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SOLID-STATE AMPLIFIER DEVELOPMENT AT FREIA

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Abstract

The FREIA laboratory is a Facility for REsearch Instrumentation and Accelerator development at Uppsala University, Sweden, constructed recently to test and develop superconducting accelerating cavities and their high power RF sources. FREIA's activity target initially the European Spallation Source (ESS) requirements for testing spoke cavities and RF power stations, typically 400 kW per cavity. Different power stations will be installed at the FREIA laboratory. The first one is based on vacuum tubes and the second on a combination of solid state modules. In this context, we investigate different related aspects, such as power generation and power combination. For the characterization of solid-state amplifier modules in pulsed mode, at ESS specifications, we implemented a Hot S-parameters measurement set-up, allowing in addition the measurement of different parameters, such as gain and efficiency. We developed also a new solid-state amplifier module at 352 MHz, using commercially available LDMOS transistors. Preliminary results show a drain efficiency of 71% at 1300 W pulsed output power.

INTRODUCTION

The FREIA laboratory will test and develop superconducting accelerating cavities and their high power RF sources, following the requirements for ESS [1]. FREIA will also host smaller experiments within accelerator and instrumentation development. In the current design, ESS LINAC is composed of 26 spoke cavities at 352 MHz [2]. The prototypes RF power sources (400 kW nominal) will be tested at FREIA. Two different technologies will be investigated by the industry: the first to be installed is based on vacuum tubes, using two TH595 tetrodes from Thales and the second is based on a combination of solid state modules, each delivering around 1 kW. The FREIA laboratory will also test a prototype cryomodule containing two spoke cavities, presently under development at IPN Orsay. High power soak testing, controls development and research on Lorentz detuning will be investigated. In addition, the cryomodule will be tested at high power, requiring two RF power sources. In this paper, we investigate different aspects essentially related to the power generation using solid-state amplifiers (SSA). In addition, we investigate power combination, a 100 kW level power combiner is presented elsewhere [3].

HOT S-PARAMETERS SET-UP

A measurement set-up is configured for the characterization of SSA modules, see Fig. 1. This set-up allows a direct measurements of all S-parameters while the module delivers high output power, i.e. hot S-parameters. The output power considered is in the order of few kW, presently in pulsed mode. Characteristic parameters as gain and efficiency could be monitored over time, allowing realistic operation measurements. Reliability measurements, where the amplifier is in prolonged operation could also be envisioned, over a long period of time.

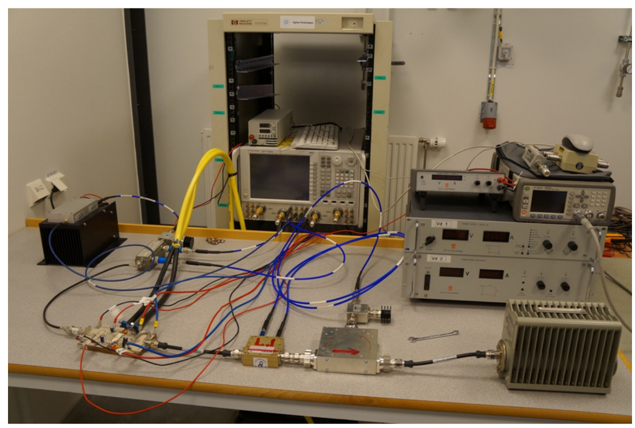

Figure 1: Hot S-parameters set-up.

The network analyser (PNA N5221A) has two internal signal generators. The first one is used to drive the amplifier at the user selected power levels using port 3 (S3), see Fig. 2. In this set-up, the network analysers' ports are externalized using bidirectional couplers, the calibration being performed at SSA's mating ports. The PNA's second source is used to drive the S-parameters measurements at port 1 (S1) and port 2 (S2). The PNA is configured in frequency offset mode between the two internal sources, which allows to perform the hot-S parameters measurement with a frequency sweep of 25 MHz between 340 MHz - 365 MHz, while the carrier frequency is set at 352 MHz. At port 1, S3 and S1 are combined via the PNA's internal directional coupler. At port 1, the reference measurement R1 as well as the reflection measurement A are performed after 25 dB attenuation used in addition to a bi-directional coupler, with a measured coupling coefficient of 27 dB, at 352 MHz.

* presently at ESS

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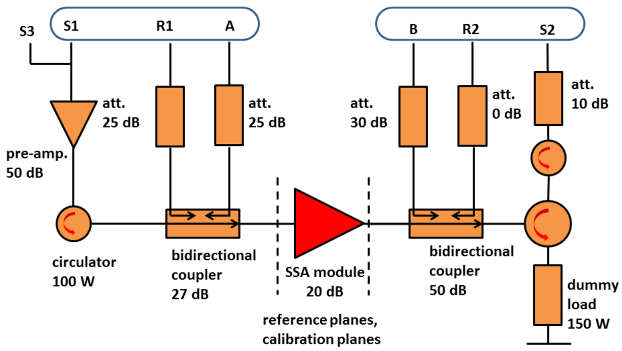

Figure 2: Hot S-parameters set-up schematics.

A pre-amplifier is used at port 1, with a gain of 50 dB, the maximum required input power for the SSA is roughly 43 dBm. An additional circulator is used for the injection of S1 and S3 while protecting the pre-amplifier. At port 2, a bi-directional coupler with a measured coupling coefficient of 50 dB at 352 MHz is used in addition with an attenuator of 30 dB, set on the reflection measurement B, to protect the PNA. At this port B, the incoming high power is also measured. The reference measurement R2 has no additional attenuation. An additional 10 dB attenuator is used to protect the second source S2 and two other circulators are used for the injection of S2 into the SSA's output port for the hot-S22 measurement.

EVALUATION OF AN10967 DEMO BOARD

The AN10967 demo board from NXP [4], using the BLF578 LDMOS transistor, see Fig. 3 was used as an investigation vehicle for the characterisation of the hot-S parameters' measurement set-up. In addition, different operating conditions, following ESS parameters were investigated, such as impact of the quiescent current on gain and efficiency. The characteristic ESS's parameters are as follows: pulses of 3.5 ms length, 14 Hz repetition rate and 5% duty cycle [2]. Finally, thermal photographs are compared in CW and pulsed mode operation to investigate the components' temperature in operation.

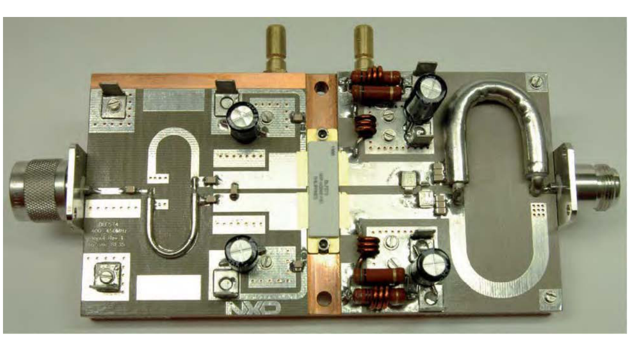

Figure 3: The AN10967 demo board from NXP [4].

Hot S-parameters Measurements

The measured hot S-parameters of the AN10967 are presented in Fig. 4. The S-parameters are measured in a frequency bandwidth of 25 MHz, between 340 - 365 MHz, while the carrier frequency is set at 352 MHz. The input impedance is well matched over the bandwidth, with an input reflection coefficient S11 roughly at -16 dB for all measured output powers. The output power spans over the power sweep from 150 W to 1200 W. The biasing conditions set the quiescent current I_{Dq} = 100 mA and the drain voltage V_{DS} = 50 V. A high variation of the transistor's output impedance with the output power is measured, with the best matching at 900 W, when the amplifier reaches also a maximum gain, see Fig. 5. After 900 W output power, the amplifier starts to enter into gain compression at the same time as matching deteriorates at 352 MHz, i.e. moving away from the middle of the Smith-chart, in Fig. 4.

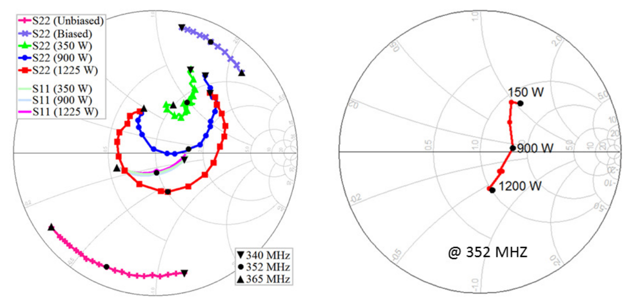

Figure 4: Hot S-parameters of AN10967.

Gain and Efficiency Measurements

Three different quiescent drain currents, I_{Dq} = 40 mA, 100 mA and 200 mA are investigated, see Fig. 5. The gate voltage is adjusted accordingly, around V_G = 1.5 V and the drain voltage V_{DS} = 50 V. Measurements start at 150 W and go up to 1200 W output power, when the module is typically 2 dB into gain compression. Efficiency continues to increase smoothly, up to 74% at 1200 W output power.

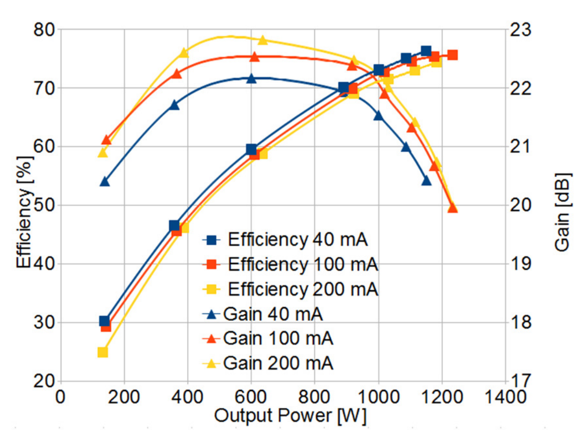

Figure 5: Gain and efficiency measurements of AN10967.

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Thermal Measurements

Thermal measurements are performed using a FLIR camera, see Fig. 6. The temperatures increases only by a few degrees (max. 25 °C) above the room temperature (20 °C) when the amplifier is delivering 1200 W output power, operating at ESS parameters with I_{Dq} = 100 mA and water cooling (about 8 l/min). In comparison, the maximum temperature reaches 155 °C, in CW operation.

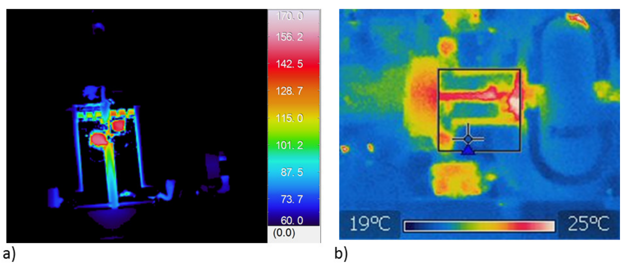

Figure 6: IR for operation in a) CW and b) pulsed mode.

SSA DEVELOPMENT AT FREIA

Through research collaborations with NXP and ESRF, we are improving our know-how in SSA power generation and power combination. We investigate different amplifier architectures such as push-pull and single-ended operating in different classes, towards improving the overall efficiency. Preliminary results using NXP's BLF188XR LDMOS transistor are presented for a single-ended amplifier at 352 MHz, see Fig. 7. Differently from [4], we do not implement baluns, coaxial or PCB integrated as in this case all components could be machine surface mounted.

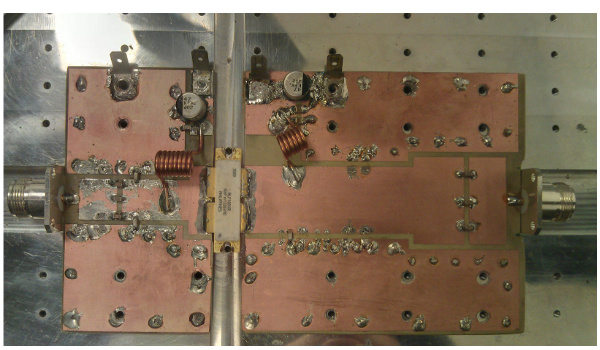

Figure 7: FREIA's 1300 W SSA at 352 MHz.

Gain and Efficiency Measurements

The SSA module is designed for Rogers Corp. TMM3 substrate with a dielectric constant of 3.45, substrate thickness of 0.76 mm and copper thickness of 35 μm. The module is measured in pulsed mode with ESS characteristics. The gain and efficiency versus output power are presented in Fig. 8 for a drain voltage V_{DS} = 50 V and quiescent current I_{Dq} = 40 mA. Preliminary results show a drain efficiency of 71% at 1300 W output power.

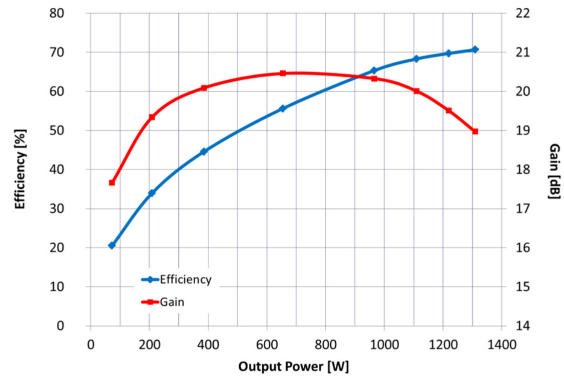

Figure 8: Gain and efficiency measurements at 352 MHz.

Thermal Measurements

Similar to AN10967, the temperature slightly increases up to 31 °C (room temperature is 20 °C) when the amplifier is delivering 1300 W output power at 71% efficiency, with water cooling (about 8 l/min) and at ESS parameters.

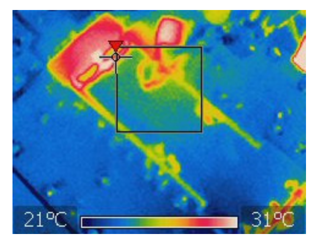

Figure 9: Thermal measurement of FREIA's SSA in Fig. 7.

CONCLUSION

The output impedance is considerably changing with the output power and needs to be taken into account for power combination purposes. For high power generation, improving overall efficiency implies both improving SSA module efficiency and reducing power combination losses.

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