DEVELOPMENT OF A 500-MHz SOLID-STATE RF AMPLIFIER AS A COMBINATION OF TEN MODULES

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Abstract

The recent development of semiconductor technology has proved that a solid-state RF amplifier is an attractive alternative high-power RF source for numerous accelerator applications. Because of the great redundancy and reliability of solid-state amplifiers present in many facilities worldwide, the development of a kW-level RF power per module using compact planar baluns has also been undertaken in NSRRC. Ten amplifier modules are combined to achieve stable output power 8 kW as an initial conceptual realization of a basic power unit within a combined network. This article describes each portion of the amplifier with the experimental results.

INTRODUCTION

Solid-state RF amplifiers have proved to be reliable and attractive CW RF power sources for accelerator applications [1-3]. Some R&D work has been done to improve the design and structure of the amplifier module itself [4] in NSRRC. The main feature of the developed solid-state amplifier circuit in NSRRC is a planar balun and stable operation of CW at output power 1 kW. With such great power per module, the required module numbers for systematic power combination become decreased by a third relative to the present CW 500-MHz power module, about 650 W [5]. Fewer modules would be built for the same total RF output power.

Under such a condition, the importance of each module becomes great because of its enhanced contribution to the overall output power. The failure of one module during operation would bring a larger impact on the other modules and the total output power. The health status of each module thus becomes more important than in those systems using modules of less power. An early diagnosis of the health status of each module would be helpful to prevent multiple module failure at the same machine shift. To decrease the impact of one module failure within a combined group, the unit number within a basic combination group must also be increased. The reliability thus becomes important, and is improved on increasing the capacity of cooling with water and air.

SYSTEM DESCRIPTION

A high-power solid-state amplifier consists of several basic combined groups; the basic combining group typically contains eight modules in parallel [1-2]. In this case, if one module of the eight fails, to maintain the original total output power, the other modules would need to increase output power about 0.58 dB (14.3 %). There is also a combined group containing nine modules [3]; when one of the nine modules fails, a power increment of each other module by 0.52 dB (12.5 %) would be required to maintain a constant total output power. For a combined group comprising ten modules, one failure would cause a power increment about 0.46 dB (11.1 %) of the other nine modules. For a PA module with saturation power 1 kW, maintaining a constant output power with one failure can support maximum output power 9 kW in a nominal operation with ten units in combination. To include cable and combination losses, the nominal maximum output power must be 8.5 kW with 850 W from ten modules or 950 W from nine modules. The basic combined group, shown in Fig. 1, would be a basic unit for more power combination.

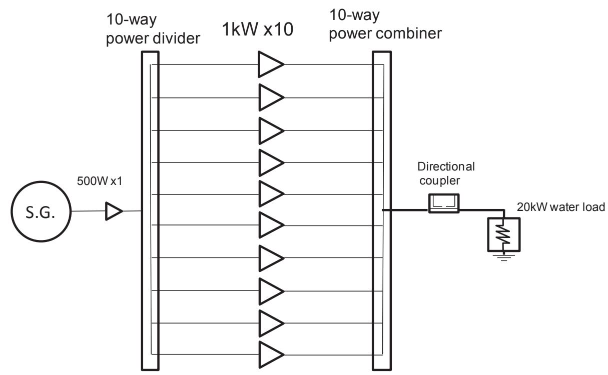

Figure 1: Basic combined group of ten modules for total output power 8.5 kW.

Block Diagram for a Power Amplifier Module

The power amplifier module generally contains an amplifier circuit, a circulator and a stripline load. With the output circulator and load, the amplifier would be unconditionally stable because of the isolation of the output and the amplifier circuit. As the amplifier module itself can contribute RF power up to 950 W, the status of each amplifier module becomes significant, such as its temperature, output power and air-cooling fan rate, and can serve as indicators of its health. With this status information, personnel can find the worst one in advance and replace or repair it during machine maintenance (see Fig. 2).

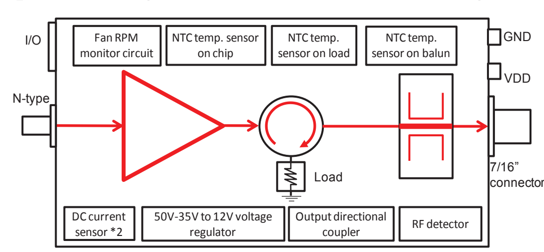

Figure 2: Block diagram of a complete amplifier module.

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Layout of a Power Amplifier Module

Based on the above requirements, the amplifier module layout was designed accordingly. The module contains a water-cooling plate just below the circuits and RF components. The critical components have a water-cooling channel just underneath to increase the heat dissipation. This module would thus contain a RF interface, a DC power interface, a signal interface and a water interface. The parameters related to the operation can be obtained from the signal interface independently (see Fig. 3).

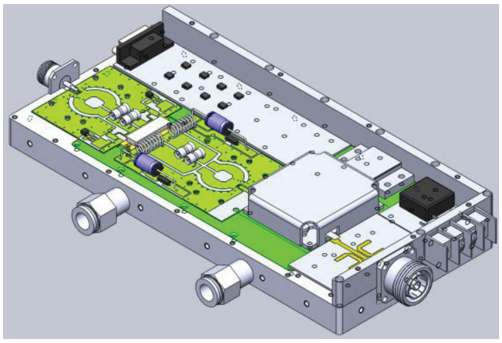

Figure 3: Layout of an amplifier module.

Ten-way Power Divider and Combiner Design

To fit best with a ten-way application, a power divider and combiner are designed at 500 MHz and manufactured in house. The power divider is accomplished with strip lines forming quarter-wavelength impedance transformers, as shown in Fig. 4. After dividing the output power of a driver amplifier and distributing it to each amplifier, a high-power combiner is required for power combination. The input connector of a combiner is 7/16" and the output port is connector 3-1/8 EIA, suitable for input about 1 kW and output 10 kW, as shown in Fig. 4.

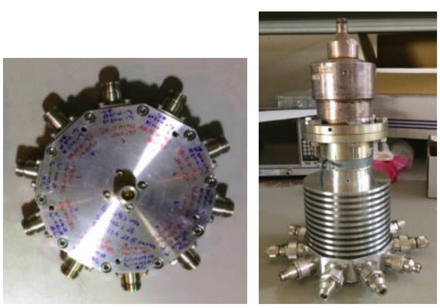

Figure 4: Ten-way power divider and combiner.

Copper Water-cooling Plate

For power components, proper cooling is important for stable and reliable operation of the system. In a power amplifier module, the most critical and power-generating part is the LDMOS chip of area about 3 cm^2. The best way to dissipate its heat is to attach the transistor directly to a water-cooling channel, so as to minimize the thermal resistance with least thickness. Designing a thin gap between the chip and cooling water would achieve the best heat dissipation. A thin copper plate is thus designed and manufactured to support the continuous wave (CW) operation of high-power RF components including LDMOS, circulator and load. The concept of a water-cooling channel through the highly integrated cooling plate is shown in Fig. 5. The thickness of copper between the RF components and the cooling-water channel is only 1 mm.

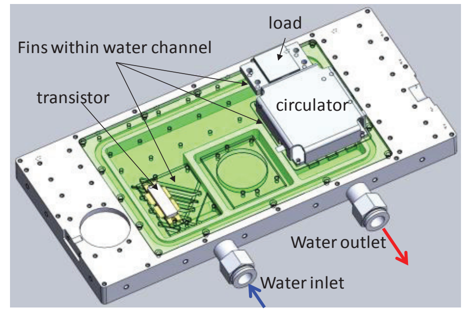

Figure 5: Design of a water-cooling plate for enhanced dissipation of heat from high-power CW RF components.

Water Manifold for PA Modules

Through the specific design of a water-cooling plate, the water piping for each amplifier module becomes independent. If the cooling water is connected in a series fashion, the water temperature seen by each module varies as the temperature rises after passing several modules. This effect not only decreases the lifetime of a transistor that sees a higher junction temperature but also affects the performance of each amplifier module as the operation of semiconductor devices depends strongly on temperature. For this reason, a water manifold connected in parallel is designed for a ten-way combination, as shown in Fig. 6. Each module would have the same inlet water temperature for an improved equivalent performance distribution.

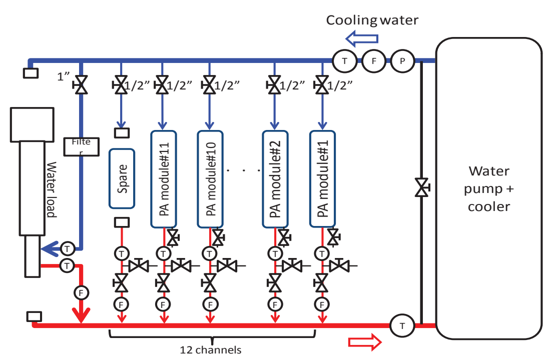

Figure 6: Water manifold with parallel connection of each module.

System Integration Layout

Before power combination in multiple stages, a single-stage combination for ten modules is required to ensure that a ten-way power combination is applicable. That combination would be the basic power unit for generation of increased RF power. The ten-way combination layout is shown in Fig. 7.

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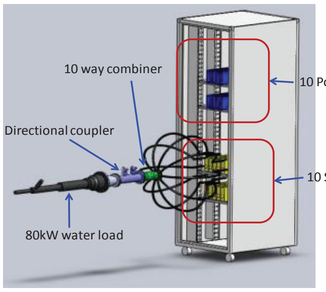

Figure 7: Layout for ten-way combination.

EXPERIMENTAL RESULTS OF HEAT MANAGEMENT

The failure of a power amplifier module results mainly from three factors -- electromigration of a transistor due to a thermal effect [6], thermal fatigue of the Tin solder [7], and an RF arc due to large instant reflected power [5]. As the designed module operates at a large output power that also introduces a corresponding heat loss on a transistor, an improved heat sink for more rapid dissipation of heat is necessary. An improved heat sink with a cooling fin under the transistor is tested below. Besides the chip itself, the output planar balun acquires a high temperature because of its poor thermally conducting structure (no direct metal contact is applicable for a planar balun). The high temperature is the source of solder fatigue. The air-cooling fin is soldered onto the balun while an additional DC fan is added to bring some air flow to prevent thermal fatigue of the solder. The test results are shown below. To avoid a RF arc due to great VSWR reflected power, the dielectric strength of air is enhanced on adding a piece of dielectric material between the stripline connector and ground.

Water Channel Fin Under Chip

The DC power is directly applied on adjusting the gate voltage and thus turning on the LDMOS. V_{ds} is 50 V with varying I_{ds}. A temperature sensor is in contact with the flange of the chip. On varying the rate of water flow and the DC power, the flange temperature can represent the cooling capability of the copper heat sink. For a water flow rate greater than 4 L min^{-1}, the flange temperature becomes stable. A greater flow rate would be better, but the flange temperature apparently does not decrease, as shown in Fig. 8. With such a small water flow rate (only 4 L min^{-1}), the junction temperature would be less than 150 ^{o}C which corresponds to a TTF more than 100 years at full-power operation, as shown in Fig. 9.

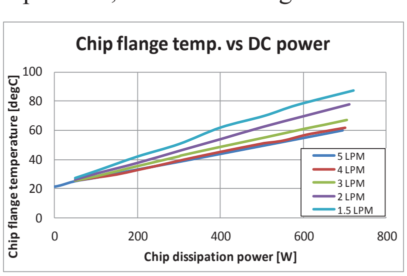

Figure 8: DC power vs LDMOS flange temperature.

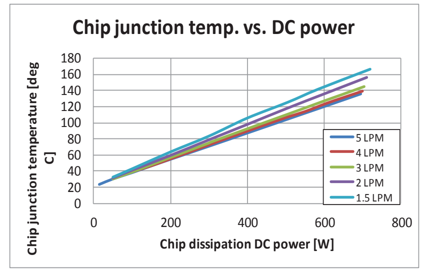

Figure 9: DC power vs LDMOS die junction temperature.

Air-cooling Fin on the Balun

A proper air flow over a planar balun assists dissipation of heat from the balun. In a microstrip line, the rise in temperature would increase the loss; the loss also increases the temperature until a thermal balance with the environment is attained. With some air flowing over the planar balun, the temperature greatly decreases by more than 25 ^{o}C and has more RF power, about 15 W, at saturation, as shown in Fig. 10 and 11.

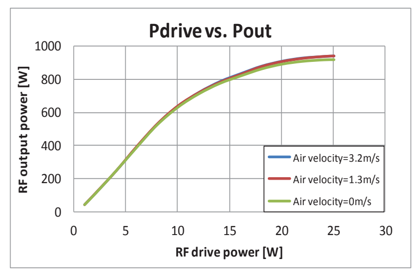

Figure 10: Air-flow velocity at a planar balun vs output power.

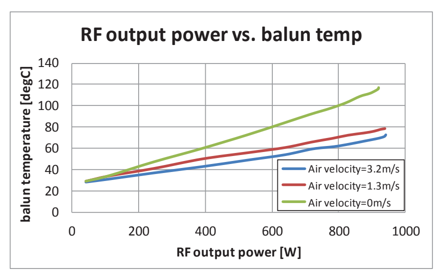

Figure 11: Balun centre temperature vs air-flow velocity.

CONCLUSION

A systematic design for a ten-way combination in a 1-kW amplifier module is presented. The saturation power is decreased slightly to 950 W to satisfy a redundant requirement of group power 8.5 kW with one module failure tolerance. The sensors to indicate the health status and circuits of a module are added for advanced failure diagnosis. Additional highly efficient cooling capability is readily applied with a small rate of water flow and a slight air-cooling force, as well as enhanced electric strength implemented for stronger and more reliable module design. With such improvements, the system integration is expected to have a decreased module quantity, greater power density, increased reliability and decreased maintenance effort.

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