DESIGN AND TESTING OF A 12-kW, 352-MHz SOLID STATE RF SYSTEM AT THE ADVANCED PHOTON SOURCE*

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Abstract

A 12-kW, 352-MHz rf power amplifier system was designed and constructed at the Advanced Photon Source (APS) as a research and development test bed for eventual development of a 200kW cw rf system capable of supporting accelerator beam operation. The system utilizes six 2kW laterally diffused metal oxide field effect transistor MOSFET (LDMOS) rf amplifiers, an output cavity combiner terminated with a WR2300 waveguide output flange, and a monitoring system based on programmable logic controller technology. The combining cavity has a total capacity of 108 two-kilowatt inputs to support eventual operation up to 216kW maximum output power. Design details and operational performance of the 12kW system will be discussed.

INTRODUCTION

A 12-kW, 352-MHz solid state rf system was designed and built to evaluate the feasibility and performance of the resonant cavity output combiner concept in rf power amplifier systems for particle accelerator applications. The compact physical size of the cavity combiner over conventional high-power coaxial combiners is recognized as an advantage in the design of high-power solid state systems. This rf system will be utilized as a test bed to optimize the combining cavity design and performance for the APS application. It will also be used to test the effectiveness of dynamic drain voltage control in maintaining peak operating efficiency over the output power range of the system [1].

SYSTEM DESIGN

The core concept of the 12-kW, 352-MHz solid state system is a resonant cavity output combiner, which is supplied rf power from six individual 2-kW amplifier chains. The output coupler of the cavity combiner also provides a direct transition to WR2300 waveguide, and is terminated, through a short straight waveguide run including a directional coupler section, to the final rf load. Front and rear views of the 12-kW system are shown in Fig. 1. A common pre-driver/splitter supplies rf drive power to all six amplifier chains, each of which consist of an input attenuator, phase shifter, 100-watt driver stage, driver output directional coupler, 2-kW power amplifier, followed by a directional coupler and output circulator. Each amplifier chain drives one input port of the combining cavity. All six 2-kW final amplifiers are mounted on a common water-cooled cold plate, which is supplied de-ionized water at a flow rate of 4 gallons per minute. Drain power for the 2kW final amplifiers is provided by a single commercial dc power supply. A programmable logic controller (PLC) provides parameter-monitoring, interlock, and local control/monitoring functions through a touch-screen user interface.

Figure 1: Left, front view showing operator controls and adjacent low-level rf control rack (blue). Right, rear view showing the cylindricular output combining cavity, waveguide transmission system, and terminating rf load.

COMBINING CAVITY DESIGN

The combining cavity was designed to enable various configurations for testing amplifiers. It consists of eighteen removable panels available for input ports. A coaxial to waveguide transition was used to transfer power from the cavity to WR2300 waveguide, as shown in Fig. 2. The input couplers are magnetically coupled along the periphery of the cavity, while the output coupler is heavily overcoupled along the cavity axis. The geometry is constructed from silver-plated aluminum to maintain high conductivity. The tuner is mechanically operated with a frequency range of +/- 3MHz to accommodate manufacturing tolerances and thermal effects at higher power. Each input coupler is tuned by adjusting a cross-member along its horizontal posts. Due to the non-homogeneous electromagnetic fields along the length of the cavity, the location of the cross-member is unique for each amplifier along a panel. Tuning for critical coupling was achieved by sliding the cross-member of an individual input coupler, while the other input couplers were shorted, until a reflection coefficient of $\Gamma = \frac{1-N}{1+N}$ was produced, where N is the total number of amplifier inputs. The combining cavity was optimized for high-power operation where thermal effects were evaluated and the peak electric field was minimized. The maximum coupling of the output coupler is designed such that its peak electric field at 100kW was less than

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0.5 MV/m. The output coupler is adjustable in order to maintain critical coupling for various configurations as additional amplifiers are inserted into the remaining panels.

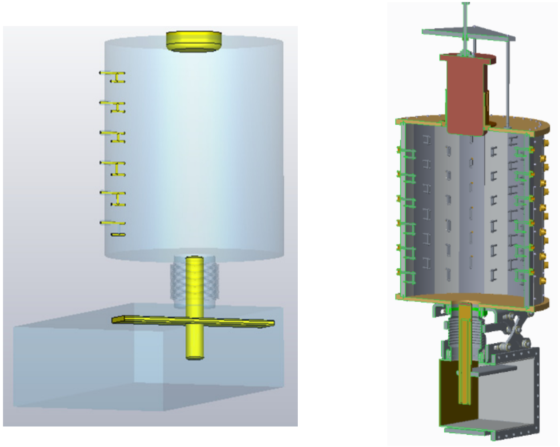

Figure 2: Geometry of the combining cavity: Left, simulation model of six-way version. Right, cross-section CAD rendering of fully populated geometry with 108 inputs.

2-KW AMPLIFIER MODULE

Each 2kW amplifier utilizes a single NXP MRFE6VP61K25HR6 LDMOS push-pull transistor device, rated at 1.25kW cw output power at a drain voltage of 50 volts (see Fig. 3). The amplifier was designed for operation at a drain voltage of 60 volts in order to achieve 2kW output power. A circulator is used between the amplifier output and the combining cavity input, to maintain a constant 50-ohm load to the amplifier.

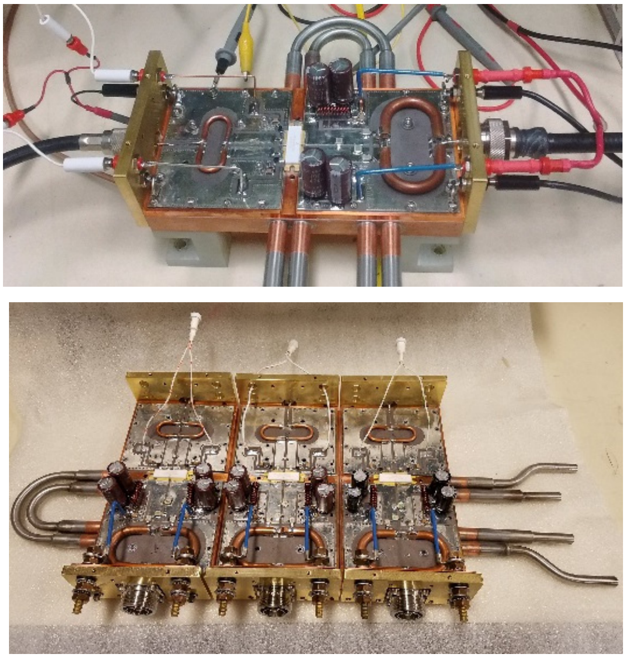

Figure 3: Top, first prototype 2-kW amplifier under test. Bottom, three of six amplifiers mounted on a common cold plate.

After optimization, the first prototype amplifier produced 2.021kW cw output power at the 3dB gain compression point with no sign of instabilities. The DC to RF efficiency was 75.4 %, at 18.59 dB rf gain. The highest harmonic power produced was the third, at a level of -39dBc. The 3dB bandwidth of the amplifiers was approximately 50MHz. After thermal stabilization at the 2 kW operating point, the transistor case temperature reached 84.4ºC [2]. This translates to a die temperature of approximately 144ºC, resulting in a reasonable mean-time-to-failure expectation [3]. The same design was replicated over six additional units, and each demonstrated similar performance (see Fig. 4). Cooling of the six amplifiers was achieved by mounting them on both sides of a water-cooled copper cold plate that was supplied with 4 gallons per minute of deionized water.

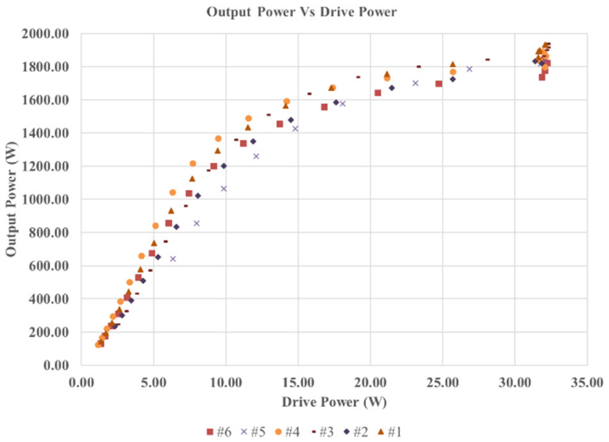

Figure 4: Comparative performance of all six 2-kW amplifiers.

AMPLIFIER COOLING

The 2kW amplifier uses a conventional water-cooled copper cold plate and carrier. Prior to fabrication, Finite Element Analysis (FEA) was performed to increase the confidence that the cooling scheme was adequate to achieve high reliability [2]. Using vendor supplied transistor geometry and material properties data, simulations showed that the transistor die temperature could be held to under 150°C with 800W being dissipated into a single cold plate/carrier. Thermal validation testing using both a transistor and a small 580W heater closely matched the thermal simulation results. Simulation results were then used to generate a thermal graph, which can be used to predict the case and die temperatures by referencing the temperature of a thermocouple placed on the transistor flange.

SYSTEM PERFORMANCE

The system has logged approximately 30 hours of operation at a maximum output power of 6kW, primarily to study thermal performance of the amplifiers and combining cavity, and to test compatibility with the existing analog low-level rf hardware used at APS. Figure 5 shows data on thermal stabilization of the 2kW amplifiers and the combining cavity from a cold start. The amplifiers achieve thermal stabilization roughly 30 minutes after turn on, at which point output power remains stable. The combining cavity did not achieve thermal stability, even after four hours of continuous operation, which indicates a need for better cavity cooling or active cavity tuning. In its current configuration, the cavity losses are 0.18dB, representing 260 watts of dissipated power at 6kW total output.

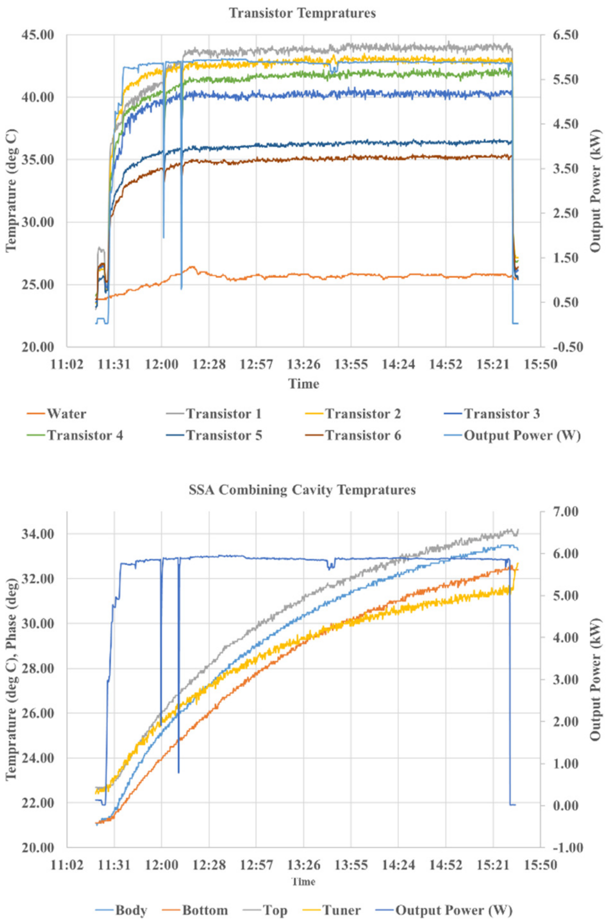

Figure 5: Thermal stabilization over time of the six 2-kW amplifiers (top), and the combining cavity (bottom). The rf output power was a constant 6kW cw in both cases.

A low-level RF (LLRF) feedback control system was configured to control the total output power and phase of the amplifier system as drain voltage was varied from 40V to 50V in one-volt steps, with approximately one minute of operation at each step. Figure 6 shows data plots of overall system phase and total power output, in both open and closed-loop conditions. The data shows that the rf phase shift of the system is approximately 2° per volt change in drain voltage, an amount that is easily correctable by the LLRF system. Plotting the phase and output power versus drain voltage reveals that the closed LLRF loop regulates the output power and phase to a constant set point with varying drain voltage.

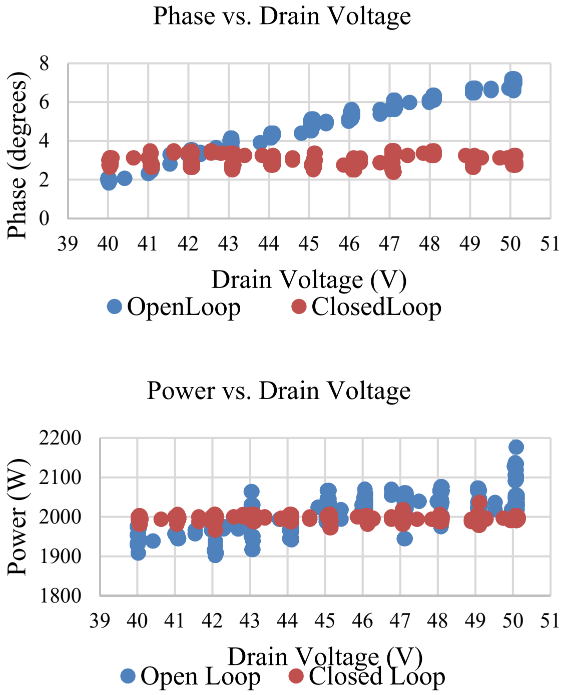

Figure 6: Open-loop (blue) and closed-loop (orange) system measurements of rf phase as a function of drain voltage (top), and rf output as a function of drain voltage (bottom).

CONCLUSION

The use of a resonant cavity output combiner is being examined as a way to minimize the overall size of a modular, high-power solid state rf system. Data from initial testing of the combining cavity in this 12kW system show a strong correlation to design simulation data. Testing of the system is ongoing, including plans for operation up to 40kW cavity input power by adding sixteen more amplifier modules, and implementation of dynamic drain voltage control to maintain high operating efficiency over the dynamic range expected in the APS accelerator application.

REFERENCES

[1] D. Horan, G. Waldschmidt, “Performance of the 352-MHz 4-kW CW Solid State RF Power Amplifier System Using 1-kW Push-Pull Devices,” in *Proc. Particle Accelerator Conf. (PAC’11)*, New York, NY, USA, March 28-April 1, 2011, pp. 1059-1061.

[2] NXP Application Note AN1955, “Thermal Measurement Methodology of RF Power Amplifiers”.

[3] NXP RF Power LDMOS Transistor Data Sheet, document number MRFE6VP61K25H, Rev. 4.1, March 2014.