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NOVEL 500 MHz SOLID STATE POWER AMPLIFIER MODULE DEVELOPMENT AT SIRIUS

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Abstract

A new solid state power amplifier (SSPA) module is being developed at the Brazilian Center for Research in Energy and Materials (CNPEM) to drive one of the superconducting RF cavities to be installed at Sirius, its new 3 GeV fourth generation synchrotron light source. Several prototypes have been built and tested in-house, and a planar balun was designed to achieve a push-pull configuration at deep class AB operation. Efforts to optimize heat exchange in various ways have been made. Results obtained thus far are presented and the next steps concerning development are discussed.

INTRODUCTION

Since 2010 the Brazilian Synchrotron Light Laboratory (LNLS) has employed solid state power amplifier (SSPA) modules on UVX's storage ring, its late second generation synchrotron light source located at Campinas, Brazil. The 476 MHz amplifier design was conceived at SOLEIL, and the modules were put together on 50 kW amplifiers. For Sirius' first phase of operation, new 500 MHz modules were developed and utilized to build its 40 kW booster amplifier and two 60 kW storage ring amplifiers, with 2 more amplifiers being assembled to drive one of the superconducting cavities that are expected to be installed in 2023 [1].

For the remaining amplifiers needed to power the second superconducting cavity, a new amplifier module is being designed and tested. This development intends to improve some characteristics of the currently employed amplifier modules, like RF output power and efficiency, effectively reducing production and maintenance costs. Part of the motivation also comes from the fact that the project has a long time span and, in the meanwhile, new LDMOS devices have been released on the market.

DESIGN PROCEDURE

The first design step was to choose the transistor that would amplify the RF signal. In that regard, Ampleon's 9th generation LDMOS device BLF978P seemed like a reasonable candidate, for it is the successor to Ampleon's BLF578, which is already used on Sirius' current amplifier modules and has proven its reliability over the years. BLF978P has higher gain and is able to achieve higher output power levels [2]. The device is meant to be operated in a class-AB mode with a push-pull configuration. Table 1 summarizes the main characteristics and goals of this amplifier modules' design.

It was possible to perform load-pull analysis on this device's nonlinear model provided by the manufacturer and extract input and output impedances for matching circuits. The next subsections will be dedicated to describe some of the module's elements.

Table 1: Module Specifications and Goals

Description	Goals
LDMOS device	BLF978P
Class of operation	AB
Output power	> 800 W
Efficiency	> 65 %
Drain-source voltage	48 V
Quiescent drain current	20 mA

Balun

To achieve a push-pull configuration of the amplifier it is needed to transform the single-ended RF input signal into a differential pair. Conversely, the amplified RF signal needs to be brought together again into a pair of conductors to exit the amplifier. A balun was employed to this purpose. To improve repeatability and reduce production costs, an effort was made to design a planar structure, without the need to solder coaxial cables directly onto the PCB. This concept has been developed on previous works by NSRRC and the same principles were employed on this case [3].

A view of the balun's simulated structure on HFSS can be seen on Fig. 1. The input reflection coefficient, amplitude and phase balance values obtained are presented on Fig. 2. The assymetry that is intrinsic to the structure can be compensated through a stub on one side of the balun and tweaking of the central slot. Altough this version was not employed on the prototype, it serves to show this structure's capabilities and potential.

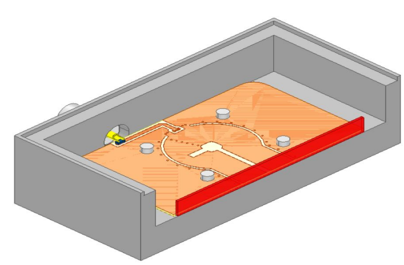

Figure 1: Input balun structure simulated on HFSS.

Circulator and RF Termination

A circulator and a RF termination are utilized after the output balun to isolate the device from the subsequent combining stages of the amplifier. This is important for two reasons: it prevents impedance modulation on the output

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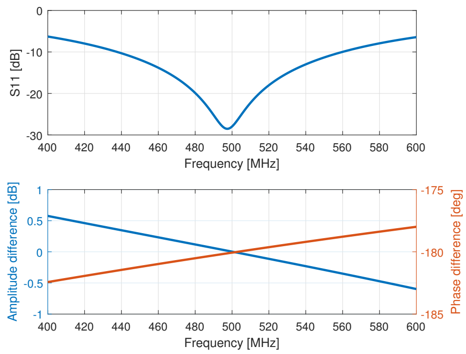

Figure 2: S11, amplitude and phase difference between output traces of the simulated input balun.

that could be caused due to mismatches on the combining stages and protects PCB components in case of power being reflected back to the amplifier module. Given its narrowband nature, it can also decrease harmonics power level on the output.

PROTOTYPE PERFORMANCE

Some prototypes were built in-house, with soldering and assembly done by hand. Figure 3 presents gain and efficiency curves with respect to output power. At the 1 dB compression point, it was possible to achieve 886 W output power and 68.9% efficiency.

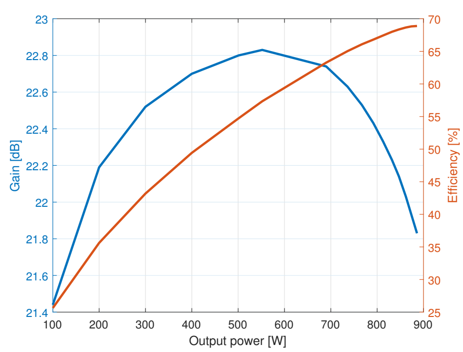

Figure 3: SSPA gain and efficiency curves with respect to output power.

Temperatures over key components of the prototype were also measured with an infrared camera. Results may be found in Fig. 4. Only the hottest capacitor's temperature is shown. The transistor temperature indicates that it is on a very safe operation point regarding its mean time before failure (MTBF). Capacitors are well below operation limits.

THERMAL MANAGEMENT

LNLS has employed amplifier modules with direct water cooling in the past, but due to some issues (water leakage, assembly dificulties) the amplifier modules at Sirius are instead mounted on top of heat sinks, composed of aluminum plates with embedded copper tubes.

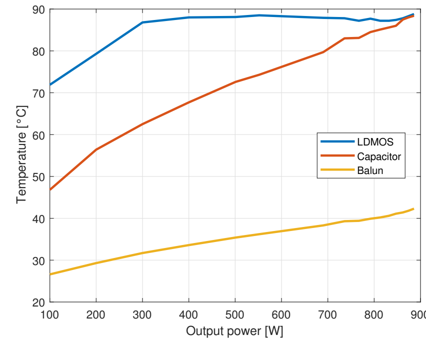

Figure 4: Temperature of several components with respect to output power.

Between the amplifier module and the heat sink a thin graphite sheet is placed to compensate for any ruggedness both surfaces may have. The amplifier module's case is made out of aluminum, with a copper cylinder pressed on a hole with almost the same diameter. A cavity is milled in the copper cylinder to mount the transistor. A silver thermal grease that ensures good thermal and electrical contact is used between the transistor's flange and copper cylinder.

Figure 5 depicts a cross section view of the amplifier module mounted on the heat sink. Graphite sheet and silver grease thicknesses are oversized for better understanding. Water flows through the copper tubes and exchanges heat with the LDMOS device. On the next subsections some efforts made to improve this feature are detailed.

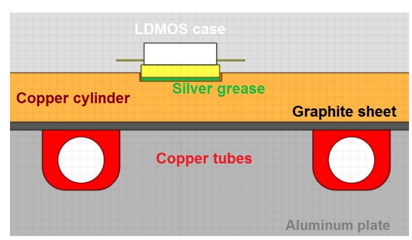

Figure 5: Amplifier module cross section view.

Thermal Gap Filler

The output balun can exhibit relatively high temperatures, so it was attempted to fill its cavity with a thermal gap filler. This compound has a dielectric constant of 3.2 and must be taken into consideration when optimizing the balun. Fig. 6 presents a picture of the amplifier module case with the thermal gap filler inside the output balun cavity.

The impact on the balun temperature was evaluated by comparing two prototypes, one with the thermal compound and the other without it, and the result is presented in Fig. 7. Close to the 800 W output power level, the temperature difference can reach up to 38 °C.

Module Case

The graphite sheet's thermal impedance is inversely proportional to the pressure applied between the surfaces on

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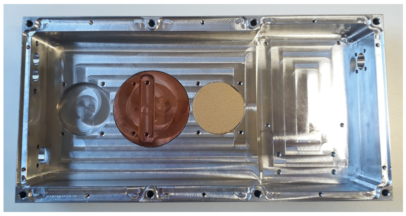

Figure 6: Thermal gap filler (yellow cylinder) inside the output balun cavity on the amplifier case module.

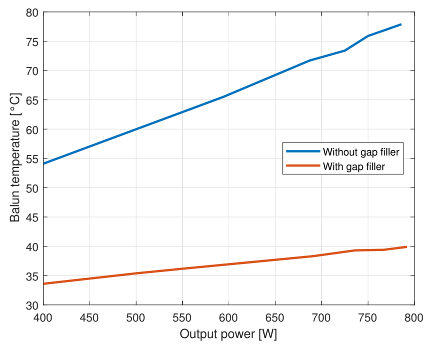

Figure 7: Output balun temperature with and without thermal gap filler.

which this thermal compound is located. This pressure is enforced by fastening screws through the sides of the amplifier case on the heat sink. However, the force transferred from the screws to the bottom surface of the amplifier case is concentrated on a rather small area around the screw. An idea to solve this issue was to mill the bottom surface of the module's case sides, so that the area of contact to the heat sink decreases. Simulations were done in Ansys Mechanical to assess the values of stress on the bottom surface on both cases.

Altough the temperatures obtained with the milled case were lower than the flat one, the amplifier's operation point were different from each other, so a conclusive statement on which one is better cannot be made. A more definite test remains to be done. However, a possible drawback already observed by milling the case was that the center of the bottom surface detaches itself slightly from the heat sink with increasing screw torque.

To assess this feature of the mounting procedure, the LDMOS's case temperature was measured with respect to the screws fastening torque on the milled case. The result can be found on Fig. 8. It suggests that there is a optimum torque for which heat exchange is best, but up to 1 Nm they presented almost the same temperature values.

DEVELOPMENT NEXT STEPS

For the next stages of the SSPA module development, a review of the amplifier PCB is foreseen, with improvements to the input and output balun. To ensure repeatability of the results presented on this paper, a small automated production

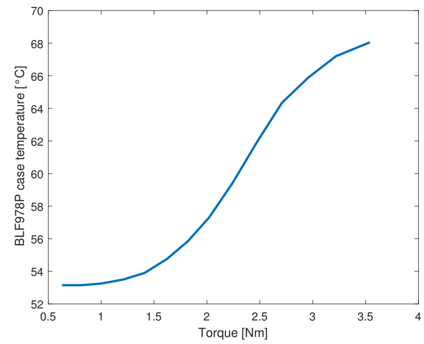

Figure 8: BLF978P's case temperature with respect to screws' fastening torque.

batch will be provided and tested. In particular, gain and phase stability are important for the efficiency of the amplifier's power combining stages. Moreover, fatigue tests will be performed to assess the device's robustness to repeated and abrupt RF turning on and off sessions.

Finally, full reflection operation tests at nominal output power will be performed to assure the RF termination installed on the amplifier module can handle this condition. Currently, a 80-way combiner cavity is also being designed at CNPEM and simulations have shown that failing modules connected to it can experience this level of power entering its output port [1]. This, in fact, is the topology expected for the next four 60 kW RF amplifiers, along with proper feeding of the amplifier modules by 8 and 10-way power dividers that are also being developed and tested in-house.

CONCLUSIONS

A RF SSPA module was designed and prototypes were assembled and mounted in-house. The goals defined on Table 1 were succesfully achieved through careful tuning of the input and output impedance matching circuits on the workbench. Some tests to improve thermal management of the device were carried, with positive results on the average temperature of the amplifier's components. Automated production of a small batch of amplifier modules will be supplied and future tests shall validate the design.

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