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A HIGH-POWER, SOLID-STATE RF SOURCE FOR ACCELERATOR CAVITIES*

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Summary

During the past few years the Defense and Electronics Center of Westinghouse Electric Corporation has developed a solid-state, 250-kW peak, rf amplifier for use with the SPS-40 radar system. This system has a pulse length of 60 μ s and operates across the frequency band from 400 to 450 MHz. Because of the potential use of such a system as an rf source for accelerator applications, a collaborative experiment was initiated between Los Alamos National Laboratory and Westinghouse to simulate the resonant load conditions of an accelerator cavity. This paper describes the positive results of that experiment as well as the solid-state amplifier architecture. It also explores the future of high-power, solid-state amplifiers as rf sources for accelerator structures.

Introduction

This paper describes test results and observations taken during the SPS-40 Solid-State Transmitter/Resonant Cavity experiments performed at Westinghouse in cooperation with the Los Alamos National Laboratory. In these experiments, the SPS-40 Solid-State Transmitter was used to drive a 448-MHz, evacuated, resonant cavity to investigate the effects of resonant loading on a solid-state rf source. Tests were designed to measure possible transmitter-power waveform degradations, phase response, and output perturbations caused by the unusual load characteristics of the resonant cavity.

The SPS-40 Solid-State Transmitter (SSTx)¹ is a four-stage rf amplifier consisting of a driver cabinet and two power amplifier (PA) cabinets as shown in Fig. 1. The SSTx provides up to 250 kW of peak power

Fig. 1. SPS-40 solid-state transmitter showing the control system in the left cabinet and the solid-state modules with their power supplies in the center and right cabinet.

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with a typical pulsewidth of 60 μ s over the operating band of 400-450 MHz. Each rf stage (labeled Preamp, Predriver, Driver, and PA in Fig. 2) consists of a number of power modules operating either in parallel with combined output ports or individually as shown in Fig. 2. The redundancy of the amplifier structure permits degradation of several rf modules without significant reduction in output power. System output power may be adjusted by varying the dc voltage supplied to the modules of any particular stage, allowing for continuous variation of rf output from 0 to 250 kW.

Transmitter/Cavity Tests

The transmitter was initially tested into a resistive load to establish baseline power output and phase-response data. The transmitter was then connected to the resonant cavity. Initially, the output of the transmitter was isolated from the cavity through an external, high-power coaxial circulator that provided 20 dB of isolation. Bidirectional couplers installed before and after the circulator provided monitoring points for forward and reflected power. A phase bridge using a double-balanced mixer was connected between the output of the Preamp stage and the cavity magnetic field probe for phase measurements (Fig. 3).

After initial cavity outgassing, rf input to the cavity was gradually increased until the cavity power limit of approximately 100 kW at 2% duty was reached. This limit was dictated by transmitter output and cavity-cooling limitations. No transmitter degradations occurred and forward power, reflected power, and cavity-field waveforms were normal. Figure 4 shows the power and cavity-field waveforms with the characteristic fill time and pulse-shutoff power reflections.

The next series of tests were performed with the external, high-power circulator removed. Again, power levels of up to 100 kW were obtained with normal transmitter and cavity operation.

Transmitter phase response to the resonant load condition was measured both with and without the external circulator. Some disturbances in the transmitter output phase response were noticed during periods

Fig. 2. Solid-state amplifier block diagram showing combining and splitting scheme to achieve 240-kW output power.

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Fig. 3. Block diagram of cavity-load test setup.

Fig. 4. (a) Solid-state transmitter output.
(b) High "Q" cavity waveform.
(c) Cavity reflected power.

of high-power reflection from the cavity (such as out-gassing). Figure 5 shows the transmitter with a typical phase response when operating into the resonant cavity through an external circulator. The cavity frequency drift was tracked by manually tuning the frequency source. The slight shift across the pulse was caused by a combination of voltage droop on the transistor collector and heating effects within the transistor die. With the external circulator removed, the phase-response waveform becomes susceptible to measurement errors induced by the reflected power. A much larger peak occurs on the leading edge of the pulse as shown in Fig. 6. This corresponds to the high VSWR at the beginning of the pulse.

Fig. 5. Phase response with external circulator $2.24^\circ/\text{cm}$.

Fig. 6. Phase response without external circulator $1.79^\circ/\text{cm}$.

Phase errors caused by reflected power can be attributed to at least two sources. First, the finite directivity of the couplers (approximately 30 dB) allows a portion of the reflected power to add with the forward-power sample at the forward-monitor port. The resultant power vector is shifted in phase from the original forward vector and results in a disturbance on the output of the mixer. It can be shown that addition of the external circulator (with reverse isolation of 20 dB) reduces the potential phase error from 1.81° to 0.18° (forward- and reflected-power vectors 90° out of phase). Secondly, reflected power turned back by the output port of the transmitter can induce further phase errors of 0.43° with the circulator and 4.30° without. Although transmitter performance is not affected by these phase errors, their presence dictates the use of improved coupling and phase detection techniques.

The SPS-40 SS1x/Los Alamos cavity tests demonstrated the feasibility of driving high-Q resonant

loads with solid-state devices. No major problems occurred with the transmitter/cavity interface. Solid-state features such as good bandwidth and variable output power proved useful when conditioning the cavity during initial turn-on.

In addition to the cavity-load experiments, further investigations into multipoint cavity power combining, phase control and amplitude control were conducted to better understand the potential benefits of solid-state rf sources for linear accelerators. Although the previous experiments demonstrated the suitability of a solid-state amplifier as a conventional single-output source, the greatest potential for solid-state amplifiers is their use as distributed, multiple-output accelerator sources. The inherently modular characteristic of solid-state amplifiers allows distribution of the rf sources along the accelerator structure. The rf phase control, amplitude control, and multipoint combining experiments demonstrated the utilization of solid-state amplifiers as distributed accelerator sources.

Paramount to the concept of a distributed rf source is a multiple-accelerator cavity input. With this technique, the accelerator itself becomes the rf power combiner instead of using an external, single-output combining structure. Cavity combining will decrease the space and weight requirements associated with external coaxial or waveguide combiners and will reduce combining losses. Also, a distributed rf system eliminates waveguide voltage breakdown concerns associated with single-output-port amplifiers. These characteristics are especially important for high power (greater than 1 MW) and space-borne applications.

Recent tests conducted at Westinghouse have demonstrated the feasibility of such a combining arrangement. In these tests, power from two separate uhf amplifiers was driven into the resonant cavity through loop-coupling probes shown schematically in Fig. 7.

Fig. 7. Dual-probe cavity-drive set-up.

Effects of probe orientation, probe spacing, and input return loss were investigated at kilowatt rf power levels. The resultant cavity magnetic-field amplitude was greater than 95% of the field amplitude for a single-drive system at the same power level. Comparable radial cavity combiner designs^{2,3} indicate that combining losses remain fixed despite the number of input ports, unlike Wilkinson-type hybrid combiners. Therefore, high-power accelerator cavities with multiple-drive ports can be designed to also combine the rf power with low loss.

Accurate phase and amplitude control loops are required for both single- and multiple-output rf-source systems. Westinghouse has developed and demonstrated appropriate phase and amplitude control-circuit techniques for integration into accelerator systems as shown in Fig. 8. A sample of the generated cavity

Fig. 8. Phase and amplitude control circuit.

field is processed in the amplitude and phase control circuits, which are operable for any power level and any number of drive ports. Test results indicate circuit performance of $\pm 1^\circ$ phase control over a $\pm 15^\circ$ range with MHz control bandwidth capability and simultaneous 1% amplitude control over a $\pm 10\%$ range with over 100-kHz control bandwidth capability.

Conclusions

The SPS-40 SSTx/Los Alamos cavity tests demonstrated the feasibility of driving high-Q resonant loads with solid-state amplifiers. No problems occurred with the transmitter/cavity interface. If small-phase disturbance is desirable during the beginning of the pulse, good isolation between the amplifier and the load is necessary. The feasibility of multiple drives to a single resonant cavity was also demonstrated. Phase and amplitude control circuits with sufficient control for multiple-loop cavity drive also have been demonstrated.

Acknowledgments

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