A 3 kW 35 TO 70 MHz SOLID-STATE AMPLIFIER

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Abstract

The design and operating experience for a wide-band 3 kW cw solid-state amplifier comprising a 50 W pre-driver, a ten-way splitter, ten 300 W amplifiers and a 10-way power combiner is described. A wide-band amplifier with short transit time and fast, full-power pulse response was required as a driver amplifier for the HERA 52 MHz system. A suitable commercial amplifier could not be located; consequently, an amplifier was developed to meet the unique demands of wide-band feedback compensation of beam loading.

Introduction

A wide-band 3 kW cw solid-state rf amplifier was constructed for the HERA 52 MHz system. Loop stability demands a rf drive system with short transit time and wide frequency response. In addition to beam injection/extraction transients, a partially filled synchrotron results in transients at least every revolution period. The 3 kW driver amplifier is used as part of the HERA proton synchrotron 52 MHz rf system; hence, a fast pulse response is required to provide transient beam loading compensation [1].

Attempts to locate a suitable amplifier with a suitable combination of bandwidth and short transit time were not achieved simultaneously. Some vacuum tube amplifiers are capable of the short transit time but lack the required bandwidth. Solid-state amplifiers capable of 3 kW cw output at 50 MHz are rare. Those that were located were not designed for short transit time. Consequently, design of a fast, wide-band amplifier was undertaken.

Specifications

General specifications for the 3 kW amplifier are summarized below:

3 dB Bandwidth	35 to 70 MHz
Pulse Risetime	< 40 ns
In-band Phase Rotation	< 15°/MHz
Maximum cw Output 3 kW	
Minimum Gain, Flatness	40 dB, ±2 dB
Maximum Load VSWR	2.5:1
Maximum Input VSWR	2.5:1
Input, Output Impedance	50 Ω, 5Ω
Harmonic Distortion wrt Fundamental	
3rd Harmonic	< -20 dB
All Others	< -25 dB
DC Supply	48±2 V, 100 A
DC to rf Efficiency	≥ 65% at full power

Module Design

The Motorola MRF151G TMOS power FET was selected because its low capacitance (350 pF input, 225 pF output) permits a fast-responding, wide-band design. The MRF151G is packaged with two FETs on one flange for use within push-pull amplifiers. Each FET pair has a 300 W rating; consequently, ten 300 W units are parallel combined to produce 3 kW. Use of 10 parallel units permits graceful degradation in the event of unit failures. An eleventh amplifier - the pre-driver - was designed to produce up to 50 W. This pre-driver powers a 10-way splitter, producing the 2 W nominal inputs required by the 300 W amplifiers. A single 300 W unit is shown in Fig. 1.

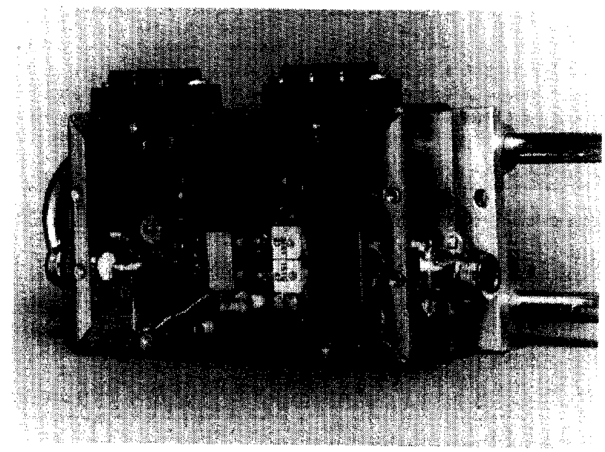

Fig. 1. A 300 W Amplifier and Heat Sink.

The 300 W module was developed from a circuit design by Granberg [2] and altered to meet the requirements of the HERA rf system. Primary design changes are as follows:

- Low-inductance, high-capacitance coupling of dc supply to FET drains is used to provide for current surges during pulsed power demand.
- Voltage stabilization and filtering are used in the input bias circuit to isolate the input from the output. This was found to be particularly useful during pulsed operation.
- Input and output matching transformers are tuned such that the desired bandwidth is achieved without the use of local feedback within the amplifier; consequently, greater gain and efficiency is obtained.

Greater passband ripple is a drawback of not using local feedback; however, such ripple is not a concern in this application, where the amplifier is one of many components comprising a feedback loop. Ripple is a concern only over the 52.02 to 52.05 MHz drive frequency range. Over a wider bandwidth, amplifier gain must be maintained so that it is possible to compensate for beam-induced transients.

Additionally, FET gain is typically only 22 dB. Hence, strong feedback within a 300 W module would require significant power dissipation. For example, 5.3% feedback would dissipate 15 W, drop the maximum output power to 285 W, and reduce the gain to 17.6 dB. In return for this loss of gain, passband voltage-gain ripple would be reduced by only about 30%.

A basic schematic of the 300 W module is given in Fig. 2. The configuration is the simplest form of a class AB push-pull amplifier. An input transformer and resistive "TEE" matches the FET impedance to 50 Ω. The transformer also converts the single-ended (unbalanced) input into a balanced drive for the two FETs. Conversely, the output transformer combines the two FET outputs into a single-ended, 50 Ω output.

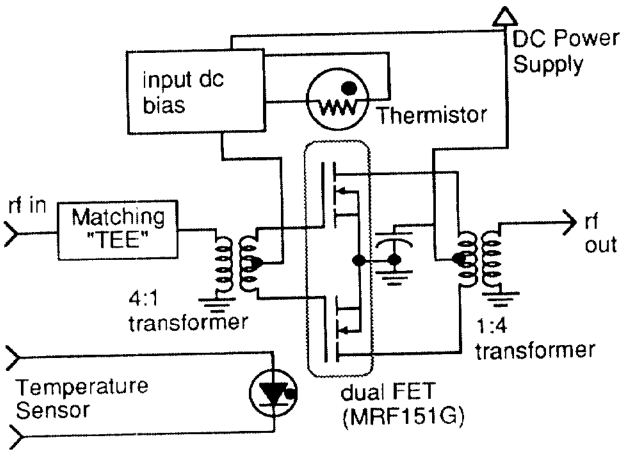

Fig. 2. 300 W Amplifier - Basic Schematic.

Power Combination

Eleven amplifier modules are used in all. Ten operate at levels up to 300 W, while one is used as a pre-driver. The pre-driver boosts the low-level input (≈100 mW) to ≈ 20 W to be split 10 ways and distributed to the power modules. The pre-driver is identical to the 300 W modules except for the resistive input matching attenuator and the bias current setting. Higher bias is used to provide greater gain and reduced harmonics for this module, which operates well below the FET ratings.

Power module outputs are combined by an 11-port "Totem Pole Structure" power combiner [3]. The combined output is fed through a 5 Ω stripline section containing both forward and reverse power directional couplers. For the HERA application, a $\lambda/4$ transmission line transformer matches the 5 Ω stripline output to the final amplifier input [4]. A schematic of the combiner is given in Fig. 3.

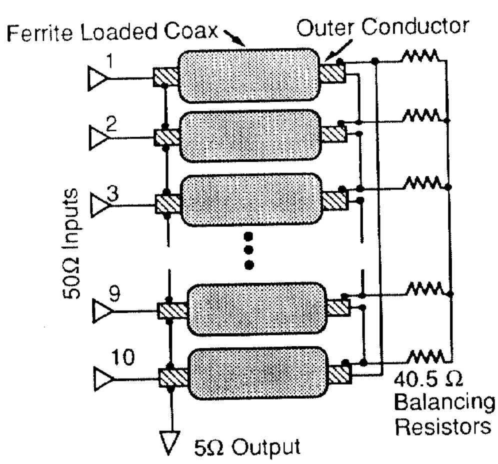

Fig. 3. Ten Input "Totem Pole" Power Combiner Schematic.

Compact, symmetric, low inductance design keeps physical line lengths short, avoids the addition of significant capacitive impedance correction, and produces good channel-to-channel isolation. Hence, combiner bandwidth and transit delay do not compromise amplifier performance. Balance resistors are water cooled, so that continuous full power operation is possible during multiple driver module failures. Physical construction is shown in the photograph of Fig. 4.

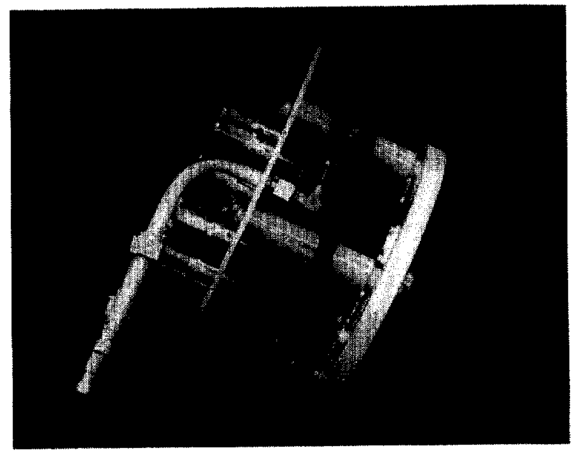

Fig. 4. Eleven-port Power Combiner with Cover Removed.

Over the 35 to 70 MHz operating bandwidth, combiner performance was measured as:

Transit time	< 750 ps
Maximum input VSWR	1 : 1.6

Transmission characteristics from one input port (with the other 9 inputs coherently driven) to the 5 Ω output are given in Fig. 5. The 50 Ω network analyzer test port reduces the 5 Ω load slightly, giving a parallel combination of 4.5 Ω. Hence, one expects the analyzer to measure 50/4.5, or 10.4 dB voltage 'gain'.

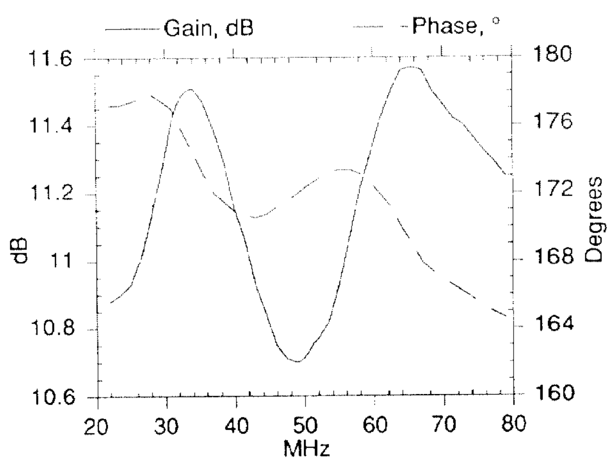

Fig. 5. Combiner Transmission Characteristics.

Protective Measures

Four protective measures are used during operation. Bias voltage is controlled by a thermistor, which is affixed to the FET flange. The thermistor reduces bias voltage with increasing temperature – preventing thermal run-away and reducing fluctuations of gain with temperature variations. Flange temperature is independently monitored by a solid-state temperature-activated "switch", called a MOXIE. Should the FET flange of any module exceed 85°C, an alarm condition is generated so that external action may be taken.

The current demands of each module are monitored. Protective action is taken in the event of excess current or significant current imbalance.

The most important protection used with the HERA system is a fast (≈ 5 μs) hardwired reverse power trip that terminates the rf input in the event that the reverse power at the combiner output exceeds a preset threshold. The 5 Ω stripline section in the combiner output permits monitoring of both forward and reverse power.

Operational Experience

Sustained full-power cw tests were carried out with the output power being dissipated in a water-cooled 5 Ω load. The ten 300 W modules were connected to the combiner by phase-matched cables (λ/4 at 52 MHz). The 5 Ω load was connected directly to the combiner output. Transmission characteristics are shown in Fig. 6. This measurement was made by placing a calibrated capacitive probe in one output line to sample the output power. Ten dB has been added to the amplitude scale so that the sum of all modules is represented.

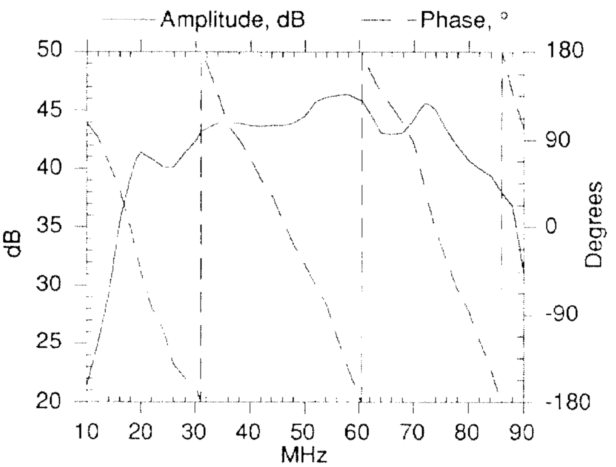

Fig. 6. Transmission Gain and Phase.

The output of each module was checked at 200 W output (each) for phase and amplitude balance. Phase variation is ±5° and amplitude variation is ±0.5 dB. Amplitude variation can be minimized at a selected operating power by adjusting module bias currents.

Typical full-power pulse response for one 300 W module is shown in Fig. 7. Note that the disparity between input and output envelopes is largely due to low-frequency feed-through of the control pulse to the rf input. This low-frequency component is blocked by the amplifier. Also notice that the input pulse exhibits a damped oscillation, which can account for a significant fraction of the output overshoot and ringing.

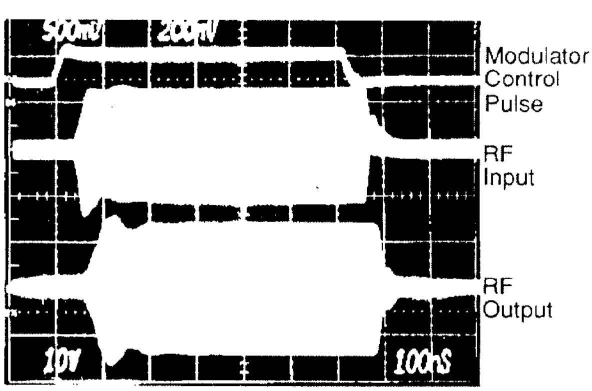

Fig. 7. Full-Power Pulse Response.

Two 3 kW amplifiers have been successfully used as driver amplifiers during the HERA 52 MHz rf system commissioning[4]. Prior to establishing the correct threshold for the fast reverse power trip, individual 300 W FETs were destroyed during high-power conditioning. Continued operation with the remaining modules demonstrated graceful degradation. Once the reverse power threshold was correctly adjusted, no further failures were experienced. Reliable operation was provided on a daily basis for about two months of commissioning and conditioning.

As part of the control system tests, the input frequency was square-wave frequency modulated with the servo-control loop closed. Frequency deviation was > 6 bandwidths of the resonant cavity load on the final amplifier; consequently, large amplitude modulation resulted in the 3 kW amplifier output (as the servo loop maintained constant cavity field). Peak output power of 4 kW for durations of 1 μs was observed during these tests.

These amplifiers are now installed at the DESY synchrotron laboratories in Hamburg, West Germany.

References

[1] L.W. Funk, et al., "52 MHz RF Systems for HERA", in Proceedings of the European Particle Accelerator Conference, Vol. 2, p. 1099, Rome, 1989.

[2] H.O. Granberg, "Building Push-Pull, Multioctave, VHF Power Amplifiers", Microwaves & RF, pp. 77 - 86, 1987 November.

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[4] M.S. de Jong, et al., "Final Testing, Installation and Commissiong of the HERA 52 MHz RF Systems", to be published in Proceedings of the European Particle Accelerator Conference, Nice, 1990.