The VSS3605, a 13-kW S-Band GaN Power Amplifier

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Abstract

The introduction of GaN as a solid state semiconductor material has enabled the manufacture of high-power, efficient amplifiers in a small volume. In 2011, CPI developed a 1300-watt S-band solid state power amplifier, CPI model VSS3607. The VSS3607 SSPA is designed around the Cree CGH31240F power transistor. In 2012, CPI power combined 12 VSS3607 amplifiers to produce a very reliable and efficient, air-cooled amplifier, CPI model VSS3605, for radar applications, including Air Traffic Control (ATC) radar systems. This paper will present details of the design and performance data for the VSS3607 amplifier, including results from a 1000-hour life test. This paper will also present performance data for CPI's 13-kW SSPA, the VSS3605.

Background

The Beverly Microwave Division of Communications & Power Industries, LLC (CPI BMD) has been manufacturing microwave and radar components for more than 60 years. Communications & Power Industries, LLC (CPI) is a global company with six autonomous operating divisions. CPI is a leading supplier of microwave amplifiers, receiver-related components, and systems to military, commercial and industrial customers. We support our customers via a world-class global network of service centers. CPI BMD has over 60 years of experience in development, production, and repair of military radar components and systems having full compliance to military standards. Our design and manufacturing processes are geared for military as well as high-reliability commercial workmanship. CPI BMD is an ISO 9001/AS9100 certified manufacturer. CPI BMD is the world's largest producer of magnetrons and receiver protectors for commercial and military radar systems. CPI BMD is also a designer and manufacturer of radar transmitters that are used worldwide. Until recently, these transmitters contained exclusively vacuum electron devices as the final power amplifier.

GaN SSPA IR&D Program

Gallium Nitride wide-band-gap semiconductor material represents a significant technological step forward for power density and efficiency in a solid state device. While microwave tubes continue to be the appropriate technology for many high power and high frequency applications, gallium nitride solid state power amplifiers are encroaching on this territory. As a manufacturer of high power microwave tubes, CPI BMD is uniquely qualified to evaluate where solid state is preferable to microwave tube technology, and visa versa. In 2011 CPI BMD initiated an IR&D program to develop modular GaN amplifiers at S-band where there are numerous radar requirements.

VSS3607 SSPA Brick Design

For a given output power, size, weight, and efficiency are critically important for mobile applications. Solid state power amplifiers incorporating GaN devices have quickly found a home in mobile applications due to the high power density and efficiency of the GaN transistors. CPI has capitalized on these attributes for the development of the S-Band SSPA for ATC applications.

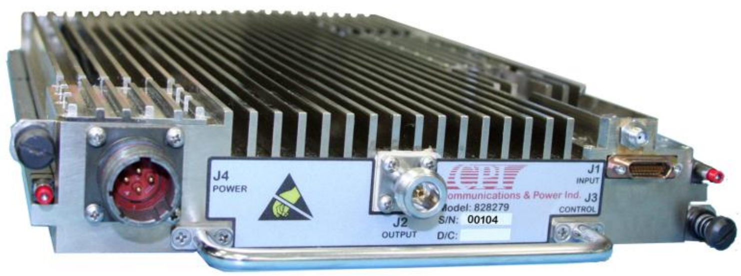

Figure 1 VSS3607 Solid State Power Amplifier

The design of the VSS3607 SSPA utilizes an isolated in-phase combining structure to sum the powers from individual transistors while maintaining isolation between adjacent devices. The combiners provide greater than 20-dB return loss for the transistors and the output N-Type connector.

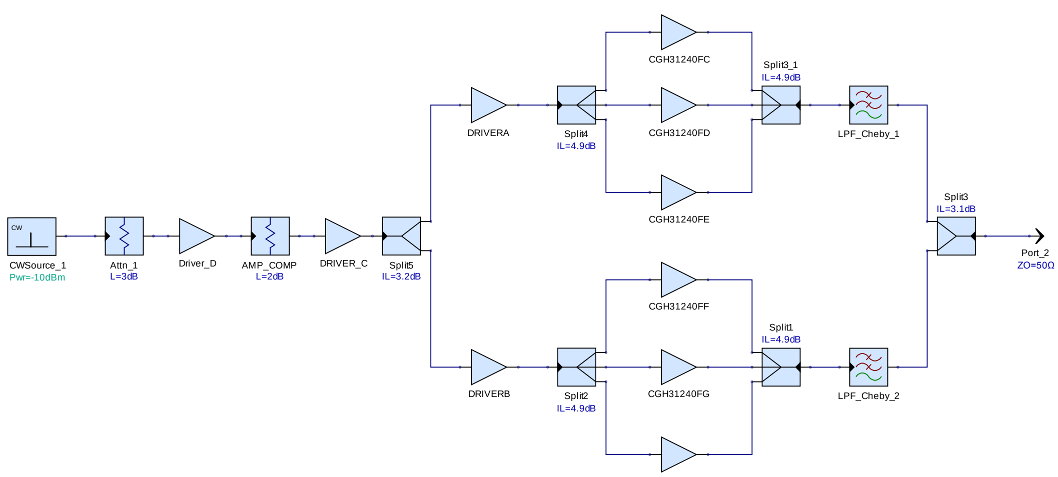

Figure 2 Schematic design of VSS3607 SSPA

The combining structures include integral low pass filter structures to reduce the second and third harmonics of the transmitted signal by greater than 30 dB. The combining efficiency from the GaN power devices to the output connector, including the low pass filter, is greater than 90%. The CPI-proprietary combiners enable an overall amplifier efficiency of greater than 35% in the VSS3607 SSPA, where overall amplifier efficiency is defined as the ratio of RF output power to DC input power.

The VSS3607 SSPA is hermetically sealed and internally temperature compensated. Packaged GaN FETS and MMICS ensure high reliability under extreme environmental conditions. Table 1 summarizes the data for the VSS3607 SSPA.

Frequency Range	2.7 to 2.9 GHz
Peak RF Power	1.3 kW, saturated
Pulse Width	1 to 100 microsecond
Small Signal Gain	62 dB nominal
Duty Cycle	10%
Pulse Droop	0.5 dB
Output Power Flatness	1 dB
Harmonic Output	-35 dBc maximum
Noise Power Density	-100 dBc into a 1 MHz bandwidth
Prime Power	30.5 VDC at 13 Amps
Size	9.5 inch x 1.75 inch x 15.5 inch
Weight	11 pounds

Table 1 Key Parameters for VSS3607 SSPA

Output power as a function of frequency and temperature is plotted in Figure 3 for the VSS3607 SSPA. This data was taken at 100 microsecond pulse widths at 10% duty. The output power is plotted at three ambient temperatures, -32 °C, +25 °C, and +50 °C. Some slight degradation in power is seen at cold and hot temperatures.

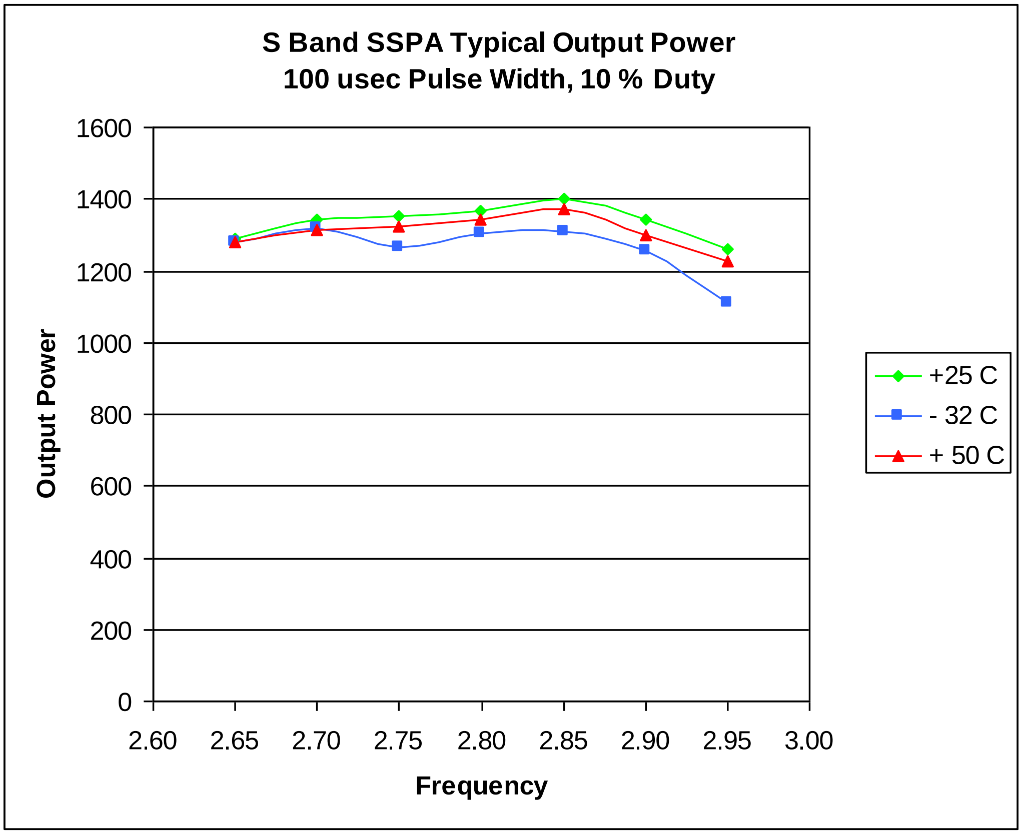

Figure 3 Output power as a function of frequency and temperature.

Pulsed waveforms are shown in Figures 4 - 8 at an operating frequency of 2.8 GHz. The output power is displayed at increasing pulse widths for the VSS3607 SSPA at a fixed pulse repetition frequency of 1 kHz. Power is measured with a pulsed power meter. These waveforms were taken at ambient temperature. Power levels as measured at the two markers are shown at the top of the pulsed power meter displays in Figures 4 - 8.

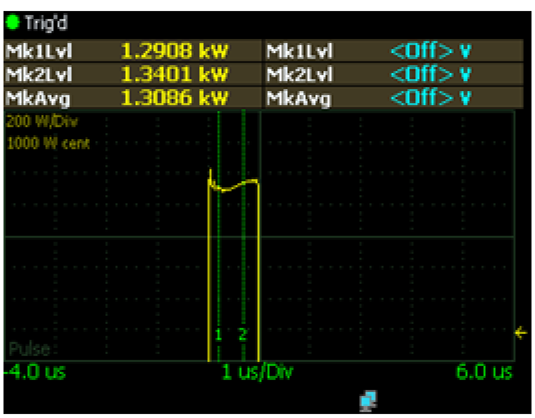

Figure 4 Power at 1 usec pulse width and 1 kHz pulse repetition frequency.

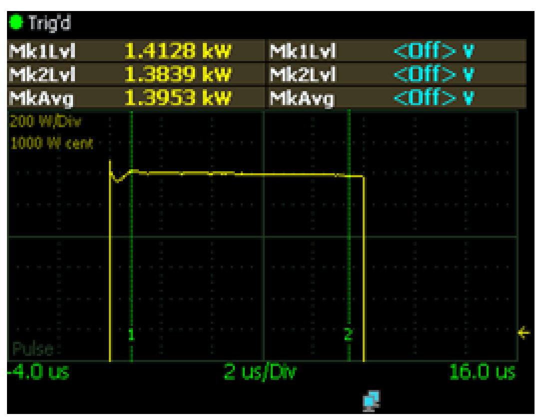

Figure 5 Power at 10 usec pulse width and 1 kHz pulse repetition frequency

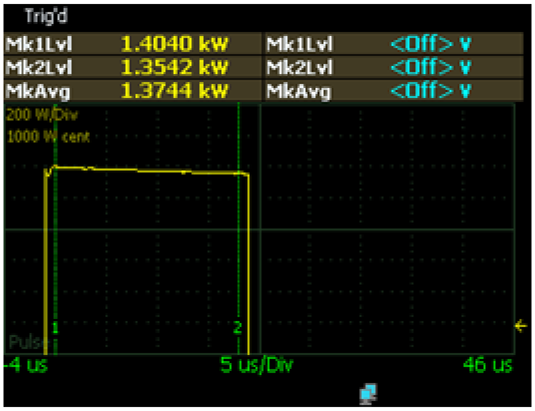

Figure 6 Power at 20 usec pulse width and 1 kHz pulse repetition frequency

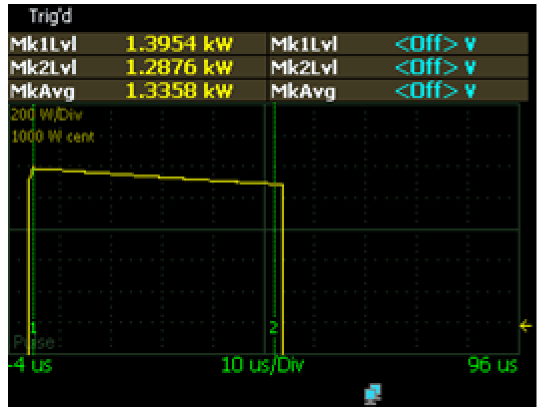

Figure 8 Power at 100 usec pulse width and 1 kHz pulse repetition frequency

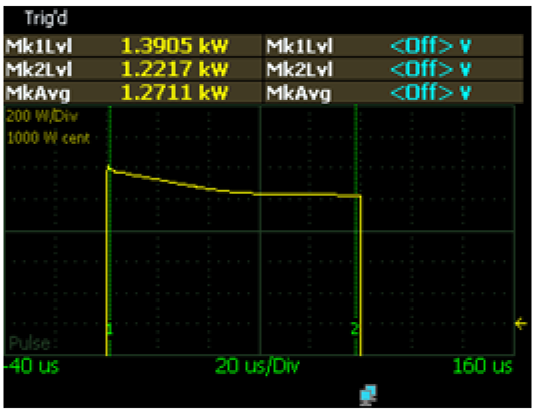

Figure 7 Power at 50 usec pulse width and 1 kHz pulse repetition frequency

VSS3607 SSPA Life Test

Pulsed transmitter designs undergo stress to the active and passive RF components and power supply and modulator components. Materials may stress-relieve or fracture due to cycled thermal gradients. In pulsed transmitter designs, the average power is only a fraction of the peak power; however, the instantaneous thermal gradients can be high during the pulse and during the pulse transitions. Repetitive heating and cooling cycles stress aspects of the design from the modulator, active and passive devices, bond wires and combiner structures. An operating RF life test of a pulsed SSPA which stresses all aspects of the transmitter design is essential in demonstrating transmitter reliability.

There is very little GaN solid state semiconductor material life test published and even less on GaN used in high power pulsed applications. Accelerated life test data exists for some GaN transistors. While some transistor manufacturers have published life test data at elevated temperatures which can be used to extrapolate transistor life under operational temperatures, CPI wanted to test the GaN transistors and the SSPA design under pulsed RF conditions to validate the robustness of the devices and amplifier design. A 1000+ hour life test was conducted on the VSS3607 amplifier while operating at 100 usec pulse width and 10% duty factor. The VSS3607 SSPA was operated, at ambient temperature, in a rack assembly that mimicked the cooling air flow of a system configuration. The RF output was monitored for peak power using a USB pulsed-power sensor and the phase stability was monitored using a quadrature-detector-type phase bridge. The power and phase data was automatically logged every 5 minutes for the duration of the life test. Power supply voltages and currents and the ambient temperatures were recorded periodically. Figure 8 shows the pulsed power as a function of time during the life test. The phase varied by less than ± 5° during the life test.

The results of the life test indicated a very stable design. The power level from the VSS3607 SSPA initially dropped 10 watts in the first 100 hours of the life test and then stabilized for the remainder of the test. The VSS3607 SSPA had been burned in at elevated temperature and thermally cycled prior to the life test.

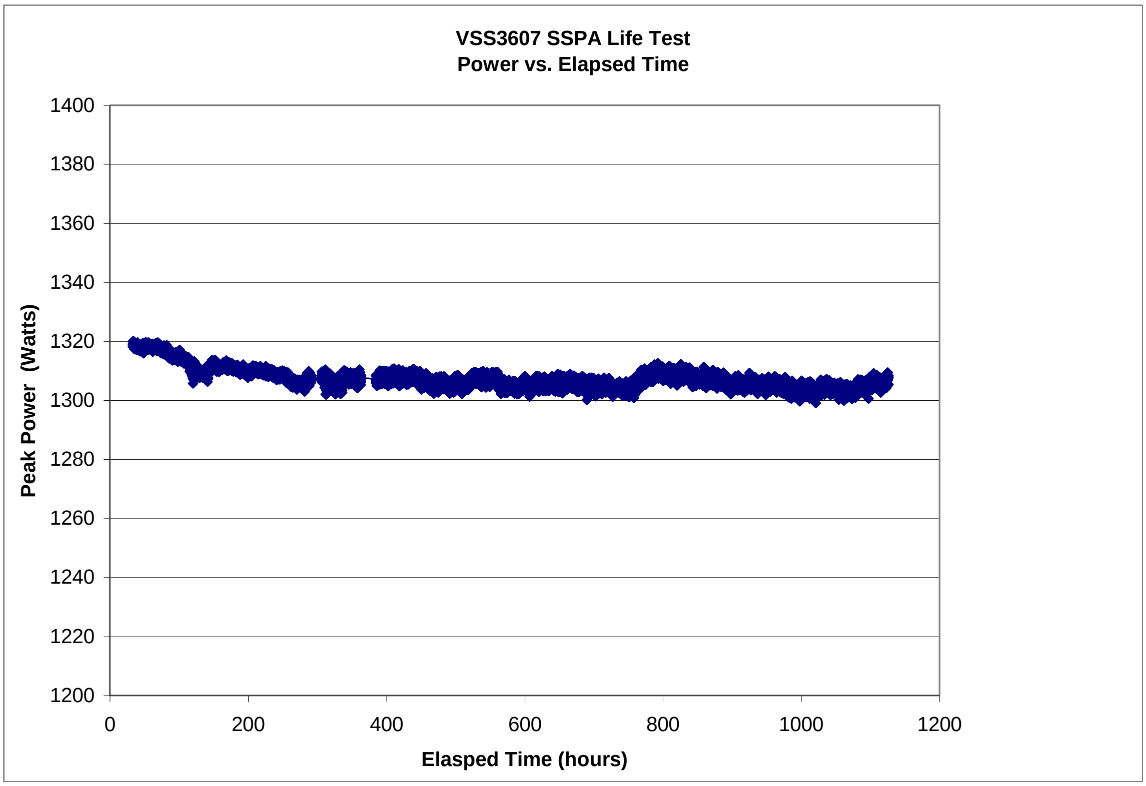

Figure 9 VSS3607 life test data

CPI's Thirteen Kilowatt Power Amplifier, the VSS3605

The VSS3605 amplifier was designed for mobile, air-cooled applications. As such, the overall size and weight and efficiency are driven by the choice of the power combiners. The generation of the 13 kW of output power from the coherent addition of multiple 1.3 kW SSPA bricks was optimized by using custom-designed combiners. CPI has extensive expertise with high power levels and designed the key output combiners using the three-dimensional finite element code, HFSS.

Power combining can be accomplished with various means including corporate, radial and waveguide combining. A good explanation of the tradeoffs can be found in other publications. The tradeoffs are frequency dependent. Waveguide combiners are large and bulky at low frequencies because the lower the frequency the longer the wavelength while at higher frequency the waveguides are small and implementing the combiner in a coaxial structure can be mechanically difficult.

The output combiner used for this amplifier is a combination of non-reactive radial and spatial waveguide combining. The radial combiner was selected for its low loss and wide bandwidth characteristics. The radial combiner was designed to be non-reactive which means that the individual arms are resistively loaded providing 20 dB isolation between adjacent ports. The isolation ensures that the power gracefully degrades as individual SSPA bricks are turned off for reduced range and power consumption or due to the failure of an individual amplifier.

In the event N amplifiers are turned off, the total power is reduced to:

$$P_{reduced}\ (T\text{-}N) = (N/T)^2 * P_{total}$$

where $P_{reduced}$ = combined power from T-N amplifiers
T = total number of amplifiers
N = number of amplifiers turned off
P_{total} = combined power from T amplifiers

For example, if the total combined power output is 13 KW with all 12 SSPAs functioning, then the power would be reduced to 84% of the final output power if only 11 amplifiers are functioning.

$$10.92\ \text{kW} = (11/12)^2 * 13\ \text{kW}$$

Radial combiners are not binary by nature. This characteristic allows for the straightforward combination of any number of SSPA amplifiers including even or odd numbers to appropriately size the transmitter for specific applications. For the VSS3605 SSPA, the output from two six-way radial combiners are combined spatially in waveguide to provide efficient, compact 12-way combining. The separate radial combiners allow the combiners to optimally fit in the desired area and reduce the length of the coax cables connecting the combiners to the individual VSS3607 amplifiers.

The phase matching of individual components was critical in achieving the optimal performance of the amplifier. The passive components and the SSPA bricks were matched to less than +/- 1 degree.

Figure 10 shows the VSS3605 SSPA in the laboratory under test. Table 2 summarizes the key characteristics of the VSS3605 SSPA. Power as a function of frequency is shown in Figure 11 for the VSS3605 SSPA. In Figure 11 the power is plotted as the input power is varied from -1 dBm to + 1 dBm. The data shown in Figure

11 was taken at 100 usec pulse widths and 10% duty factor. The output power of the VSS3605 SSPA is shown at various pulse lengths in Figures 12-16. The data in Figures 12-16 was taken at a 1 kHz pulse repetition frequency and at a dc voltage of 31 volts and a current of 100 amperes.

Figure 10 VSS3605 SSPA under test at CPI

Frequency Range	2.7 to 2.9 GHz
Peak RF Power	13 kW, saturated
Pulse Width	1 to 100 microsecond
Small Signal Gain	71 dB nominal
Duty Cycle	10%
Pulse Droop	0.5 dB
Output Power Flatness	1 dB
Harmonic Output	-35 dBc maximum
Noise Power Density	-100 dBc into a 1 MHz bandwidth
Prime Power	120 / 208 or 220 / 380 or 240 / 416 VAC 3 phase WYE with neutral, 50 or 60 Hz
Size	19 inch x 25.5 inch x 23.5 inch
Weight	230 pounds

Table 2 Key characteristics of the VSS3605 SSPA

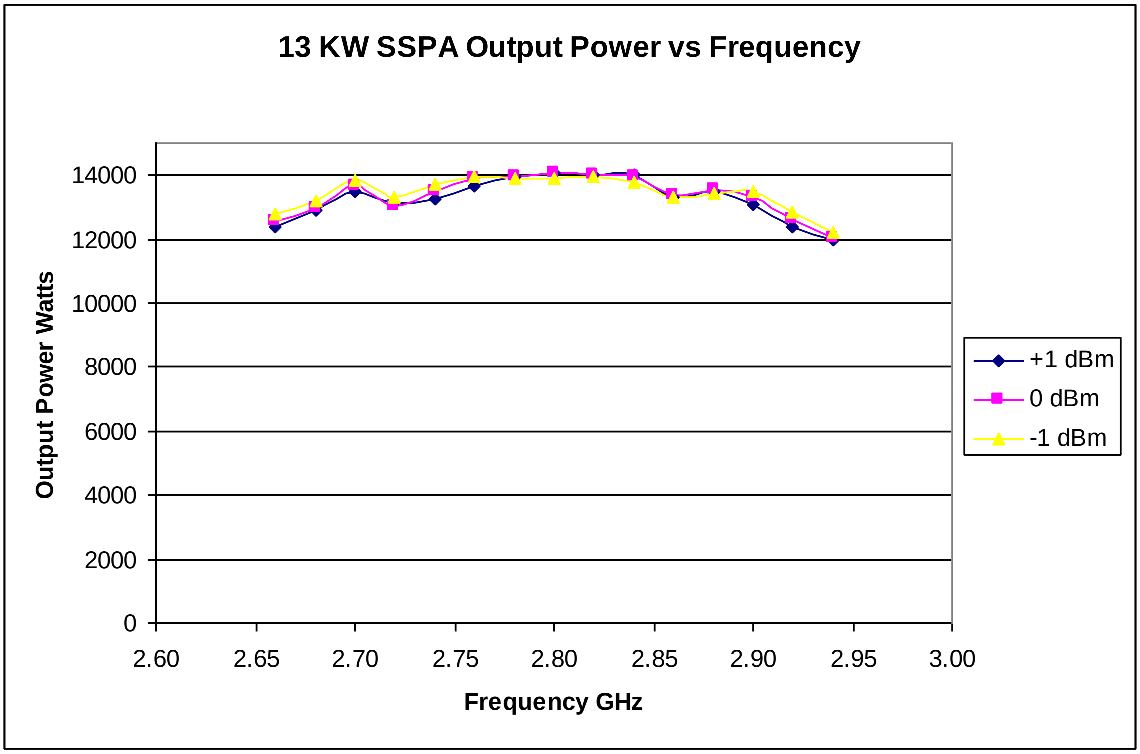

Figure 11 Power as a function of frequency for VSS3605 SSPA

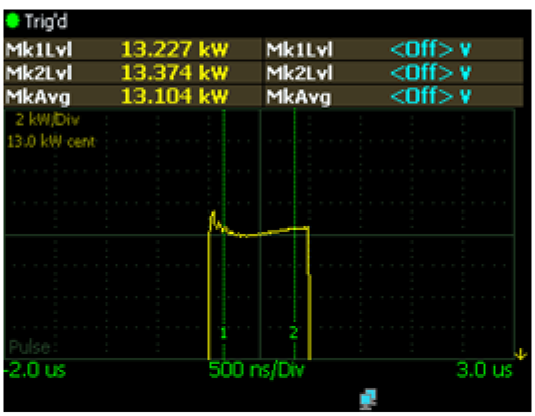

Figure 12 Power at 1 usec pulse width and 1 kHz pulse repetition frequency

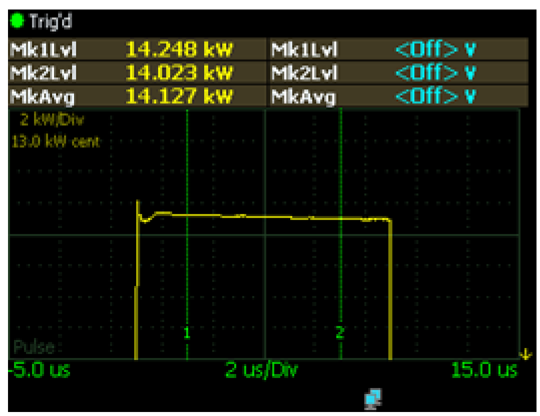

Figure 13 Power at 5 usec pulse width at 1 kHz pulse repetition frequency

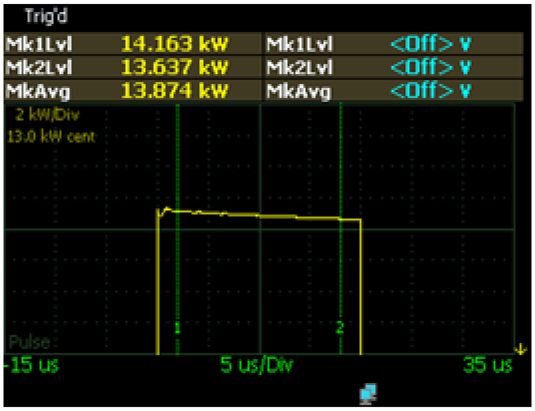

Figure 14 Power at 10 usec pulse width at 1 kHz pulse repetition frequency

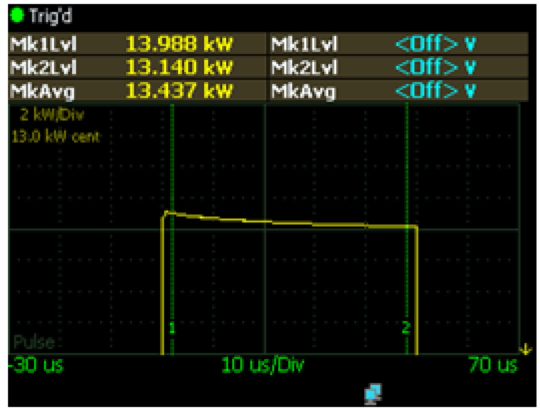

Figure 15 Power at 20 usec pulse width at 1 kHz pulse repetition frequency

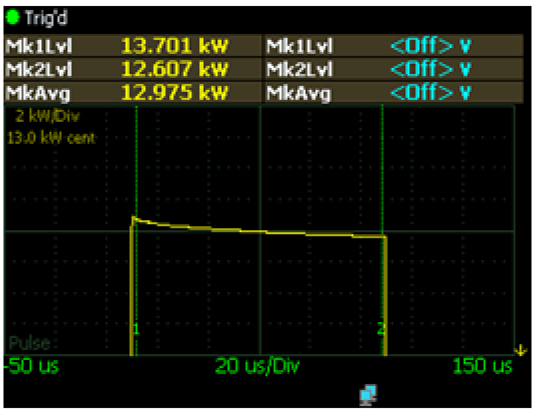

Figure 15 Power at 100 usec pulse width at 1 khz pulse repetition frequency

Summary

CPI has developed and extensively tested the VSS3607 GaN SSPA which operates at 1.3 kW at 2.7-2.9 GHz. CPI has demonstrated efficient and compact combining of 12 VSS3607 amplifiers into the 13-kW, 2.7-2.9 GHz, VSS3605, high power SSPA. This amplifier extends CPI's proud heritage of high-power, high-reliability RF transmitters into a new technology regime. CPI's GaN SSPAs can be readily combined into amplifiers with other form factors for power levels from 1 kW to 20 kW in a cost-effective manner. CPI is currently extending the amplifier frequency to 3.5 GHz for other radar applications.