GaN CLASS-F POWER AMPLIFIER FOR KLYSTRON REPLACEMENT*

A. V. Smirnov#, R. Agustsson, S. Boucher, D. Gavryushkin, J.J. Hartzell, K.J. Hoyt, A. Murokh, T.J. Villabona, RadiaBeam Systems Inc., Santa Monica, CA 90404, USA

Abstract

The vacuum-tube-based RF amplifiers are relatively inefficient and becoming obsolete as the RF world has been progressively converting to solid state technology. Currently, the JLAB upgrade program requires 340 amplifiers capable of 8 kW CW at 1497 MHz while operating at more than 55-60% efficiency to replace their klystrons. Here we explore the possibility of a klystron replacement employing high electron mobility packaged GaN transistors applied in an array of Class-F amplifiers. The inputs and outputs of the many modules needed to make a complete amplifier are connected via precise, in-phase, low-loss, broadband, combiners-dividers. We describe early prototypes of the amplifiers as well as the combiners-dividers and discuss the design features and challenges of such a scheme. This approach can be applied to other national facilities and also for replacement of the klystrons in Middle Energy Electron-Ion Collider which requires about 1.8 MW CW power in total to be produced at 952.6 MHz frequency including 2x12.5 kW power for "crabbing" and 0.53 MW for electron cooling.

INTRODUCTION

Despite the ubiquitous use of high-power vacuum tubes in radars, accelerators, and material processing industries, there are a number of disadvantages compared to solid-state power amplifiers (SSPAs): high voltage (HV) power supplies required for vacuum tubes increase the size, complexity, and weight of these systems, the HV network is subject to arcing which limits reliability and safety while increasing cost and footprint, the HV system is sensitive to environmental conditions (humidity, temperature, dust, corrosion), and importantly, the shrinking market for tubes imposes growing production costs and higher long-term risks.

The original RF power system at the Thomas Jefferson National Accelerator Facility (JLab) operates at 1497 MHz frequency and consists of 340 klystrons (model VKL7811). The VKL7811 klystron upgrade proposed by CPI foresees adding a solenoid magnet and its power supply, making the system so large that it will not fit in existing locations. Inductive Output Tubes (IOT) were considered as a replacement [1]. However, IOTs are not available at 1.5 GHz, would need to be redesigned to avoid solenoid coils, and require a booster (preamp driver) as they have ~15 dB lower gain than a klystron.

As an alternative to klystrons and other vacuum tubes, RadiaBeam is developing high-power amplifiers based on gallium nitride (GaN) high electron mobility field effect transistors (HEM FET) which offer significantly higher efficiency than vacuum tube devices. Although each individual device operates at much lower power, its compact size enables many of them to be operated in parallel to achieve the power needed to replace klystrons. However, most of known high power transistors are traditionally employed in a pulse mode and usually for radar applications. For example, drain efficiency of the CGHV14500 high electron mobility transistor (HEMT) from CREE, operating in L-band at up to 500 W of pulse power, is 67-72% [2, 3]. This does not mean that CW operation is not possible. As a matter of fact, the CGHV14250F transistors have demonstrated stable operation in continuous wave (CW) mode, producing 200W power at 1.5 GHz frequency, 65°C case temperature, 63% drain efficiency, and 40 dB gain [3]. In this paper we describe our efforts to design and build a complete klystron replacement based on such a transistor, including the requisite many-way combiner/dividers needed.

AMPLIFIER MODULE DESIGN

After exploring the commercially available GaN transistors available at this frequency, we decided to experimentally investigate two models, both produced by CREE, namely the CGHV14250 [4] and CGHV14500 [4,5,6]. According to preliminary analysis when considering the total amount of wasted power and the heat load for class B-C operation, the CGHV14250 transistor seems more attractive than CGHV14500. Table 1 compares the expected results for two cases: a) assuming no improvement is achieved over Cree's demonstration amplifiers (pessimistic scenario); and b) assuming a 14% improvement is achieved over Cree's design (optimistic but reasonable realistic scenario) using our class-F scheme.

Table 1: Performance Estimations

Scenario	Units for 8 kW output	Total power draw
CGHV14500 46% efficient	30	17.6 kW
CGHV14500 60% efficient	30	13.5 kW
CGHV14250 46% efficient	39	13.0 kW
CGHV14250 46% efficient	39	10.6 kW

Although increasing the engineering complexity of a device employing 39 parallel amplifying modules, the increased overall efficiency of the CGHV14250 led us to use that transistor in our system design.

asmirnov@radiabeam.com

Analytical and numerical analysis of E-Class and mixed E-F Class design approaches indicated that though they are relatively simple, there is a fundamental problem related to their inherently high ratios of peak voltage and drain bias voltage (so called voltage swing). Calculations show that the voltage swing approaches ~3.8 for E-Class and minimum 3.08 for E-F Class. For both CGHV14250 and CGHV14500 transistors the maximum rated drain voltage is 125 V and breakdown voltage is 150V. That means that for given limitations of breakdown voltages the CREE GaN transistors would be significantly limited in maximum power unless we pursued a pure class-F design. Preliminary analysis shows that Class F amplifier may provide <2.5 V voltage swing at substantial efficiency. Therefore we made a decision: to focus on designing of F-Class amplifier, and especially using CGHV14250F transistor.

Having decided on a transistor and architecture, we began designing the RF circuit by simulating a class-F amplifier with a three-stage, low-pass, output matching network (OMN) for L-band (Figure 1). To do this we have made an Agreement with CREE and gained access to other CREE non-linear models of equivalent circuits related to their high power L-band transistors and used Agilent Design Software.

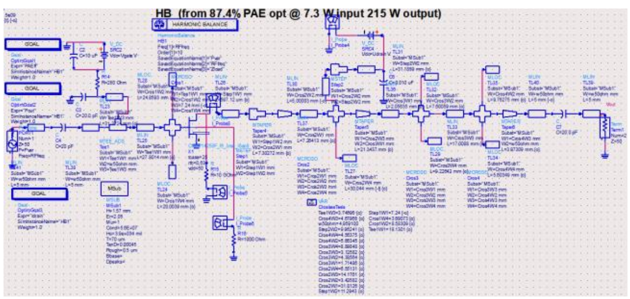

Figure 1: RF circuit developed and optimized for the CGHV14250F transistor with HB ADS module for one of PCB variants having 70 µm thick lamination and 1.57mm thick CuFlon substrate.

The next step was to select the PCB substrate type, lamination, and thickness. This selection process is a complicated trade-off between critical current density in the lamination, sufficiently high Q-factor for stubs (low loss tangent), fabrication cost, suitability for transistor mounting, availability of different thicknesses, simplicity of connector matching, and small enough final size.

The optimization goal is maximizing efficiency while providing close maximum rated power at 1497 MHz and being well below breakdown voltage and maximum drain current of the transistor. After the optimization is completed the OMN was realized with transmission lines (stubs). That resulted to the layout given in Figure 2 for that variant of 3.18 mm CuFlon thickness having 70 µm lamination.

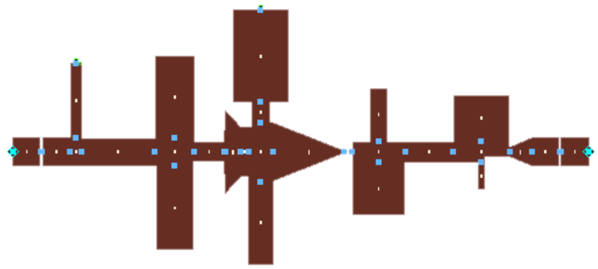

Figure 2: RF circuit developed and optimized for the CGHV14250F transistor (shown in yellow) with HB ADS module for one of initial PCB variants having 70 µm thick lamination and 3.18mm thick CuFlon substrate.

We recently completed the design process and had the PCB produced by a third party vendor. We are now integrating it into a complete test bench with a pre-amplifier and water cooling. Very preliminary results indicate an instability at 3 MHz that will require additional work on the PCB design. However, power and efficiency measurements in pulsed mode before the instability dominates are in agreement with simulations.

MULTI-WAY COMBINER DESIGN

The parallel-module approach to developing a klystron replacement requires a way to divide a low-level RF signal into many input feeds for each module, and then another high-power combiner to re-join each of the now amplified feeds. In order to prevent loss of power and unwanted reflections, the relative phase from each peripheral port to the center port must be constant. Additionally, the surface electric field through the combiner/dividers must be kept below the threshold where the dielectric gas (ideally air) will breakdown. A key way in which high power breakdown is mitigated in our design is that unlike conventional radial combiners [7], the combiner we designed does not contain low-impedance “bottlenecks” and so do not have small coaxial gaps with high local electric fields (overvoltage.

Using HFSS, we designed a 21-way combiner divider with SMA port on the periphery and a type-N central port (Figure 3). Although these connectors and the dimensions of the combiner are limited to a few hundred watts, the prototype device proved out the EM design, and allowed us to explore the manufacturing techniques required to build these devices.

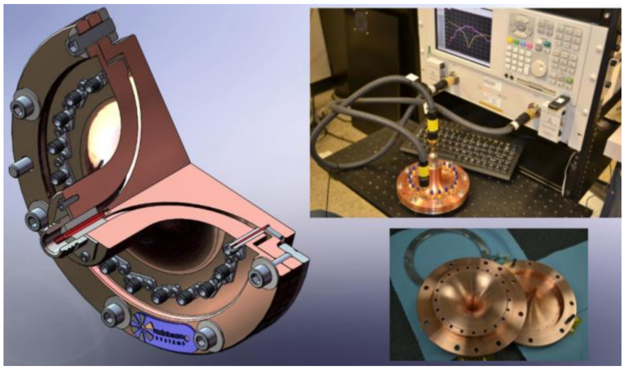

Figure 3: [LEFT] combiner/divider CAD model, [RIGHT] testing the prototype device and the prototype disassembled.

Measurements of the prototype (Figure 4) showed excellent agreement with the simulated performance, especially considering that the two halves were clamped rather than brazed. We have subsequently designed a larger, high-power version that employs type-N connectors on the peripheral ports and an EIA 1-5/8 connector on the central port that can handle the kilowatts of power required for the full system.

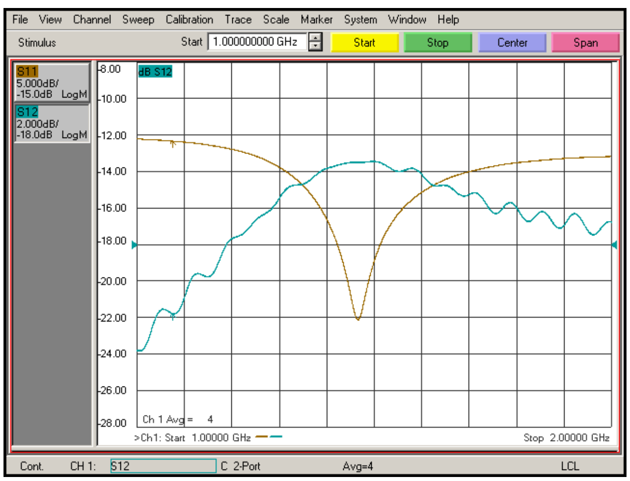

Figure 4: Testing results of the prototype device. The coupling is best at 1.47 GHz (minimum S11, yellow) and at that frequency, S12 is -13.54 dB which is very close to the simulated value of -13.222 dB.

SYSTEM DESIGN

The final system requires a minimum of 39 modules, a pre-amplifier to coherently drive each of the modules, the requisite divider and combiner, water cooling manifolds, DC power distribution, and module controllers (Figure 5). The module controllers require significant effort to design so that they can provide temperature compensation, enable flexible, independent, and smooth turning of the amplifying units on and off, as well as optimum biasing for maximum efficiency in a wide dynamic range of input and output power levels. In addition, accurate biasing of the transistors can compensate the natural power spread from one amplifying unit to another to improve coherency of power summation in the output combiner.

The mechanical design of the full system is also significantly more complicated, as there are many power, control, water, and signal feeds to be accounted for. The whole device must then be packaged in a durable, convenient cabinet with the same footprint as the klystrons they are being designed to replace.

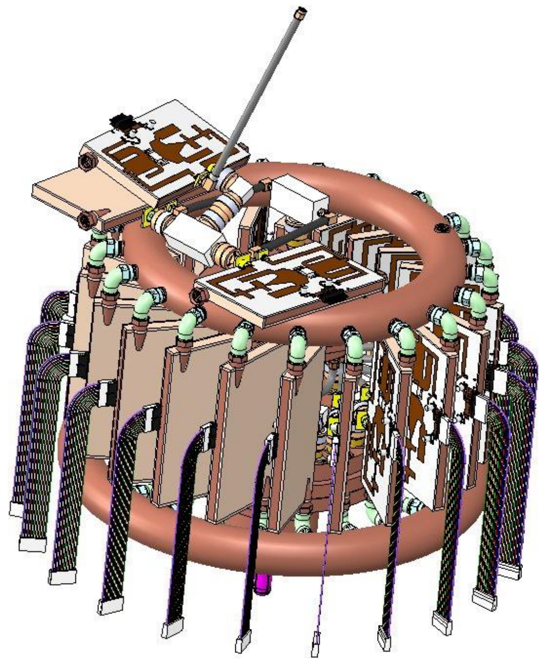

Figure 5: CAD rendering of high power unit with combiner, divider, preamp, and control and DC power leads.

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