CFA amplifier that is presently developed within WP4. The whole chain could serve as an RF power generator for the RFQ at 750 MHz that was developed by CERN.

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Annex: Glossary

Acronym	**Definition**
SSPA	Solid State Power Amplifier
GaN	Gallium Nitride – semiconductor technology
VDD	Drain voltage – DC supply voltage
LDMOS	Laterally-diffused metal-oxide semiconductor is a planar double-diffused MOSFET
MOSFET	Metal–oxide–semiconductor field-effect transistor