Design of 1 kW GaN Solid-State Power Amplifier at 2.45 GHz

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Abstract

This paper presents the design, implementation and experimental results of a 1 kW GaN solid- state power amplifier operating at 2.45 GHz. The solid-state power amplifier employs twelve single-stage high-efficiency GaN-HEMT power amplifiers that are operated in Class-F mode. Output from the single-stage high-efficiency GaN power amplifiers are combined using low loss power combiners. The GaN device constituting the amplifier is a commercial off-the-shelf device that is designed for high voltage operation. The 1 kW GaN solid-state power has been designed to operate with either RF pulsed and continuous wave mode inputs.

Introduction

The paper describes the design and measured results of a 1 kW solid-state power amplifier (SSPA) operating over 2.42 to 2.48 GHz. The SSPA employs highly efficient state-of-the-art Gallium Nitride high electron mobility transistors (GaN-HEMT) that are operated in Class-F mode. The outputs from twelve of these devices are combined using a low loss power combiner configuration. The GaN-HEMT used in this application is commercial off-the-shelf (COTS) device that can work under RF continuous wave (CW) or pulsed mode conditions.

Considerable challenges had to be overcome in the development the 1 kW SSPA for operation under CW mode and are highlighted in the paper. The development of the solid-state power amplifier comprised of: (i) amplifier line-up concept; (ii) design of high power single amplifier stages; (iii) design of power distribution and combining networks; (iv) design of the electronic power supply conditioning circuits; (v) mechanical and thermal design of the mechanical housing with thermal. The paper describes the details of the design activities, fabrication and test of the 1 kW SSPA.

Power Amplifier Design

The 1 kW GaN solid-state power amplifier line-up is shown in Figure 1 and consists of three amplification stages with the pre-driver having a small signal gain level of 20 dB, the driver with a gain level of 17 dB and the output power stage with a gain level of 13 dB respectively. In order to meet the 1 kW CW output power, twelve commercially available off-the-shelf 120 Watt GaN-HEMT devices were combined together using low loss microstrip power combiner and divider.

The GaN-HEMT devices employed in the SSPA are fabricated on SiC substrate and have a breakdown voltage greater than 150 V. The devices operate in depletion mode and therefore require a negative voltage at the gate. The device drain terminal requires 50 Volts to operate with a current consumption of approximately of 4 Amperes when delivering 120 Watts of output power. The GaN-HEMT device will draw a very large drain current when the drain voltage is applied without the negative gate voltage. In order to prevent the latter from happening sequence circuits were required to supply the correct gate and drain voltage to the device terminals in the correct order and therefore minimise any damage.

The SSPA power management and control circuits also incorporated additional protection circuits that shut down the SSPA in case of excessive thermal heating and high reflected RF power resulting from large load VSWR variations at the output of the SSPA.

Figure 2 shows the small-signal gain and input/output return-loss simulation of the 1 kW solid-state power amplifier. The predicted small-signal gain is nominally 50 dB and the input and output return loss are better than 12 dB and 15 dB, respectively over the design frequency range of 2.42 to 2.48 GHz. The 1 kW solid-state power amplifier was designed to achieve maximum power-added efficiency (PAE) while maintaining a high output power over the operating frequency range of 2.42 to 2.48 GHz.

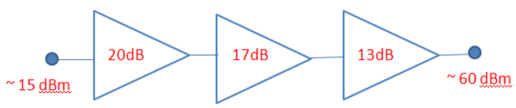

Figure 1 Amplifier line-up

The single stage 120 W power amplifiers were designed to operate under Class-F mode to provide optimum output power and power-added efficiency [1][2]. Figure 3 shows the simulated output power and power added efficiency of the 1 kW SSPA at 2.45 GHz. The predicted output power is 60 dBm with a power-added efficiency of 46%. Figure 4 shows the predicted output power and power-added efficiency over 2.42 to 2.48 GHz.

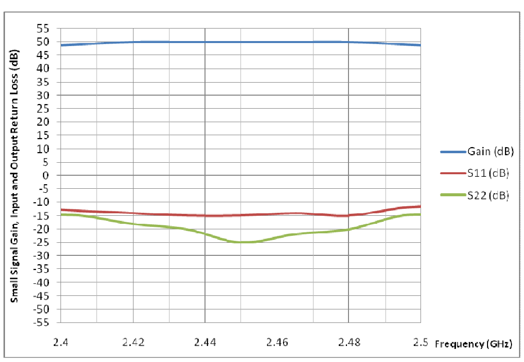

Figure 2 Simulated small-signal gain, input and output return-loss.

Power distribution and combining network design

The solid-state power amplifier was realized using twelve nominal 120 W power amplifiers that were combined to achieve an output power of 1 kW. This was achieved with two six-way combiners.

The measured back-to-back insertion-loss of the power divider connected to the combiner is 1.5 dB as shown in Figure 5, and the return-loss was better than 18 dB over 2.42 to 2.48 GHz.

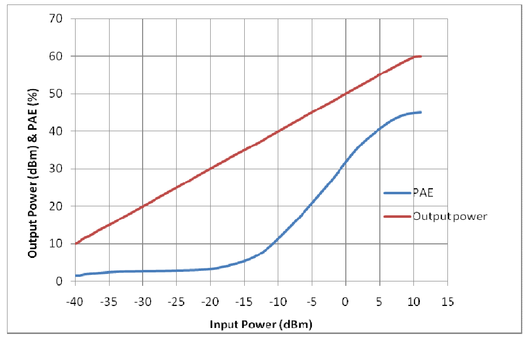

Figure 3 Simulated output power and PAE at 2.45 GHz.

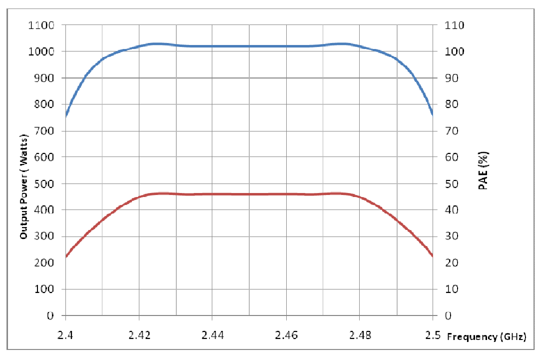

Figure 4 Simulated output power and PAE over 2.42 to 2.48 GHz.

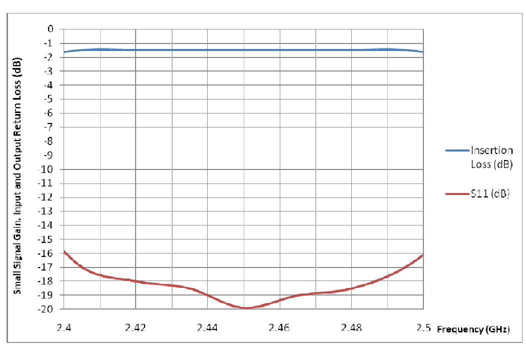

Figure 5 Measured insertion loss of back-to-back power divider and combiner.

Mechanical and Thermal Design

It was necessary to include thermal compensation inside the mechanical housing for the SSPA to maintain reliability and longevity as GaN-HEMT devices are a source of excessive heat generation. Each GaN-HEMT device dissipated approximately 90 Watts of power. The conventional technique employed to cool power an amplifier is by using heat sinks with fan assisted cooling. The 1 kW SSPA using the latter approach is unable to cope with the high heat density that is generated when operating in CW mode. Computational Fluid analysis (CFD) using the CAD software package Solid Works® was carried out which showed that forced air cooling is not be appropriate. With an air flow rate of 216 m^3 per hour the surface temperature is approximately 168℃, which is far too hot as shown in Figures 6. At this very high temperature the SSPA will have a very short life and therefore is not an option to employ. The thermal heat generated by GaN-HEMT devices was dissipated using liquid cooling which provides an effective thermal protection for the GaN-HEMT devices.

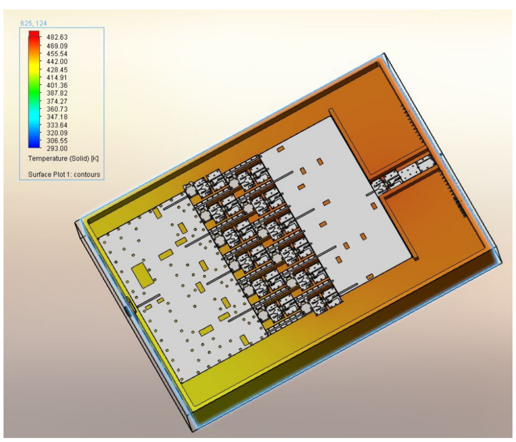

Figure 6 Thermal simulations - air cooling of SSPA.

Figure 7 shows the thermal analysis carried out using liquid cooling. The cooling liquid flow rate of 2 litres per minute is required to remove the high heat generated and ensure that maximum surface temperature of approximately 23°C is maintained. Lower operating temperatures will make the SSPA system far more reliable and vastly more efficient. In the case of water flow failure, the SSPA module is shut down and this is accomplished by monitoring temperature using thermal sensors mounted within the SSPA housing.

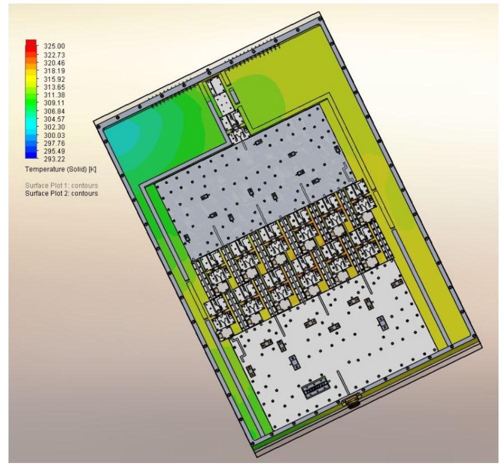

Figure 7 Thermal simulations - water cooling of SSPA.

Power Management and Control circuit

The SSPA power management and control circuit consist of the necessary switching and DC power for the GaN power devices. The power management circuit incorporates: (i) drain voltage switching; (ii) negative gate voltage implementation and adjustment; and (iii) sequencing and control circuits that are applied to the high power GaN-HEMT devices.

Figure 8 shows typical recommended power-up and power-down sequences for the drain and gate bias voltage applied to each of the high power GaN-HEMT devices. The SSPA power management is also integrated with a control circuit which will shutdown the DC power upon an error signal that is detected. The error signals to be detected are defined as: (i) error signal due to over temperature from the relevant temperature sensor situated within the SSPA housing; and (ii) error signal due to high reverse power from power monitor detector. Figure 9 shows the designed and fabricated power management and control printed circuit boards.

SSPA Fabrication

The fabricated SSPA is shown in Figure 10. The fabrication of the aluminum housing was a considerable challenge due to the physical size of the structure and the very tight tolerance of machining that was required. The soft-board RF circuits, microwave passive components and the active GaN-HEMT devices were all screwed onto the highly precision machined internal floor of the housing. The fabricated SSPA was tested under CW mode of operation with the output of the SSPA connected to a high-power water cooled RF load, as shown in Figure 11. The heat sinking for the SSPA and the high power RF load was maintained by using water cooled chiller.

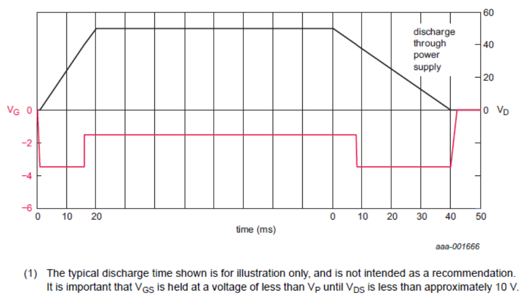

Figure 8 GaN Drain and Gate bias sequence.

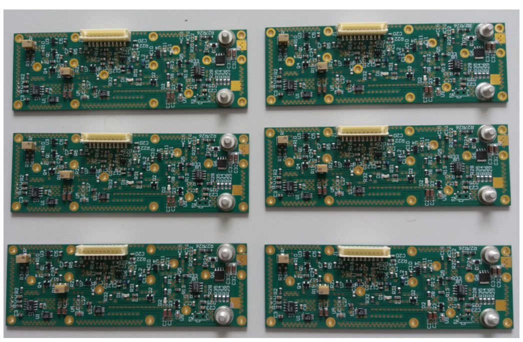

Figure 9 Fabricated power management and control printed circuit boards

Figure 10 Fabricated SSPA.

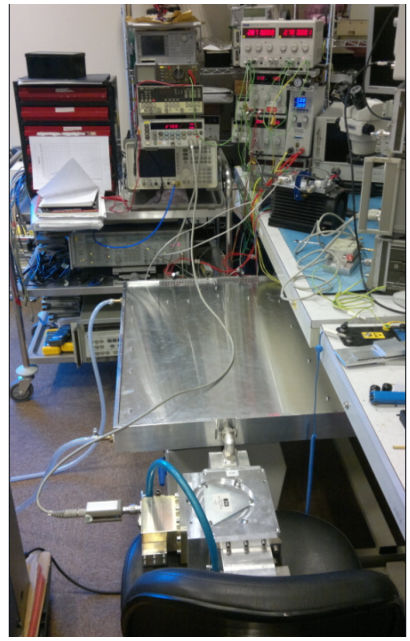

Figure 11 Testing SSPA under CW condition.

Measured Results

The measured small-signal performance with the housing temperature set to +25 ℃ ± 5℃ is shown in Figure 12. The small-signal gain obtained was 50 dB with a gain variation of less than ±0.25 dB across the operating frequency range of 2.42 to 2.48 GHz. The measured small-signal input return-loss was better than 11 dB and the output return-loss was better than 15 dB over the operating frequency range.

The measured large-signal performance for output power and power-added efficiency was carried out on the fabricated amplifier with the amplifier base plate temperature set to +25 ℃ ± 5℃ when operated under continuous wave (CW) mode. Figure 13 shows the maximum measured output power at 2.45 GHz is 1 kW and the corresponding power-added efficiency at 2.45 GHz is 45%. The output power and power-added efficiency were measured across the operating frequency range of 2.42 to 2.48 and are shown in Figure 14. The output power was over 1 kW and the power added efficiency was 45% across 2.42 to 2.48 GHz.

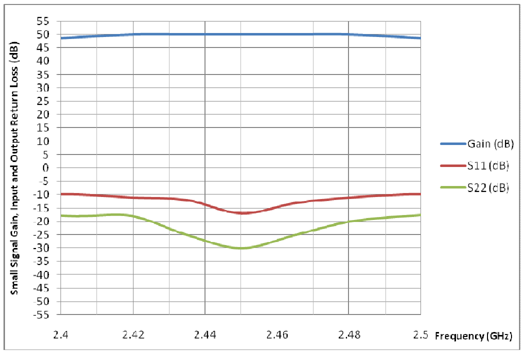

Figure 12 Measured small-signal gain, input and output return-loss.

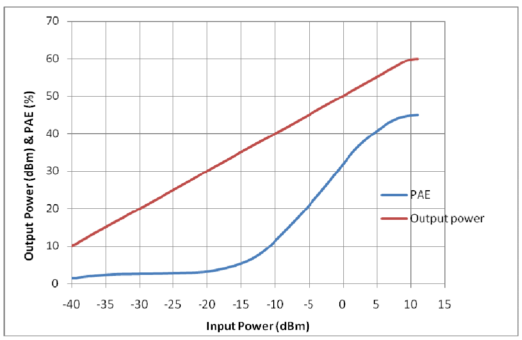

Figure 13 Measured output power and PAE at 2.45 GHz

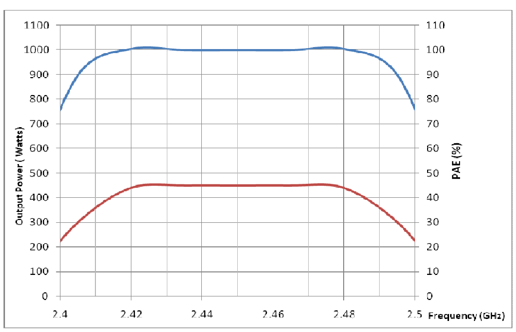

Figure 14 Measured output power and PAE over 2.42 to 2.48 GHz.

Summary

The paper has described the design, fabrication and measured results of a 1 kW SSPA based on a GaN-HEMT operating in Class-F. The measured results confirm the power amplifier exhibits excellent RF performance with good correlation with the simulated performance. The SSPA achieved a nominal small-signal gain of 50 dB, with an output power of 1 kW and power-added efficiency of 45 % under CW mode of operation across the frequency range of 2.42 to 2.48 GHz.

References

[1] A. Virdee, B.Virdee and K Ahmed, "High Power GaN Amplifier for High Efficiency Applications," *ARMMS Conference*, April 2017.

[2] F. H. Raab, “Class-F power amplifiers with maximally flat waveforms,” *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp. 2007–2012, Nov. 1997. [2] Y.-F. Wu, A. Saxler.