A UHF 1-kW Solid-State Power Amplifier for Spaceborne SAR

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***Abstract* — A 2-stage 40 dB gain 1 kilowatt transmitter pallet for remote sensing synthetic aperture radar (SAR) applications in P-band from 420 to 450 MHz is presented. The unique feature of this paper is the use of GaN transistors operating from a 75 V drain bias. All commercially-available GaN transistors operate from 60 V or less drain supply, but using 75 V increases the load impedance at the fundamental and reduces the output capacitance which enables the optimum impedance to be presented to the FET at the harmonics even at kW power levels. As a consequence, we report 75% minimum power-added efficiency from a two-stage amplifier across the entire 420 - 450 MHz bandwidth under 100 µs with 10% duty cycle. This is 15% higher efficiency than is typically achieved with traditional TWT implementations.**

***Index Terms* — Amplifier, high efficiency, high gain, GaN, UHF, space, radar, remote sensing.**

I. Introduction

The North America Space Administration (NASA) and the European Space Agency (ESA) have programs with the objective of making scientific measurements of the earth biomass to understand the global carbon cycle [1, 2]. Power amplifiers for space applications typically employ travelling wave tube (TWT) active devices thanks to their immunity to radiation and efficiency in the 60% range. However, TWT's operate in the kilo-volt range and require a heavy and bulky power supply; therefore there is a desire of migrating to solid-state active devices. A NASA solid-state airborne SAR system for science and technology research operating in L-band is described in [3]. A derivative of this SAR system for biomass research in the lower UHF frequency range is described in [4]. A low earth orbit (LEO) satellite system enables longer term data gathering and more valuable scientific information for phenomena occurring over several month or year cycles. With space-operated instrumentation it is mandatory matching high output power with high efficiency to keep power supply requirements and weight manageable. State-of-the-art solid-state amplifier technology is gallium nitride (GaN) high electron mobility transistors (HEMT). In reference [5] a recent approach using a PWM-based transmitter for P-band is presented, achieving over 70% at 40 W output power. A more advanced GaN based system funded by ESA is well documented in refs. [6] and [7]. This design uses a large antenna (>10m diameter) to make surface measurements of the earth biomass so that the output transmit power only need to be in the 150 W range. The 150 W GaN amplifier module has 50 dB gain and 65% PAE. It is built on a 20-mil thick printed circuit board (PCB) to meet multipaction requirements. If subsurface imaging information is desired, loss through the surface is high and more power is needed. Long wavelengths are preferred for this specific application as they can penetrate into the ground [8]. Antenna size is also an important issue as large antennas are more difficult to accommodate on interplanetary missions. Therefore, the approach presented here relies on a smaller antenna coupled with a higher power transmitter, which is suitable for either subsurface imaging of earth-science or space-science missions. The main focus of the work presented in this paper is to demonstrate a 1 kW GaN-based high power amplifier pallet for ground-penetrating applications in P-band.

II. 1-kW Pallet Amplifier Design

The requirement for a 1 kW output power is achieved by paralleling two 500 W high gain GaN devices. Fig. 1 shows the proposed amplifier block diagram with two 500 W devices in the output and a 20 W driver device. Typical operation of SAR systems in this band use 88 µs pulse width and 6.7% duty cycle in a band from 432 MHz to 438 MHz, as reported in [7] for the ESA BIOMASS program.

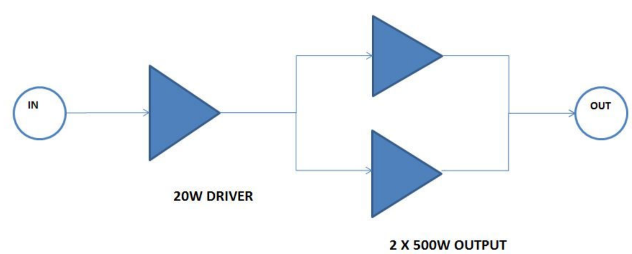

Figure 1: Planned 1 kW Amplifier Module Block Diagram

Since our 1 kW design is not assigned to a specific mission yet, for development purposes and more flexibility we have used a signal of 100 µs pulse width and 10% duty cycle and the frequency band is from 420 to 450 MHz. The 500 W device consists of two GaN HEMT power bars of 250 W each, operating at 75 V bias as described in [9], developed by Integra Technologies, Inc. [10]. This device achieves 500 W output power with greater than 80% drain efficiency across the 420 MHz to 450 MHz bandwidth. The assembly of two power bars inside the package is shown in Fig. 2. The ceramic package has a flange made of copper-molybdenum alloy with thermal conductivity of 220 W/m-°K and 40-mil thickness. The device uses an input LC resonance to increase the input impedance of the die and the drain is bonded directly to the output transistor lead. This direct bonding allows for fundamental and harmonic tuning outside the transistor package. Thick film series input resistors are used to enhance stability given the very high gain of the device when operated at 75 V.

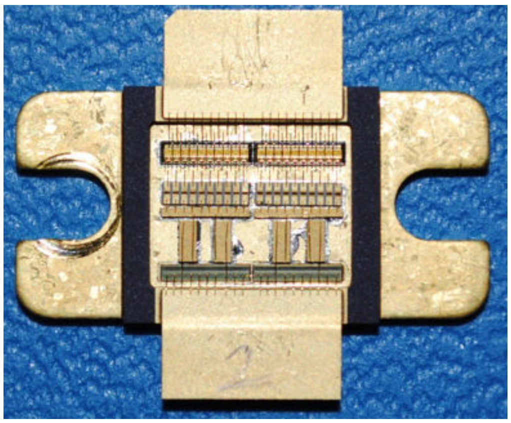

Figure 2 - Assembly of two GaN chips positioned next to the output package lead (top side of figure).

The schematic diagram for the 500 W device is shown in Fig. 3. On the output, the test circuit uses a drain bias line section adjusted in length to affect the impedances at the harmonics. The fundamental frequency is matched with shunt capacitors placed along a 50 Ω line at appropriate distances from the device to optimize the fundamental frequency load. On the input section, the fundamental frequency is also matched with shunt capacitors placed along a 50 Ω line at appropriate distances from the device.

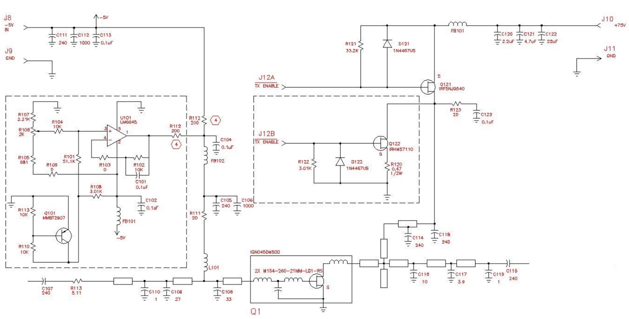

Figure 3: Schematic of the 500W device with matching network.

The fundamental and harmonic load impedances are tuned to achieve high efficiency. The load impedance of the 500 W device was measured at the reference plane and de-embedded to the current generator (CG) reference plane as shown in Fig. 4. Cds is 21 pf and the output series inductance is 0.05 nH. The de-embedding also included a transmission line model for the device package ring frame. Table 1 reports the impedances for the 500 W device at the fundamental, 2nd and 3rd harmonics de-embedded at the current-generator reference plane, and compares the normalized impedance with the theoretical values that define class E, F and inverse F mode of operation as outlined in refs. [11-12]. Measured data indicate that the 500 W amplifier operates in a hybrid mode, combination of class E and inverse F. More RF data for the 500 W output device were reported in ref. [13, pages 5-6].

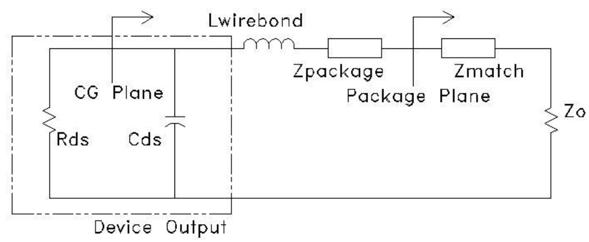

Figure 4 – Model of Device Output and Current Generator Load Impedance

Table 1: Normalized Load Impedances for Class E, F and inverse F compared to measured data.

Freq	Class E	F	F^{-1}	Norm. Z	Meas. Z [Ω]
f_0	1 + j0.725	1	1	1+ j0.215	8.71+ j1.87
$2f_0$	- j1.785	0	∞	0.051 - j1.166	0.44 - j10.16
$3f_0$	- j1.19	∞	0	0.006 - j0.57	0.05 - j4.95

Next the 2x 500 W module with a 20 W driver is analyzed. The amplifier module also includes a mute circuit to shut down the transmitter when the radar is in receiving mode, adapted from ref. [14]. 3-dB hybrid couplers are used at the input and output of the two 500 W devices. Output matching networks are the same as for each individual 500 W device. The input and output matching networks for the 20 W driver were similarly optimized. Its assembly uses PCB material RO4350B, 0.020” thick for Multipaction mitigation, with 1/1 oz. copper. Carrier material is 6061-T6 Aluminum, 0.25” thick, with plated 80~150μ" electro-less Ni, copper cyanide flash and electrolytic Ag 100~200μ". PCB finish is ENIG, Ni 80~150μ", Au 3~5μ". Solder mask is applied over bare copper per IPC-SM-840. The module weighs only 280 gr. and its volume is only 17 cm x 9 cm x 3.1 cm. Fig. 5 shows the assembled 1 kW pallet prototype.

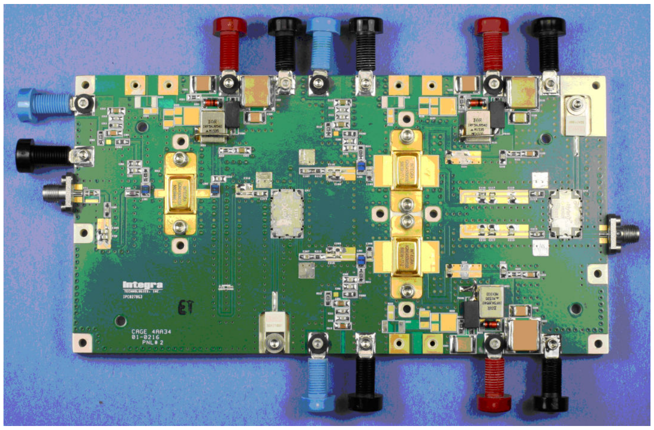

Figure 5: Picture of the assembled 1 kW Pallet Amplifier.

III. AMPLIFIER RF PERFORMANCE

The full amplifier performance was measured at 25° C base plate temperature. Data at saturated power are shown in Figs. 6 and 7. The low droop indicates the junction temperature of the GaN devices is not affecting the pulse shape. Gain is >42 dB with a 1 dB variation across the band and drain efficiency is 76% at saturated power.

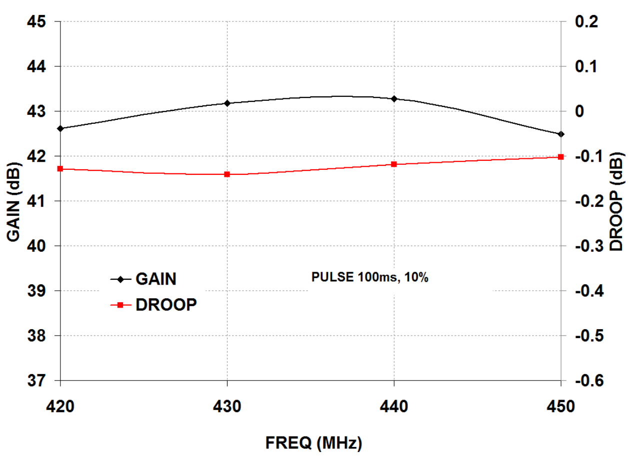

Figure 6: Gain and pulse amplitude droop at saturated power for the 1 kW amplifier. Pulse width is 100µs and duty cycle is 10%.

Transient thermal measurement of the 500 W device under a worst case 1 ms pulse width and 10% duty cycle has shown a peak junction temperature of 155° C during the transient when the case temperature is 80° C thus verifying safe operation. The measured transient junction temperature profile is shown in Fig. 8. To fully assess stability, K and B1 factors were derived from measured s-parameter data. If K > 1 and B1 > 0 the amplifier will be unconditionally stable for all source and load impedances [15]. The design of gate and drain bias lines of the output devices is critical for stability. In the gate bias line a 20 Ω resistor is in series with the 39 nH RF choke. Additionally, a ferrite bead inductor of 67 Ω impedance at 25 MHz is used in the drain bias line next to the decoupling capacitors. A series 3.3 Ω resistor was added to the gate matching networks resulting in improved stability.

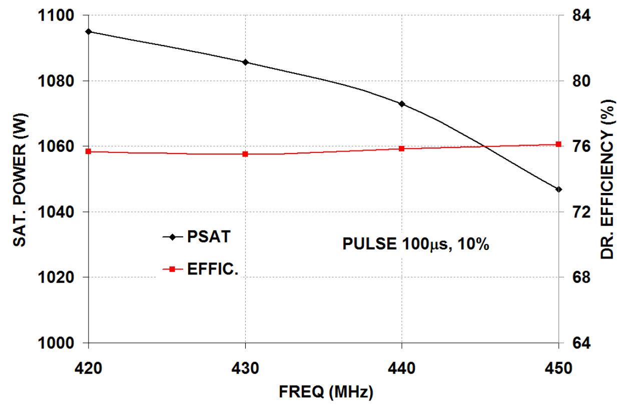

Figure 7: Saturated power and drain efficiency versus frequency.

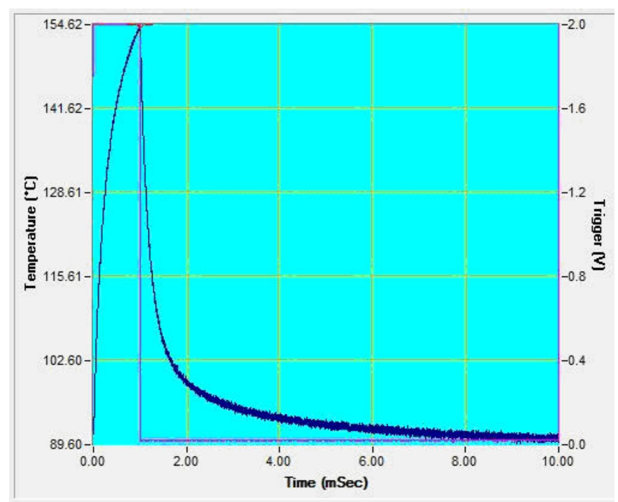

Figure 8: Measured transient temperature during the pulse on-state of the 500 W device with the case temperature at 80 °C. Pulse has 1 ms width and 10% duty cycle for worst case analysis.

Further reliability investigations for the 75 V RF GaN devices have been carried out by measuring the load line at 25 V, 50 V and 75 V when operated in class AB. The measurements were taken on a 1.8 mm unit cell of the same design at different power level with CW waveforms, as shown in Fig. 9 [16]. As the bias voltage increases, so does output and dissipated power resulting in increased junction temperature and reduction in saturated current. The data show that the device can reliably operate at 75 V without DC-RF dispersion or knee voltage walk-out.

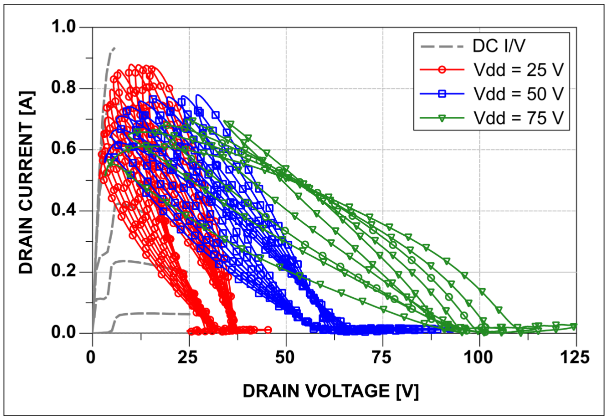

Figure 9 – Measured load line on a 1.8 mm unit cell at 25 V, 50 V and 75 V with operation in class AB.

Since the development of the 75 V GaN devices utilized in the presented design, further efforts with high voltage RF GaN devices have led to a single ended 1 kW device operating at 150 V with efficiency above 75% across the 420 – 450 MHz band, as reported in reference [17]. Although the design of a 1 kW amplifier module for spaceborne radar systems utilizing the latest 150 V 1 kW single-ended device has not been pursued, it is appropriate pointing out that in such approach there is no need for the 3-dB couplers, which together with having a single device rather than two translate into further size and weight reduction, always desirable in space applications. Fewer components also lead to improved system reliability. 150 V bias could lead to potential breakdown voltage issues in the bypass capacitors and with the MOSFET devices in the transmitter mute circuit. However, these issues can be mitigated with appropriate modifications in the design.

IV. Conclusion

A 1 kW output power amplifier with >75% efficiency and >40 dB gain suitable for spaceborne subsurface imaging in the UHF band has been described. Given the strong attenuation in ground-penetrating long wavelengths, the high output power is a key requirement for subsurface imaging in spaceborne SAR systems. The proposed design matches the high output power capability with high efficiency by using RF GaN transistors specifically designed for 75 V operation rather than using off-the-shelf 50 V devices. The amplifier achieves approximately 15% higher efficiency than is possible with existing TWT solutions. A suggestion for future work has also been presented utilizing a recently reported single-ended 1 kW device operating at 150 V for further size and weight reduction, while still achieving > 75% efficiency.

Acknowledgement

Dr. Tushar Thrivikraman and Dr. Gregory Sadowy from NASA/JPL are acknowledged for their support through the SBIR Phase II grant to Integra Technologies, Inc. under Contract Number NNX14CP07C. F. Boueri and Dr. J. Walker of Integra are also acknowledged.

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