DEVELOPMENT OF A SOLID STATE RF AMPLIFIER IN THE KW REGIME FOR APPLICATION WITH LOW BETA SUPERCONDUCTING RF CAVITIES

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Abstract

Projects based on the use of low beta superconducting cavities for ions are under operation or development at several labs worldwide. Often these cavities are individually driven by RF power sources in the kW regime [1, 2]. For an ongoing project a modular 2 kW, 176 MHz unconditionally stable RF amplifier for CW and pulsed operation was designed, built, and tested In order to optimize the performance of the power transistors and other thermally loaded components an extended thermal analysis was performed to develop a high performance water cooling system. The paper outlines the design concept of the amplifier and presents characteristic experimental results obtained from a series of 6 high power amplifiers.

INTRODUCTION

Solid state MOSFET VHF power amplifiers are very attractive for individually driven independently phased superconducting cavities in proton or heavy ion linear accelerators. This attraction is a consequence of such features of MOSFETs like linearity, low noise, high efficiency, reliability, low cost and long lifetime.

The objective in designing the amplifier is to meet the requirements imposed by the superconducting cavities in a linear accelerator.

The paper describes the main building block of the amplifier a 275 W module. It gives an overview of the amplifier concept and reports on the first experimental results.

THE 275 WATT MODULE

The high power amplifier is designed using a modular approach. Each module is based on a single RF power MOSFET and is hosted in shielding aluminium housing (Figure 1). Two water cooled copper boxes are inserted into the bottom of the housing to take care of the cooling necessities. The power transistor and power terminator are directly bonded to these boxes. The housing is equipped with two N-type RF connectors and DC feed-through with RF filters.

Electrical Design

Each 275 W module is based on the 50 V dual silicon N-channel enhancement mode vertical D-MOS transistor Philips BLF278 [4]. The amplitude and phase splitting/combining as well as the first and last stages of the matching circuits are realized by electrically short input and output baluns. The input and output matching networks are composed of two sections, designed using lumped as well as distributed components. Four tubular trimming capacitors are used for the precise individual tuning of the matching circuits. Special loading networks at the input and output are used to prevent any common-mode oscillations. Integrated circuit voltage regulators stabilize gate-source voltage.

The quiescent drain current of the power transistor were adjusted to 1A (0.5A per transistor section) at 50VDC of the drain voltage to ensure a class-AB operation. One of the 275 W modules is shown in Fig. 1.

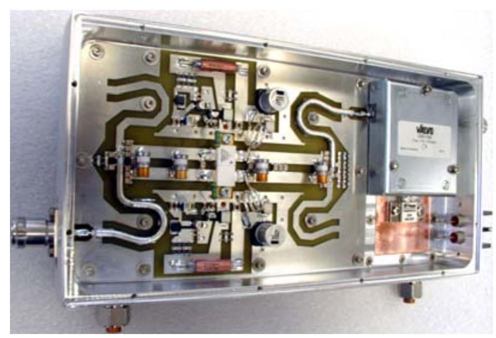

Figure 1: 275 W amplifier module.

A customized VALVO circulator VBB 1160 [5] is mounted inside of the amplifier housing. This enables an operation of the modules under mismatched conditions including full reflection at maximum output power. A surface mount 400W RF terminator is connected to the third port of the circulator to absorb the reflected power.

Thermal Considerations

There are two heavily thermal loaded components in the module, namely power RF transistor and RF terminator. The heat produced by the power dissipated in the transistor (about 250 W at nominal RF power) must be transferred to a heat sink. This is also valid for the power dissipated in the terminator under full mismatch condition (275 W). In order to prevent the main features (gain and efficiency) of the transistor from degradation and to avoid damage of the terminator the heat developed must be removed effectively. Thermal loading of these two components has been simulated by using the ANSYS computer code [6]. The simulations were done under the following worst case conditions. The transistor operates at the maximum output power with 50% efficiency and full power reflection to the terminator. The maximum allowed

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temperature of the heat sink in the vicinity of the transistor is 80 °C and 100°C in the terminator vicinity. The inlet water temperature is 25°C. The cooling boxes are connected in series. The simulations ask for a required water flow of 1l per minute with a corresponding pressure drop 0.3 bar and an increase in water temperature of 10°C. Subsequent tests of the individual modules and the amplifier showed very good agreement with the simulated values.

Module Test Results

All the modules have been individually tested before combining them to a high power amplifier. Several tests were carrying out by using a network analyzer to determine the S-parameters at low power as well as a power meter, an oscilloscope and a spectrum analyzer to measure characteristics at high power. In the latter case the monitoring devices were connected either to a directional coupler between the module and the load or to a high power attenuator.

In order to build six 2 kW power amplifiers 48 modules have been fabricated. Additionally 6 modules were manufactured to serve as drive amplifiers. In total 54 modules have been tested. Measured characteristics of a typical module are shown in Fig. 2. In Fig. 2 the gain of the module is represented by the red curve and the efficiency is shown by the blue curve.

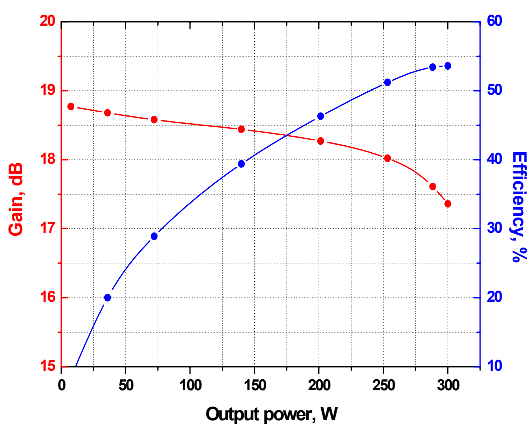

Figure 2: Gain (red curve) and efficiency (blue curve) of a 275 W amplifier module.

As seen from Fig. 2 the nominal output power corresponding to the output one-dB-compression point OP1 is 275 W. The gain is 17.7 dB at the nominal output power and the efficiency is higher than 50% for output power bigger than 240 W for this particular module. For all 54 modules the gain at the nominal power was measured to be scattered within 0.6 dB.

Harmonic distortion was found to be low enough for cavity excitation applications. The content of harmonics at the nominal output power was measured to be -46 dBc and -62 dBc for the 2nd and for the 3rd harmonics respectively. Noise and any other spurious signal at the output power was measured to be at least -66 dB.

Stability test showed that the gain of the modules was stable within 0.015 dB over an 8-hour period of time at nominal power after warm-up. The phase was stable within 0.3°.

Because of the specific application the modules must operate under the full mismatch condition at the output for a time period as long as 4 hours. The corresponding test was carried out successfully.

The modules are equipped with bimetal cut-outs in order to protect the power transistors form overheating. The thermal switches are bonded to the transistor cooling box. During the test at the nominal output power the cooing water was turned off to simulate a cooling system failure. When the temperature of the cooling box approaches about 50°C the switch breaks the DC voltage line in about a minute. It takes about 4 minutes for the box to be cooled down to the temperature of 35°C, at which the bimetal switch recovers.

THE 2 KW AMPLIFIER

The 2 kW Amplifier is composed of 8 modules connected in parallel. The amplifier is hosted in an 8-unit high 19” case. The amplifier is equipped with an N-type RF connector for the input power, 7/16”-type RF connector for the out put power and with DC terminal block. In order to load equally the modules within one amplifier the 54 tested modules were divided into 7 groups: 6 groups of 8 modules in each for 6 amplifiers and 1 group of 6 modules to serve as drivers. The first amplifier was composed of 8 modules with a gain scatter of 0.1 dB around the average value of 17.3 dB.

Amplifier Design

The input to the amplifier power is split by an 8-way quarter-wavelength power splitter shown in Fig. 3.

Figure 3: 176 MHz Splitter/Combiner.

The splitter is characterized by a return loss of -35 dB and an isolation of -18 dB at 176 MHz. After amplification of the signal by 8 parallel modules the signal is combined again by an 8-way combiner identical with the splitter. The insertion loss of the splitting-combining network including the cables to connect the modules was measured to be 0.26 dB.

The 8 modules are attached to the cooling water distribution system by Swagelok® inter-connectors. The assembled amplifier is shown in Fig. 4.

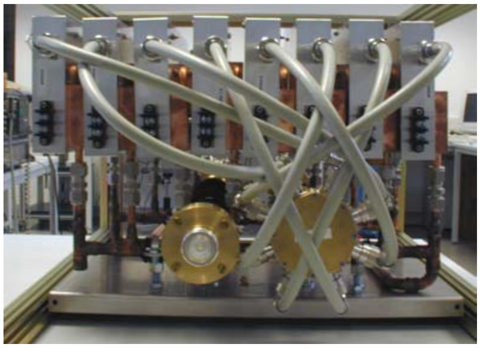

Figure 4: 2 kW amplifier.

Amplifier Test Results

The test of the amplifier was carried out using a high power directional coupler connecting the amplifier with a high power terminator and a power meter. The set-up is shown in Fig. 5.

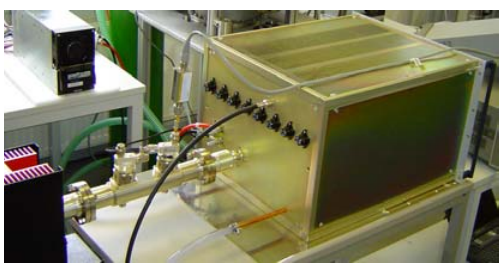

Figure 5: The first 2 kW amplifier under test.

Measured characteristics of the first amplifier assembled are shown in Fig. 6. In Fig. 6 the gain of the amplifier is represented by the red curve and the efficiency is shown in the blue curve.

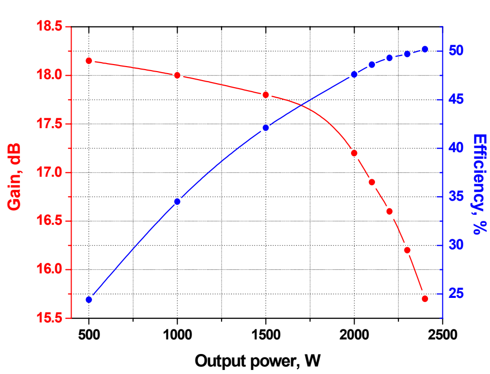

Figure 6: Gain (red curve) and efficiency (blue curve) of the first 2 kW amplifier.

As seen from Fig. 6 the nominal output power corresponding to the output one-dB-compression point OP1 is 2.1 kW. The gain is 17.1 dB at the nominal output power and the efficiency is approaching 50%. The amplifier was successfully tested under full reflection condition at the maximum power of 2.4 kW and in asymmetric regime when one or a few modules were switched off. With better cooling it was possible to increase the gain at P1 point by 1 dB.

Harmonic distortion and stability of the amplifier is determined by the behaviour of the individual modules and was measured to be very similar to those of the modules (see section *Module Test Results*). Each module of the amplifier is overheating protected and a signal LED indicates that at least one of the modules fails.

CONCLUSIONS

A 2 kW 176 MHz solid state power amplifier has been designed, built and successfully tested up to the maximum output power of 2.4 kW. The amplifier is unconditionally stable and can be used either for CW or pulsed operation of superconducting resonators. The amplifier has a modular design and can be easily converted to ensure a required power level. Six amplifiers of this kind have built in the frame of an ongoing accelerator project. All six amplifiers are driven by one 6-channel drive amplifier and controlled by a LLRF system [3]. Extended versions of the amplifier with an output power from 2.4 kW up to 4.8 kW are certainly feasible on the basis of the described amplifier concept.

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