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DEVELOPMENT OF A 1.5 GHZ, 1 KW SOLID STATE POWER AMPLIFIER FOR 3RD HARMONIC SYSTEM OF THE ALBA STORAGE RING

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Abstract

ALBA is a third generation synchrotron light source located near Barcelona, in operation since 2012. In order to improve the operation, a third harmonic system has been designed for the storage ring to stretch the bunch length and so, improve the beam lifetime and increase the stability current thresholds. The design of the system consists of four High Order Mode (HOM) damped normal conductive active cavities operating at 1.5 GHz [1], supplied with 20 kW of RF power each cavity, which provide a total voltage of 1 MV to the electron beam. The 20 kW RF power transmitter system is based on 250 W solid state power amplifier modules added in parallel. Four of these modules are first combined to form a 1 kW amplifier. This paper presents the designs of the 250 W power amplifier modules, the splitter and the combiner, as well as the measurement results of a 1 kW prototype crate.

INTRODUCTION

In synchrotron light source facilities short lifetime is always one of the main concerns. Among others, it is dominated by intra-beam scattering (Touschek effect). To minimize this effect, one possibility is to stretch the electron bunches using a secondary RF system. Hence, a 3rd harmonic system for the ALBA Storage Ring has been designed to not only increase the beam lifetime but also damp the coherent instabilities through an effect known as Landau damping [1].

This proposed secondary RF system is composed of four HOM damped normal conductive active cavities at 1.5 GHz [2, 3]. Each cavity will be powered by a 20 kW RF power transmitter and therefore presenting a total voltage of 1 MV for the beam.

Solid state technology used for amplifier design has many advantages over the classical vacuum tubes amplifiers, such as the elimination of vacuum and high voltage. Also the large number of active devices provides an intrinsic full redundancy of the system. Transistors with higher drain voltages and new semiconductor materials lead to higher efficiencies [4, 5]. Hence, the ALBA storage ring 3rd harmonic system is going to exploit this technology for its power source. The building block of this power transmitter is a 250 W SSPA module. To achieve the 20 kW total power per cavity, the power will be split in twenty crates of 1 kW power amplifier, made up of a 4-way splitter/combiner and 250 W SSPAs, which have been developed in house.

A 250 W SOLID STATE POWER AMPLIFIER MODULE

The starting point for any solid state power source is a primary SSPA module which indicates the total number of modules to attain the overall power level in such a modular system. The more power the primary SSPA module provides, the less modules would be required.

A 250 W SSPA at 1.5 GHz (L band), CW mode with compact size (power to size ratio), using GaN HEMT device CGHV14250 from CREE (Wolfspeed), has been designed, manufactured and tested. This single ended class-AB power amplifier has an average efficiency of 70 %, a power gain greater than 16 dB an input return loss lower than -10 dB.

The 250 W power amplifier has been fabricated on a RO4003C laminate from Rogers with a substrate of 0.5 mm thickness and 90 x 70 mm surface area. To design the impedance matching networks, micro-strip stubs were implemented instead of capacitors. This offers advantages such as the thermal issue alleviation of the Output Matching Network (OMN) in CW mode due to high voltage and current.

A top view picture of the manufactured module is shown in the Fig. 1.

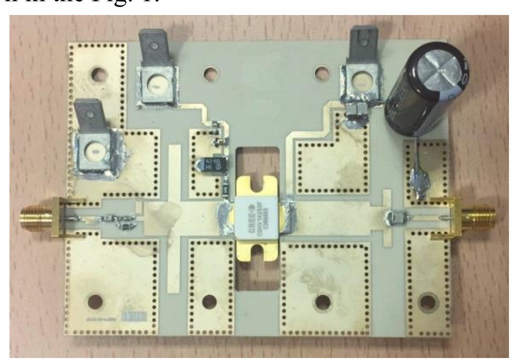

Figure 1: A 1.5 GHz power amplifier module.

For this power amplifier the transistor has been biased at drain voltage of 50 V and 500 mA of quiescent current. Both input and output matching networks were fine tuned for the maximum output power and efficiency. Since the optimum frequency was lower than expected, the sizes of the micro-strip stubs were reduced in order to tune the board once it was built.

To let the thermal power produced in transistor flow to the water cooled heat sink made of the copper, a thin layer of heat transfer compound paste was applied on the transistor flange. For better mechanical contact, the transistor was pressed down by a Teflon support and bolted down to copper base plate with two screws to an appropriate

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torque. Thermal performance of the power amplifier was evaluated by an infrared camera. Critical spots on the circuit board are transistor case and DC block capacitor as the only component in the output part of the RF path. DC choke capacitors were also performing under safe conditions.

The 250 W, 1.5 GHz SSPA were characterized with a test setup as shown in Fig. 2 and RF parameters like output power, power gain, and efficiency have been measured.

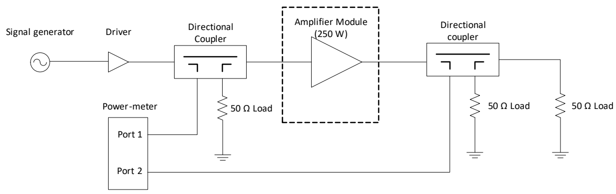

Figure 2: A 250 W amplifier module test setup.

Four of these boards were built and measured, showing a good behaviour with main parameters fitting the design values and a good repeatability as shown in Fig. 3.

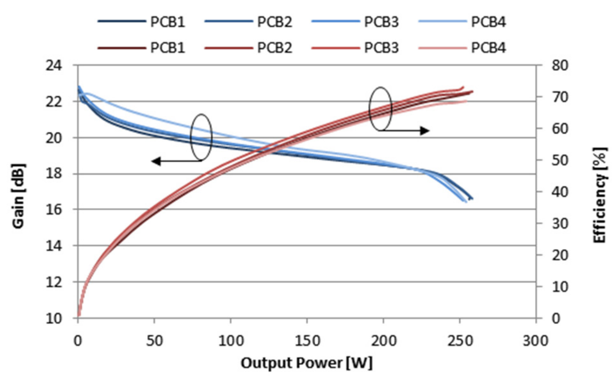

Figure 3: Four 250 W amplifier modules performance measurements.

POWER DIVIDER/COMBINER AND COUPLER

For a 1 kW power amplifier which includes four individual 250 W modules, the input power to each amplifier is provided with a 4-way power divider that splits the output power of a driver equally in four branches, not only in magnitude, but also in phase. At the output a power divider has been used to aggregate the power coming from the four 250 W modules.

For both, a distributed microstrip based power divider/combiner with tree structure has been designed and fabricated on RT/duroid 6035HTC based laminate with dielectric thickness of 1.5 mm. The Wilkinson topology has been used for this splitter/combiner.

The splitter has a transmission of -6.4±0.03 dB and a return loss of -20 dB.

The Wilkinson isolation loads in the combiner were intentionally removed because a circulator will be placed at the output of every module in order to protect again reflected power. Therefore, there will be no more concerns regarding resistor size and its power handling capability.

The power combiner transmission performance is -6.4±0.05 dB. Due to the fact that there is no isolation loads, the return loss of the combiner is 3.1±0.05 dB and a good phase and amplitude match must be assured for an optimal combination.

To monitor the output power of every module and the total power of the complete 1kW crate, a coupler with -30 dB of coupling and 20 dB of directivity has been designed and placed in the power combiner.

The splitter and the power combiner with the couplers are shown in Fig. 4 and Fig. 5.

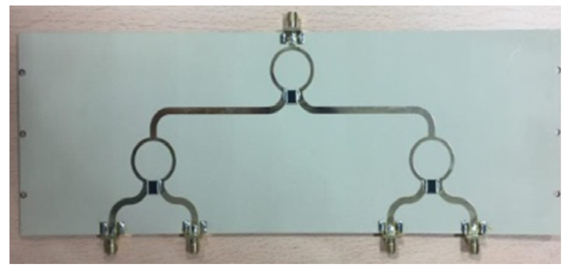

Figure 4: Power splitter.

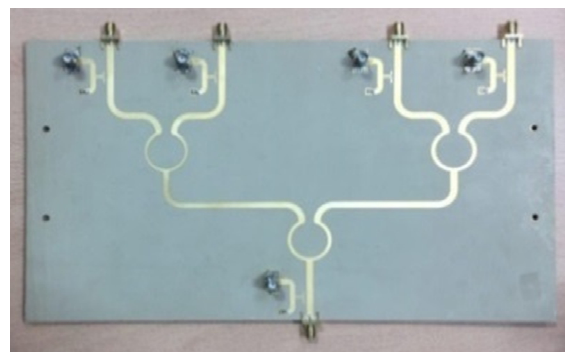

Figure 5: Power combiner with directional couplers.

1 KW POWER AMPLIFIER

The test the combination of four modules to obtain a 1 kW power amplifier, a test setup has been prepared. It includes a DC power supply to feed the amplifiers and a driver (commercial CGHV14250 test board) and pre-driver (ZHL-5W-2G-S+ from Minicircuits). A signal generator for the drive has been used, as well as some auxiliary power supplies to bias the modules. The set-up includes circulators and loads for the isolation of the modules.

The assembled 1 kW SSPA test set-up is shown in Fig. 6.

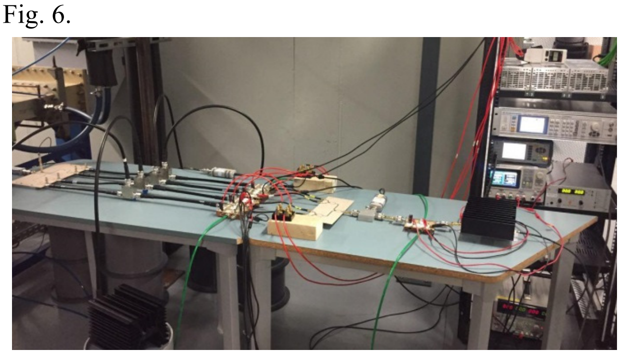

Figure 6: 1 kW SSPA test setup assembly.

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In such a modular combined system, due to non-identical performance of individual power amplifiers, as it appears in the measurement results in figure 3, unbalanced magnitude and phase in power divider/combiner ports may appear, leading to a degradation of the efficiency. In order to improve the efficiency, some considerations have been taken.

First; the individual amplifiers were tuned in order to minimize the phase difference between different modules as much as possible for their maximum output power.

Second; the phase and insertion loss of every cable used to connect the output of the modules, the circulators and the combiner have been measured and sorted so, that the 4 different branches present the less difference of phase and amplitude at the combiner input.

The influence of the second phase compensation is shown in Fig. 7. After compensation (solid line) there is an improvement of more than 10 % in the efficiency than before compensation (dashed line).

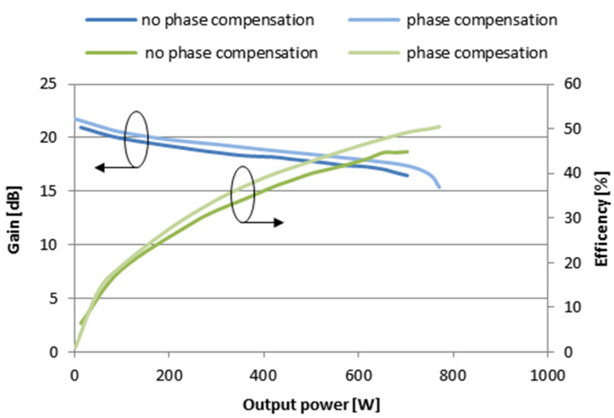

Figure 7: RF parameters measurement with and without phase compensation.

Since the cooling is one of the major issues in CW operation and high level of power, during the high power measurements, the transistor case and PCB temperature have been monitored. The IR images of all four 250 W power amplifiers are shown in Fig. 8.

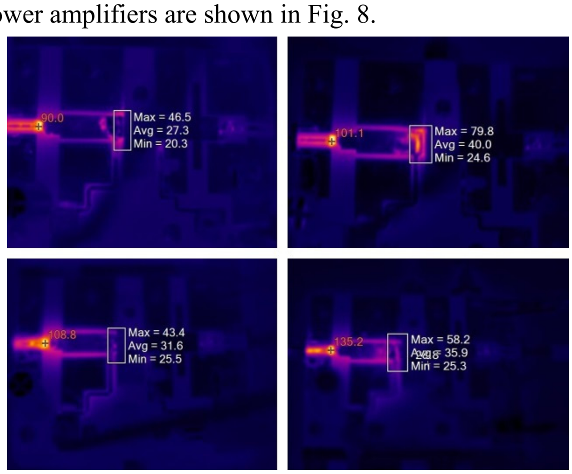

Figure 8: Thermal performance of four 250 W SSPA modules.

Table 1 summarizes the temperatures of the four modules at maximum power.

Table 1: SSPA Modules Working Temperature

Module	Drain temperature (max.)	Drain temperature (avg.)	DC block capacitor temperature
1	46.5	27.3	90.0
2	79.8	40.0	31.6
3	43.4	31.6	108.8
4	58.2	35.9	135.2

One could see that the hottest spot belongs to DC block capacitors in board number four. This means, regardless of less complexity and more power per size, that the single ended power amplifiers suffer from high order mode harmonics that must be suppressed either in the output matching network or DC feed. Otherwise; they will be exposed to high temperatures and lifetime could be degraded.

Besides, with the average efficiency of 70 % for 250 W SSPAs, the power dissipation is approximately 107 W. The efficiency of the total combined system is around 50 %. Further optimization of the cooling system could lead to an improvement of the total efficiency.

The gain and efficiency of the 1 kW SSPA in CW as well as the gain in pulse mode have been measured and plotted in Fig. 9. The efficiency for pulsed mode was not measured due the difficulty of measuring pulsed current. Maximum power for CW and pulsed mode are 770 W and 850 W respectively. Indicating that improving the cooling efficiency in CW mode, the system should be able work up to 800 W.

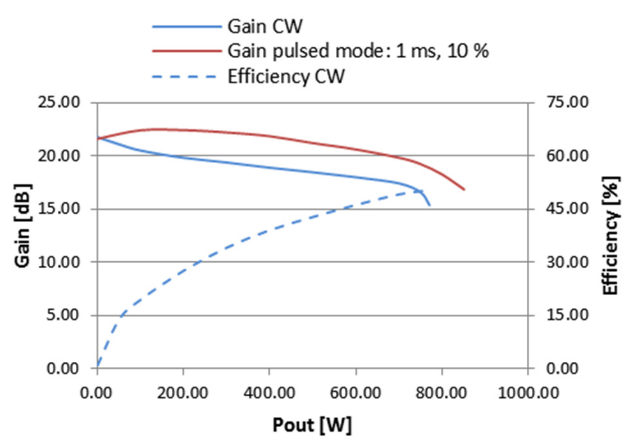

Figure 9: 1 kW power amplifier measurement results under CW and pulse mode operation.

CONCLUSION

A 1.5 GHz and 1 kW solid state power amplifier prototype for the 3rd harmonic system of ALBA storage ring has been successfully designed, manufactured and tested.

The maximum output power of 770 W in CW mode with 15.36 dB power gain and 50.49 % efficiency have been achieved, with the second harmonic at -46 dBc.

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