UPDATE ON CW 8 kW 1.5 GHz KLYSTRON REPLACEMENT*

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Abstract

JLAB upgrade program requires a ~8 kW, 1497 MHz amplifier operating at more than 55-60% efficiency, and 8 kW CW power to replace up to 340 klystrons. One of possibilities for the klystron replacement is usage of high electron mobility packaged GaN transistors applied in array of highly efficient amplifiers using precise in-phase, low-loss combiners-dividers. Design features and challenges related to amplifier modules and radial multi-way dividers/combiners are discussed including HFSS simulations and measurements.

INTRODUCTION

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 (IOTs) 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.

High-power vacuum tubes are employed ubiquitously in radars, accelerators, and material processing industries. Although the technology is well defined and established for many decades, there are also a number of disadvantages. Among those that impose certain risks for JLab future operations are relatively low efficiency (presently 33% [1]) and shrinking market for the tube that implies growing production and refurbishing costs.

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 significant potential to higher efficiencies than vacuum tube devices. Although each individual device operates at much lower power, its compact size potentially enables many of them to be operated in parallel to achieve the power needed to replace klystrons.

However, such a replacement presents a number of challenges. Most of known high power S-band or L-band transistors are traditionally designed for a pulse mode (usually for radar applications), whereas combined CW operation to our knowledge has never been demonstrated in L-band at such high, multi-kW power levels. Drain efficiency is significantly lower than that for pulsed operation, because of various charge trapping and self-heating effects enhanced by much higher internal FET thermal resistance in CW mode of operation. Also combining efficiency tends to drop quickly with number of combining ways (faster than linear [2]). Yet another challenge is that GaN high power transistors are vulnerable to instabilities especially in CW and presence of crass-talk (insufficient isolation) between the combining ways. Depletion mode devices cannot be operated without specialized control system enabling proper bias sequencing through discretionary access control (DAC), thermal compensation, and independent fine adjustment of bias voltages and temperature slope. Additional requirements for the control system include stable (tolerable to supply voltage variations) driving of large capacitive loads and impedances in a wide dynamic range. Note, kW-range solid-state amplifier systems are industrially available in S- or L- bands. However, specific (volumetric) power density for these state-of-the-art systems is about one order lower than that for klystrons, whereas efficiency is moderate (~52% in L-band [3]). Higher density of packaging is limited by cooling, need in high, low-impedance capacitances to be connected to the amplifier modules, bulky combiner-dividers (especially in L-band), and need in eased access to the replaceable modules.

UPDATE ON ACTIVE MODULES

Here we take a broader look on L-band CW performance for transistors from different vendors. In Table 1 we summarized most of important datasheet characteristics HEM GaN MOSFETs that have been considered for the active modules. In US the transistors are currently presented by four US vendors: WolfSpeed, Qorvo, MA-COM, and NPT Semiconductors. The data related specifically to CW operation are underlined in Table 1. The data are extracted from datasheets for 1.5 GHz frequency, with exception of QPD1823 data given for ~1.8 GHz frequency. Note unlike CGHV14250 and CHV14500 FETs, the CGHV14800 transistor duty factor is limited by 10% or less. Therefore it is not applicable to CW operation.

We performed CW measurements of conventional Class AB test boards supplied with intense water cooling. Some of the results are given in Table 2 for four different transistors. The performance is a somewhat lower than that voltage) probably because we used a lowered drain voltage. Nevertheless one can see CGHV14500 FET maximum CW power and efficiency are below than that we obtained for CGHV14250 test setup in CW at ~1.5 GHz frequency. Also we faced issues related to gain

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reproducibility (14 dB gain has been measured in initial tests for the same output power).

Table 1: Datasheet-Based Comparison of High Power L-Band Transistors Under (or pre-) Production in US

Model	Pout, W	Thermal resistance, C°/W	Drain efficiency, %	Gain, dB
CGHV14250	200 210	0.56 0.95	64 63	17 17
CGHV14500	370 275	0.28 0.47	58 47	16 15
CGHV14800	709 N/A	0.44 N/A	53 N/A	15 N/A
NPT2024	237 209	N/A 0.75	63 62	18 17
QPD1823 At 1.8 GHz	227 >50	N/A 1.3	77.5 37	21 N/A
MMRF5021H	N/A 250	N/A	N/A 58	N/A 16
MMRF5014H	125 125	0.21 0.86	67 45	18 14.5

Table 2: CW Measurements at 1.5 GHz Frequency for Various Test Boards Tuned at (44.4-44.8) V Drain Voltages (if not Specified Otherwise)

MOSFET setup	Pout, W	PAE, %	Drain efficiency, %	Gain, dB
CGHV14500	100 132	43 47	45 49	10.2 9.6
CGHV14250	117 158	58 50	60 53	11.7 9
QPD1823 at 1880 MHz	126 170	57 63	58 64	19.8 16.3
NPT2024 at 50 V drain	200 218	58.4 60.7	60 63	15.7 14

As it can be seen from Table 2 the maximum CW power among these test boards is achieved for the new NPT2024 transistor from MACOM at substantial gain. Using the low gain CGHV14250 (or CGHV14500) transistors would require more than 21 way for each of the two divider-combiners and more powerful preamplifier (if not integrated into the module), whereas with NPT2024 we can still rely on the 2×21 way architecture. QPD1823 may have potential for Class F 1.5 GHz provided efficient matching network can be developed.

The NPT2024 test board has been designed and subsequently "tweaked". That required dozens of matching trips to carefully optimize input and output circuitry to maximize gain, efficiency, and power (at 1 dB compression) at the 1.5 GHz frequency. Simultaneously the board has also been made rather compact as it can be seen in Figure 1.

Measurement results for the NPT2024 test board are given in Figure 2 for gain and drain efficiency plotted as a function of output CW power at 1500 MHz. Return loss and gain measured with network analyser are given in Figure 3. One can see the design is optimized close enough to the target 1497 MHz frequency. There is still a room remaining for further reduction of return loss (likely at the expense of the board length).

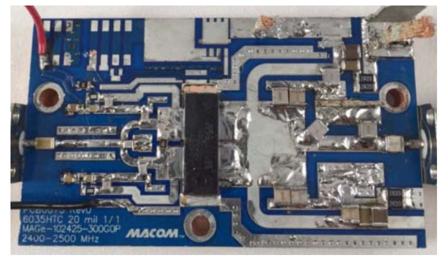

Figure 1: 200W, 1.5"×2.6", NPT2024 MACOM test board designed and optimized for 1.5 GHz frequency.

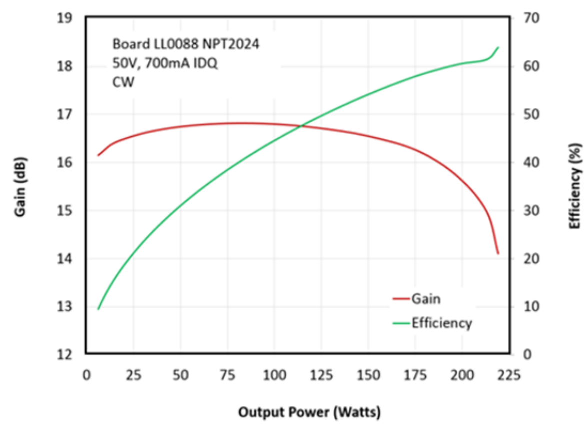

Figure 2: NPT2024 test board measurement results for gain [dB] and efficiency [%] as a function of output power [W] at 1.5 GHz in CW mode.

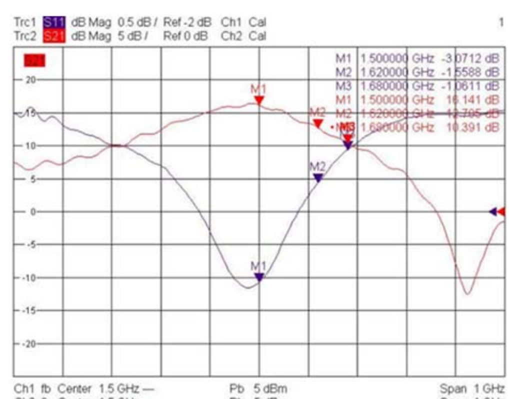

Figure 3: Network analyser plots for return loss and gain taken for NPT2024 test board at 50 V drain voltage and 700 mA current.

Thus test board measurements show feasibility of compact power module required for the 8 kW VKL7811 klystron replacement for 1.5 GHz frequency. To enable that replacement a compact and efficient, multi-way, dividing-combining circuitry with high isolation is required.

UPDATE ON MULTI-WAY DIVIDER AND COMBINER

Previously we reported a 21-way L-band divider [4]. Here we present more detailed cold measurement results for the clamped divider construction (not brazed). Careful inspection of the divider parts indicated surface imperfections (a few mills "bumps") in the vicinity of some crews holding the central conductor of the SMA jacks. In Figure 4 we show some correlation between height of the bumps and imbalance of S21 transmission between central and peripheral ports. Obviously there is a room to reduce the imbalance by removing the bumps (or changing the mechanical design of the pin holders). Nevertheless in Figure 5 one can see sufficiently high isolation between adjacent peripheral ports exceeding 23.5 dB.

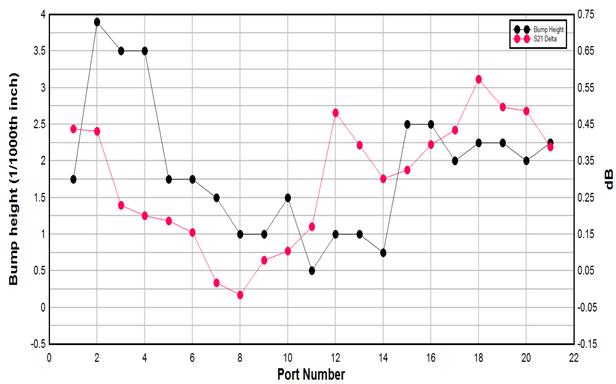

Figure 4: Absolute maximum bump height [mils] (black line) and ΔS21 transmission deviation [dB] (red) from ideal 23.5 dB between peripheral and central ports vs. peripheral port number at 1497 MHz.

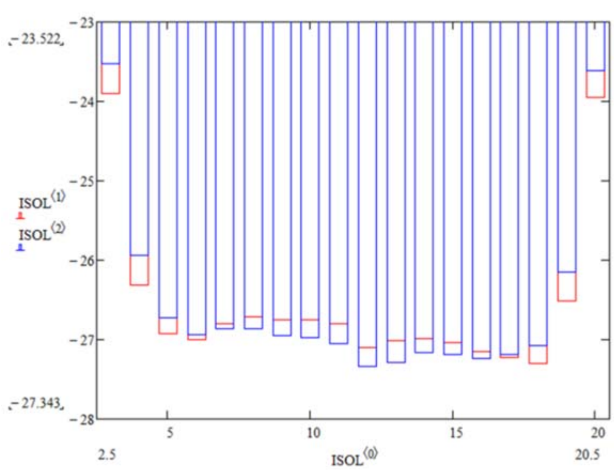

Figure 5: Peripheral inter-port isolation [dB] at 1497 MHz (blue) and for 1466 MHz (red). Central part is terminated.

A high-power 21-way combiner employs type-N connectors on the peripheral ports and an EIA 1-5/8 connector on the central port. To minimize combiner dimensions and handle reliably more than 5 kilowatts (per each combiner) we applied transformer oil filling of the transmission gap. The insertion loss simulated with HFSS at 1.497 GHz is less than 0.1 dB (see Figure 6). The combiner length is about 100 mm at 170 mm diameter.

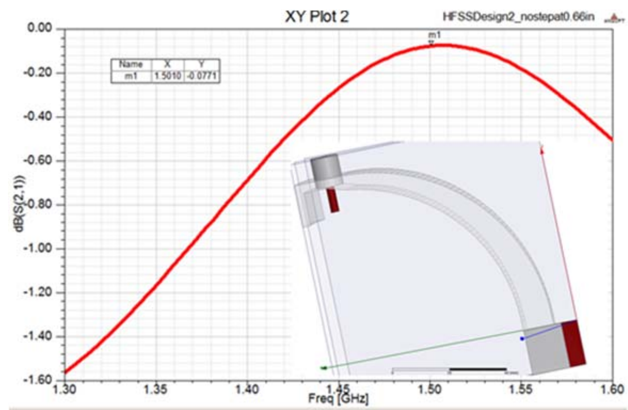

Figure 6: Insertion loss [dB] plotted vs. frequency [GHz] for one sector (inset) of optimized, 21-way, N-to-EIA-1-5/8" combiner with transformer oil filling (instead if normal air in the divider) the arc-like coaxial gap. The oil permittivity assumed is ε=4.5 and loss tangent tanσ=33 ppm.

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