A 2.5 kW, LOW COST 352 MHz SOLID STATE AMPLIFIER FOR CW AND PULSED OPERATION

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Abstract

A 2.5 kW, 352 MHz unconditionally stable RF amplifier for CW and pulsed operation has been built and tested at LNL. The amplifier, designed and developed in collaboration with LURE Orsay, is made of 9 modules, each containing one push-pull 350 W MOSFET equipped with a circulator and a RF termination. High efficiency, linearity, reliability and low cost are the main features we aimed to for this device, which was developed for intermediate beta, independently phased superconducting cavity linacs. Technical characteristics and test results will be presented.

1 INTRODUCTION

High power radio frequency amplifiers have been built for many years using electron tubes and klystrons, while the solid-state technology has been used for low power amplifiers. The present performance of RF power MOSFET's allows using the solid-state technology also in high power amplifiers [1]. MOSFET amplifiers are free from thermal runaway and secondary breakdown, which affect bipolar transistors, and they don't require periodical replacement like vacuum tubes. For these reasons, during year 2000 a new development program for a modular 352 MHz, 2.5 kW solid-state amplifier has started at LNL, in the framework of a superconducting linac project for high intensity beams. The goal of this project is to demonstrate the possibility of building a low cost power amplifier, optimized for accelerator applications, by combining a suitable number of independent modules. This project has been carried on at Legnaro in synergy with a similar project pursued in LURE-Orsay Cedex (FRANCE).

2 THE AMPLIFIER

The final stage of the amplifier is built using a set of eight modules connected in parallel by means of an eight-way power combiner. Each module must provide a RF power of at least 330 W, with a minimum power gain of 9.5 dB. Taking into account some power losses in the cables and in the combiner, a total power of 2.5 kW is then obtained. An additional module is used as a pre-amplifier by means of an 8-way power splitter. The block diagram is shown in Fig.1.

To obtain a good combining efficiency, good uniformity in the output signal amplitude of different modules is necessary. Concerning the phase, the requirements are not very strict: simple calculations show that, in the worst case, a phase spread of 20 degrees brings 1.5% losses in the output power.

Water-cooling was used for all modules to obtain a compact design.

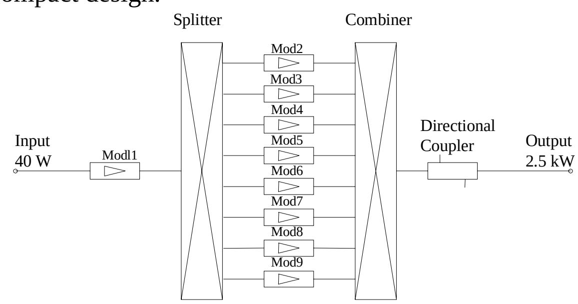

Figure 1:Block diagram

Figure 2: Photo of the amplifier

3 THE MODULE

Each module includes one push-pull power MOSFET type D1029UK produced by Semelab. The data sheets of this device declare a maximum power of 350 W at 175 MHz with a power gain of 13 dB [2]; however, similar characteristics have been found to be present also at 352 MHz, as well as the possibility to power the MOSFET

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with 30 VDC without any damage [1]. The devices we received from the manufacturer had a gain of 17 dB at 175 MHz; we could obtain for all our modules more than 12 dB at 352 MHz.

Since load mismatching is a very common event in powering superconducting resonators, a power circulator and a RF termination are included inside every module to protect the MOSFET against excess of reflected power. A low cost circulator type VDB 1078 working at 352 MHz produced by VALVO [3] and a 50 ohm 370 W RF termination were used; they are small enough to be mounted inside the amplifier module boxes. We found the solution of a distributed protection cheaper than the one with a big circulator and a RF termination at the amplifier output. The schematic drawing of the module can be seen in Fig.3.

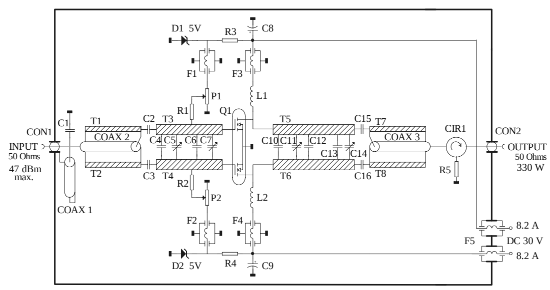

Figure 3: Schematic drawing of the module

Unconditional stability is very important in order to avoid self-oscillations, especially in case of load and/or source impedance mismatching. A great effort was done to fulfil this requirement; a solution was found at LURE by using a coaxial-cable-filter with a suitable length connected in parallel to the input of the module [1]. The same solution was adopted at LNL using a small cable about 1 m long. The exact length was found to be very critical and had to be carefully adjusted and tested for each module.

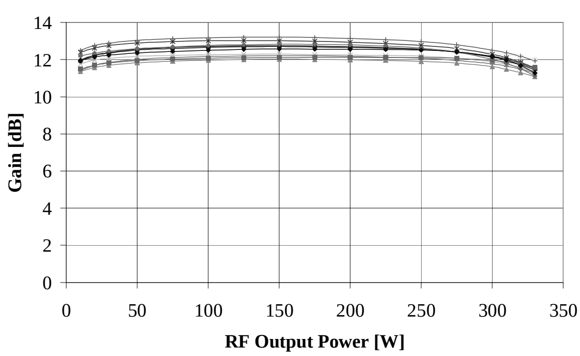

Figure 4: Gain characteristic

During 2001 eleven modules have been built, adjusted and tested obtaining an optimum compliance to the design requirements. Even better characteristics were obtained due to the unexpectedly high gain of the semiconductor devices. An average power of 330 W per module and a gain of 12 dB could be obtained.

The output phase spread among modules was kept within 15 degrees (see figure 6).

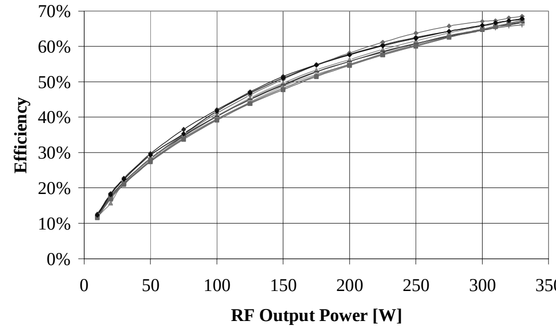

Figure 5: Efficiency characteristic

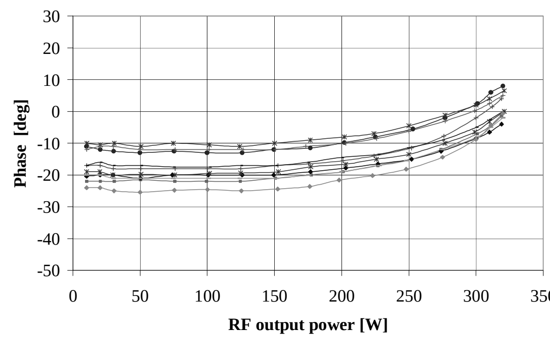

Figure 6: Phase characteristic

The module can be seen in Fig. 7. Every module is fed by an individual switching power supply, delivering 600 W at a voltage adjustable from 25 up to 32 VDC with low ripple. Since such commercial power supplies with similar characteristics are very widespread, their cost was found to be competitive with the one of a single, high power unit with equivalent stability.

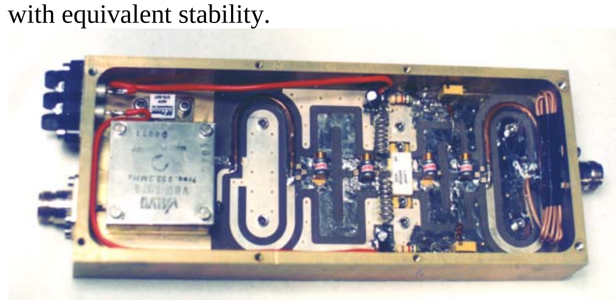

Figure 7: The 330 W module

4 THE RF POWER COMBINER

In order to sum the power coming from the modules, a homemade 8-way combiner was used. The outputs of all modules are connected in parallel and then a quarter wave line was used to bring back the impedance to 50 ohm. The same device can be used as an 8-way splitter.

The high power port flange is of the type EIA 7/8”, which can handle up to 3 kW; the 8 low power ports are equipped with N type connectors. The measured RF characteristics of this device show a good input matching of -35 dB at the working frequency, with a 3 dB bandwidth of 6.4 MHz, and -9.03 dB average transmission coefficient with a spread of 0.035 dB at the 8 low power ports.

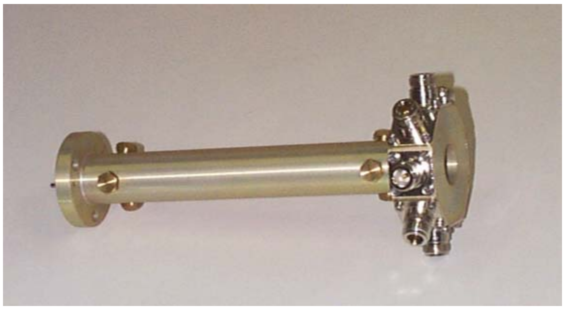

Figure 8: Photo of the combiner.

5 AMPLIFIER TEST RESULTS

After development, construction and testing of all modules and devices, the complete amplifier was assembled at the end of 2001. The modules were mounted on 2 water cooled bars; the resulting layout is very compact and the amplifier could be housed in a 19” rack 140 cm high and 80 cm deep, with a considerable amount of space still available. A flow meter with an interlock switch was used in order to protect the amplifier from water flow failures.

The amplifier test started closely after assembly.

The output power could easily reach 2.5 kW, the total gain was about 24 dB and could be maintained within 1.5 dB over the all power range (see Fig. 9 and 10).

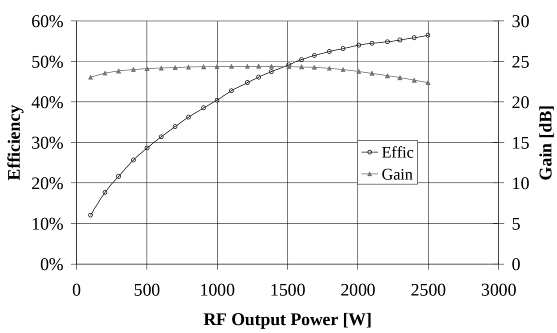

Figure 9: Gain and Efficiency characteristic

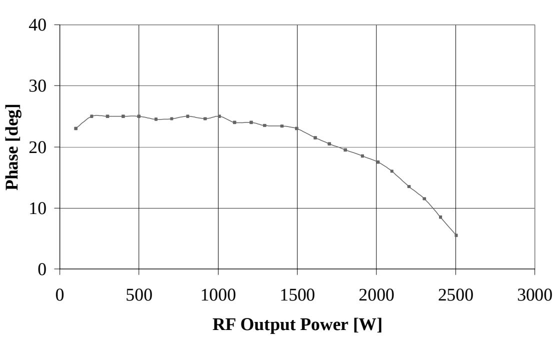

Figure 10: Phase characteristic

The measured efficiency, defined as the ratio between output RF power and the total DC power, is shown in figure 9. The DC input power was measured by means of Hall effect sensors and a data acquisition board controlled by a computer.

A LabView program was developed to display, to record the data and to set an alarm in case of failure.

The results show that the amplifier efficiency is above 50% when the output RF power is higher than 1.6 kW. The efficiency of our AC-DC power supplies is 82%.

An 8-hours test was done in order to investigate the stability of the amplifier in steady state, after temperature stabilization at various powers: 1.5 kW, 2 kW, and 2.4 kW. A very good stability in gain and phase was found, of 0.3% and 1% respectively; the last number is probably overestimated, being determined mainly by the resolution of the available testing instrumentation.

A spectrum measurement was done at the output of the amplifier in order to know the harmonic content of the radio frequency power. The result of the test at 2.4 kW can be seen in Tab. 1 and show a very low harmonics content. The amplifier was successfully used for RF measurements of superconducting cavities of the reentrant and quarter wave types.

Table 1: Harmonic content

Fundamental	352 MHz	63.8 dBm
Second harmonic	704 MHz	-55.8 dB
Third harmonic	1056 MHz	-65.1 dB

6 CONCLUSIONS

A 2.5 kW, solid-state RF amplifier was constructed and tested at Laboratori Nazionali di Legnaro. The device has shown very good characteristics of efficiency, stability, harmonics and cost. This amplifier is a prototype for medium intensity proton and ion accelerators based on superconducting resonators. The amplifier design is modular; higher RF output power can be obtained by combining a larger number of units. The next step of the development program is 352 MHz and 176 MHz amplifiers for the SPES project of a radioactive beam facility at Laboratori Nazionali di Legnaro.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] T. Ruan et al., “Low cost High Power UHF MOSFET Amplifier”, Proceedings of the 7th Annual Workshop on European Synchrotron Light Sources, ESLS 7, Berlin, Germany, November 1999.

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