HIGH-EFFICIENCY 500-W RF-POWER MODULES FOR UHF*

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Abstract

This RF-power module is a building block for a multi-kilowatt high-efficiency power amplifier system. The module employs five GaN-FET class-F RF power amplifiers with a low-loss Gysel splitter and combiner. Envelope Elimination and Restoration is used to maintain efficiency over a wide range of amplitudes. Efficiencies from 79 to 83 percent are obtained for power outputs from 500 to 600 W, and high efficiency is maintained over most of the range of outputs.

INTRODUCTION

Linear (particle) accelerators can use megawatts of RF power to accelerate protons or electrons, and typically operate on a 24/7 basis. Operation over a 3 to 10-dB amplitude range is needed to compensate for vibrations, heating, and other effects. Klystrons are currently the most widely used means of generating RF power for linear accelerators. Unfortunately, the peak efficiency of the klystrons is barely higher than 55 percent, and the efficiency varies with output power, much like that of a class-A amplifier. This results in significant power consumption and cooling requirements, which in turn result in significant operating costs.

The new system described here produces the required RF power with significantly higher efficiency, which is maintained over a wide range of outputs. Its key components are:

- Class-F RF power amplifiers (PAs) using GaN FETs,
- Gysel splitters and combiners, and
- Envelope Elimination and Restoration (EER, Kahn Technique).

Use of this system has the potential to lower operating costs significantly.

A significant advantage of this approach is that the RF PAs are always saturated. This allows them to achieve the maximum possible efficiency while eliminating the effects of gain variations due to heating and other factors, stability problems, and the like.

The "500-W module" shown in Figure 1 is the building block for multi-kW RF power-amplifier systems. It includes a driver, a Gysel power splitter, five RF PAs, a Gysel combiner, and an optional circulator. Prototypes have been developed for 325, 352, 650, and 704 MHz.

Class-F operation [1] is readily implemented at UHF and offers the maximum output power for given device ratings. These amplifier use 120-W GaN HEMT made by Cree or Qorvo. GaN FETs are preferred to LDMOS FETs at UHF MHz because their higher-frequency capability results in better waveform shaping, hence higher efficiency.

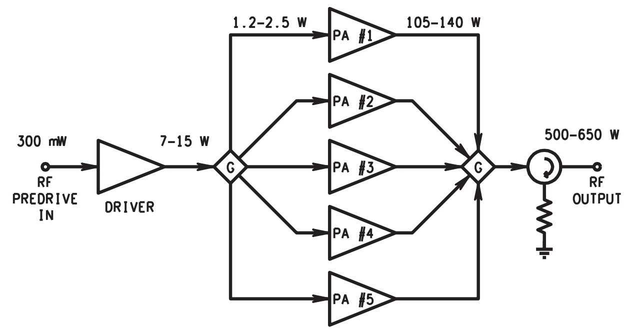

Figure 1: Block diagram.

RF POWER AMPLIFIER

A simplified circuit of the class-F power amplifier is shown in Figure 2. The output incorporates quarter-wavelength stubs for the second and third harmonics to shape the drain waveforms and thereby improve the efficiency. The GaN FET is biased near the threshold of conduction. A harmonic resonator on the input line shapes the gate-drive waveform for improved switching. The positions of the stubs are optimized experimentally, after which load pull is used to determine the fundamental-frequency matching.

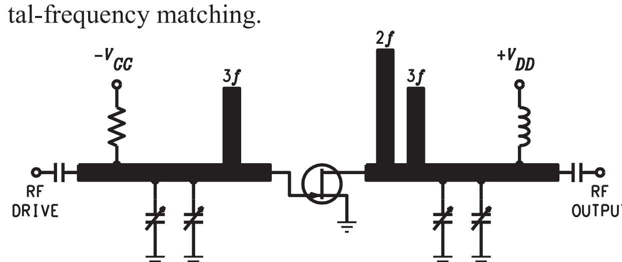

Figure 2: Class-F power amplifier.

The amplifiers are tuned to produce 120 W with maximum overall efficiency (output power divided by dc-input power plus drive power). The resultant variations of overall efficiency with output power are shown in Figure 3. The amplifiers produce 120 W with overall efficiencies from 80.5 to 87 percent. The efficiency is 70 percent or better for outputs above 7 to 12 W, depending upon the frequency. Output power is controlled by varying the supply voltage, and for these tests the drive is held constant (1.2 to 2.5 W).

Operation of the RF PAs in saturation results in excellent amplitude-modulation linearity, as shown in Figure 4. Typically, the relationship of the RF-output voltage to dc-input voltage fits a straight line within 1 percent rms. For constant drive of 1.2 to 2.5 W, the drive feedthrough is 32 to 148 mW (29 dB or more below the 120-W output). However, the addition of partial drive modulation [2] allows the level of the output to be reduced as close to

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zero as desired. Amplitude-to-phase conversion associated with variation of the supply voltage is corrected through predistortion [3].

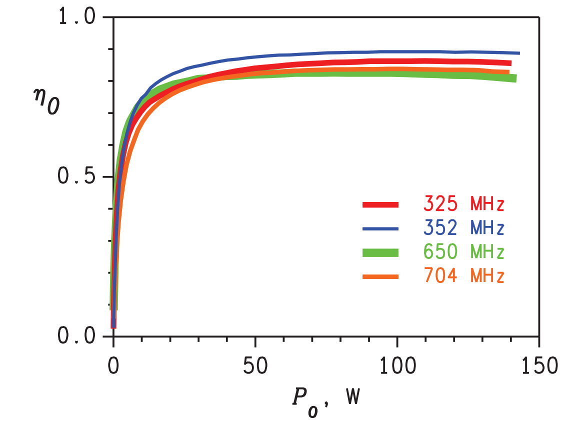

Figure 3: Efficiencies of final amplifiers.

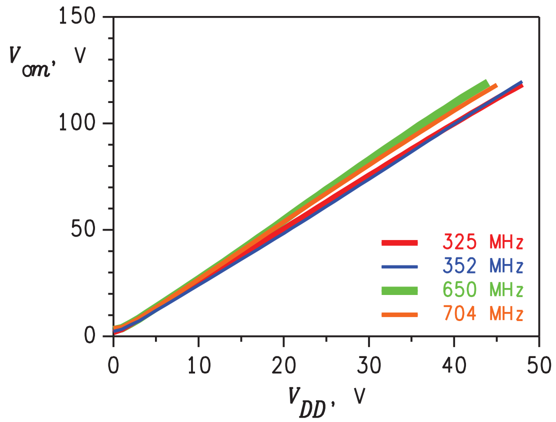

Figure 4: Amplitude linearity of final amplifiers.

After tuning, the amplifiers are matched within about 1 percent in amplitude and 1° in phase

COMBINER AND SPLITTER

The power combiner and splitter are based upon the Gysel topology [4]. The Gysel topology is a hybrid combiner similar to the better-known Wilkinson topology. However, the dump loads are unbalanced, which simplifies matching and allows them to be placed off-board. The circuit of a two-input Gysel combiner is shown in Figure 5.

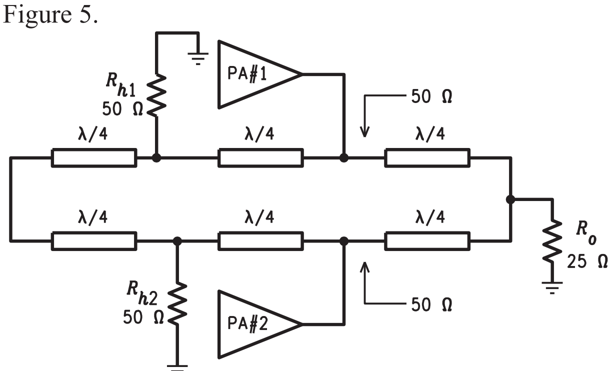

Figure 5: Two-input Gysel combiner.

The splitter uses on-board dump loads while the combiner uses remotely located dump loads. Trimmable stubs allow the frequency to be centered if necessary. Meandering is used to equalize the electrical lengths of the lines. Close matching is essential to low-loss combining. Typical performance characteristics are SWR less than 1.04, loss less than 0.15 dB, isolation 35 dB or more, phase difference 1.4° or less, and amplitude difference 0.3 dB or less.

SYSTEM PERFORMANCE

The "brassboard" five-amplifier module [5] is assembled by mounting the splitter, amplifiers, combiner, and dump loads on an aluminum sheet (Figure 6) . Commercial off-the-shelf 080 and 141 cables are used to connect the splitter to the PAs and PAs to the combiner, respectively. The driver amplifier is a lower-power version of the final amplifier and sits to the left of the five-amplifier assembly. The predrive input is about 300 mW.

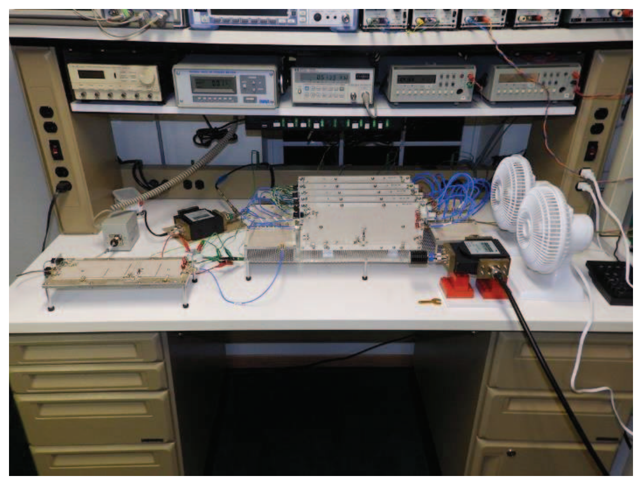

Figure 6: Five-amplifier module.

The performance of the module is shown in Figure 7 and summarized in Table 1. At full output, the drive level varies from about 8 to 14 W, depending upon frequency. At lower outputs, the drive level is chosen to produce the maximum overall efficiency.

The amplitude-modulation linearity (top) is nearly a straight line with about 1 percent rms error. For outputs of 500-600 W, efficiencies of 79 to 83 percent are obtained without the circulator. When the circulator is included, the efficiencies drop to 77 to 81 percent. The efficiency is relatively constant over a wide range of outputs, thus minimizing power consumption at all output amplitudes.

If one PA fails, the other four continue operating as if nothing had happened. The power output and efficiency drop, of course, as a portion of the power generated is then dissipated in the dump loads. The high isolation of the power combiner allows the failed PA to be swapped while the others continue to operate.

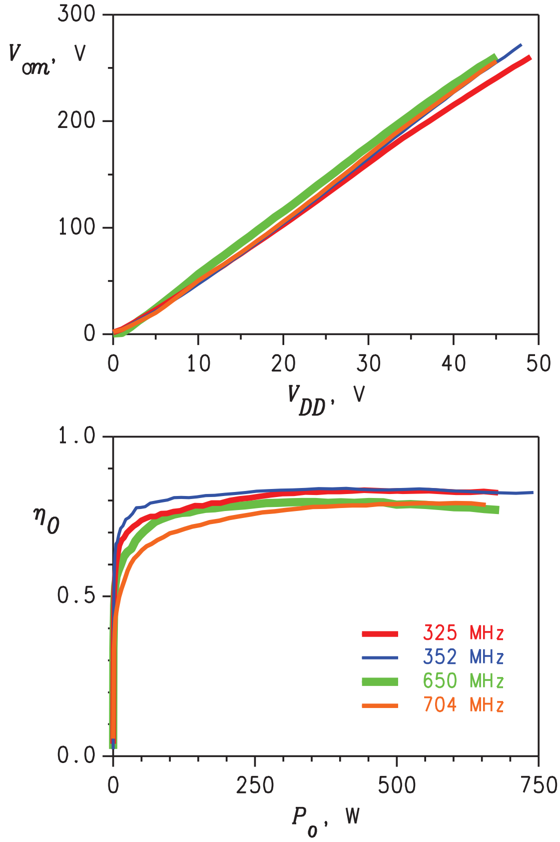

Figure 7: Performance of five-amplifier modules.

CONCLUSIONS

These prototypes demonstrate that high-power, high-efficiency amplifier systems can be implemented by careful combination of high-efficiency amplifiers and low-loss combiners. The prototype five-amplifier modules are almost as efficient as the individual PAs. In contrast to a conventional (class-A or -B) PA, efficiency is maintained over a wide range of amplitudes through supply modulation (EER).

Table 1: Summary of Performance.

f, MHz	NO CIRCULATOR		CIRCULATOR	
	500 W	600 W	500 W	600 W
325	83.0	82.6	81.3	80.3
352	83.4	83.0	82.0	81.7
650	77.4	77.9	77.4	76.0
704	78.9	79.2	76.8	76.5

REFERENCES

[1] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popovic, N. Pothecary, J. F. Sevic, and N. O. Sokal, "Power amplifiers and transmitters for RF and microwave," *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 814-826, March 2002.

[2] F. H. Raab, "Drive modulation in Kahn-technique transmitters," in *Int. Microwave Symp. Digest*, Anaheim, CA, June 14 - 17, 1999, vol. 2, pp. 811-814. (US Patent 6,256,482).

[3] F. H. Raab and M. C. Poppe III, "Kahn-technique transmitter for L-band communication/radar," in *Digest, 2010 IEEE Radio & Wireless Symp*. (RWW 2010), New Orleans, LA, Jan. 10 - 14, 2010, paper MO3A-1, pp. 100-103.

[4] U. H. Gysel, "A new N-way power divider/combiner suitable for high-power applications," in *Int. Microwave Symp. Digest*, Palo Alto, CA, May 12-14, 1975, pp. 116-118.

[5] F. H. Raab, ""650-W high-efficiency amplifier for 704 MHz," in *IEEE MTT-S Int. Microwave Symp. Digest*, San Francisco, CA, May 22-27, 2016, paper WE4E-1.