Microwave Journal

INVITED PAPER

Innovations in Pulse Fidelity for High-Power GaN Radar and EW Transmitters

Darren Miles and George Bollendorf
Empower RF Systems, Inglewood, Calif.
Bob Buxton
Boonton Electronics, Parsippany, N.J.

Radar and electronic warfare (EW) have been the primary applications for extremely high-power transmitters, driving the demand for specialized high-power traveling wave tubes (TWTs) and magnetrons. Diminishing sources of TWT supplies, coupled with their poor reliability, inefficiency, large size and high total lifetime cost of ownership are causing a migration away from tubes. While improved pulse fidelity accompanies the shift to solid-state transmitters, next-generation radar depends on further improvements in waveform fidelity and flexibility.

Next-generation radar systems utilize long pulse widths, which present specific challenges. In response, Empower RF Systems has developed technology to reduce pulse distortion as a development step towards pulse shape matching, allowing the reproduction of the input pulse without distortion. The pulse correction is performed within the amplifier in real-time. This is important because long pulse width radar is especially vulnerable to over/undershoot and droop, which can be eliminated to extend radar range and reduce receiver target acquisition time. The benefits from an EW perspective are the ability to accurately mimic adversarial pulses without pre-processing, allowing precise threat simulation and spoofing.

THE PRIMARY CAUSE OF DROOP IN SOLID-STATE POWER AMPLIFIERS (SSPAS)

This article discusses the correction of pulse droop and rising edge overshoot with data from Empower's 40 kW L-Band long duty cycle liquid-cooled pulsed amplifier, Model 2237, shown in ***Figure 1***. The prima-

Fig. 1 Model 2237 L-Band 40 kW Pulsed Transmitter.

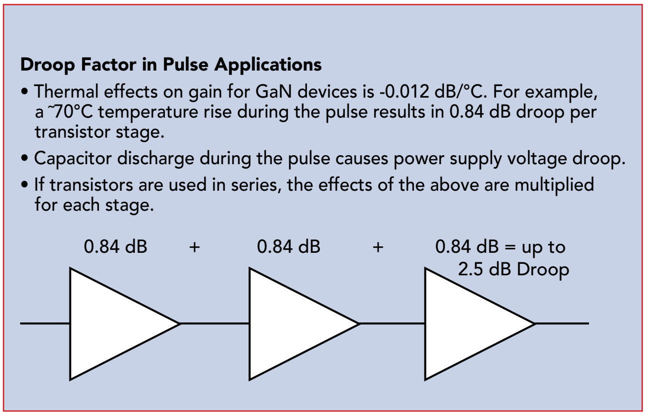

Fig. 2 **The impact of cascading stages.**

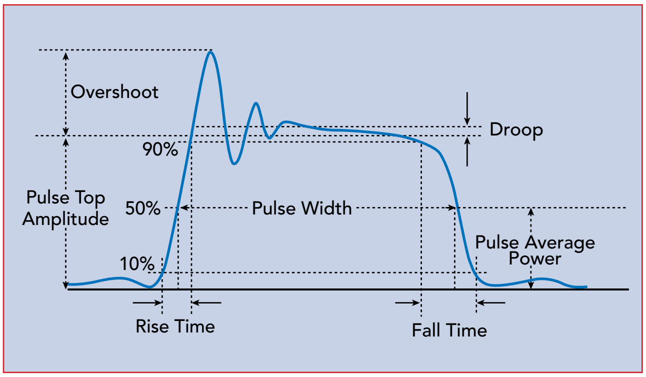

Fig. 3 **Pulse parameters.**

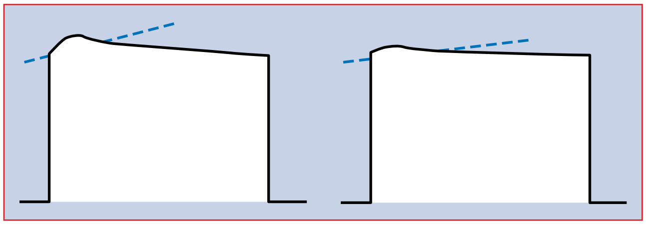

Fig. 4 **Illustration of the pulse droop correction of RF output.**

ry cause of droop in a GaN power amplifier is the thermal response of the transistor. GaN has an inverse gain relationship with temperature. The thermal response of the transistors reduces the gain by 0.5 to 1.0 dB, depending on the temperature rise during the pulse. The droop is compounded with cascaded transistors resulting in a further reduction in output power. This is summarized in ***Figure 2***. The second contribution relates to a power supply's ability to source current at high frequencies. During the pulse, the capacitive energy across the drain of the transistor discharges. This starts at the leading edge of the pulse and as the pulse progresses to the trailing edge, the gain is increasingly reduced by the resulting drop in drain current and drain voltage. These two factors can account for up to 3 dB of droop. Fixing the droop using software allows a reduction in the size and complexity of the power supply and increases average transmit power. The result is improved size, weight and power (SWaP), cost and MTBF.

PULSE PARAMETERS AND IMPACT ON RADAR PERFORMANCE

Pulse droop is defined as the distortion of a flat-topped rectangular pulse, characterized by a decline of the pulse top. ***Figure 3*** describes the characteristics of a pulsed signal. Generally, each pulse includes an overshoot and ripple at the leading edge of the pulse and a pulse droop, which is the reduction in the amplitude between the beginning and end of the pulse.

THE IMPACT OF OVERSHOOT AND DROOP ON RADAR PERFORMANCE

A radar transmitter will have a limiter to protect the amplifier output stages from exceeding the peak power ratings. When overshoot is present, the gain must be set so the overshoot of the pulse does not activate the limiter. When overshoot is absent or minimized, the amplifier output can be set just shy of the limiter threshold. In the case of droop, the power during the pulse is dropping over time, further reducing the average power. By examining the radar range equation, the impact of reduced power can be seen in Equation (1).

$$R_{max} = \left[\frac{P_t G \sigma A_e}{(4\pi)^2 S_{min}}\right]^{1/4} \quad (1)$$

Where:
R_{max} = the maximum range
P_t = the transmitter power
G = the transmitter antenna gain
σ = the target's radar cross-section
A_e = the receive antenna effective aperture
S_{min} = the minimum detectable signal.

Assuming all other terms remain constant, the maximum range varies as the fourth root of the transmitter power. For example, a 1 dB improvement in average power increases the range by 6 percent.

PULSE CORRECTIONS

Each of the two main sources of droop has a repeatable response in time. These are typically marked from the leading edge of each pulse. With fast enough sample rates, an algorithmic solution exists that can change the amplifier gain throughout the pulse in real-time.

As an example, let's take the simplest form of the algorithm. Since the junction temperature rate of change is highest on the rising edge of the pulse when the transistor is turning on and conducting, the adjustment to the gain at the beginning of the pulse must be greater than during the remainder of the pulse. Implementing this will result in a significant reduction in overshoot. The expected result of this simple adjustment is shown in ***Figure 4***.

After the overshoot section, gain adjustment of the algorithm can be employed as a second element. The math is simple; the droop has a slope, so the gain adjustment simply adds in the inverse gain slope. The applied algorithm repeats itself with each pulse. This two-step algorithm can be further refined by adding more adjustment points, however, the results of a two-stage correction are very good and are shown later. The correction algorithm resides in the FPGA firmware and contains a finite-state machine described in HDL. The correction algorithm is

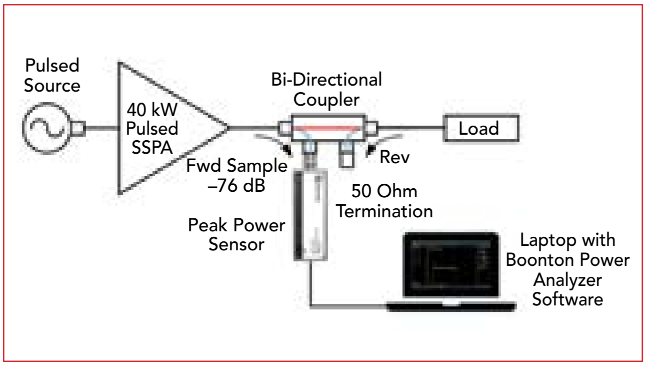

Fig. 5 **Test setup.**

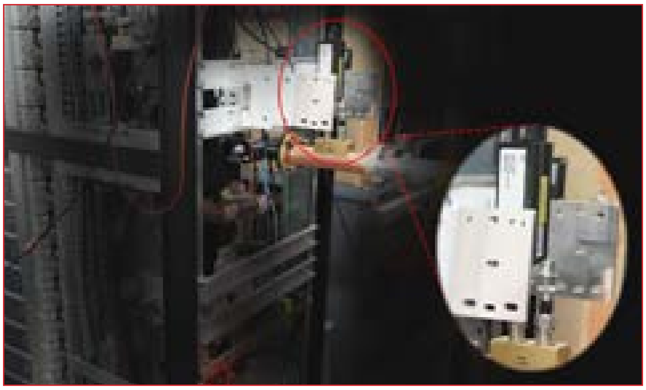

Fig. 6 **Output power coupling.**

configured with the appropriate parameters from a digital calibration process performed at the factory. The parameters include the slopes of the two-stage corrections and the initial power level at the leading edge of the pulse.

TEST SETUP (REFER TO SIDEBAR ON PAGE 68)

For demonstration, an Empower amplifier is driven with a 1.5 GHz, 500 µsec pulse, nominally at 0 dBm. A separate guard band input is used to frame the pulse for operating in true pulse mode. The amplifier is set to full gain, achieving 40 kW peak power at the output. The overall setup is shown in ***Figure 5***.

The amplifier has a bidirectional coupler at the output as seen in ***Figure 6***. The coupling factor is 76 dB. A Boonton RTP5006 USB real-time peak power sensor was used because this is the only sensor fast enough to capture the peak of the overshoot. The full power is terminated into a 50 Ω load.

RESULTS OF PRACTICAL IMPLEMENTATION

Figure 7 shows the measurement of the 40 kW SSPA output with the Boonton power sensor before applying the correction algorithm. This result was captured by the Boonton Power Analyzer Software. For a 500 µsec pulse width, the peak with overshoot measures 76.053 dBm. The end of the pulse top is measured at 74.36 dBm. The Boonton software captures the pulse envelope, which can be exported to a CSV table. From that table, the overshoot can be determined to settle around 75.2 dBm. The uncorrected pulse is then described as having an overshoot of approximately 0.9 dB (76.053 − 75.2 dBm) with a droop of approximately 0.8 dB (75.2 − 74.36 dBm).

Figure 8a shows the effect of the overshoot correction stage, which decreases the overshoot by approximately 0.6 dB from the uncorrected pulse. ***Figure 8b*** shows the effect of the droop correction stage, which decreases the overshoot again by nearly 0.6 dB. While these stages decrease the amplitude of the overshoot at the front edge of the pulse, the trailing edge of the pulse remains unchanged. The effect reduces the overall energy of the pulse, a poor tradeoff for the benefit of flattening the pulse. Once the pulse is flattened, however, the gain of the system can be increased since the reduced overshoot will no longer activate the amplifier peak limiter. This is shown in ***Figure 9***.

For the final result of Figure 9, the maximum peak power was adjusted by increasing the system gain. This results in a system gain higher than that of the uncorrected pulse example. For simplicity of illustrating the method, the gain adjustment has been described as the last step. In actual implementation, the correction factors are established ahead of time and stored, so setting the system to the optimized maximum gain is the first step. Next, the pulse rises and the overshoot is corrected with a final

Fig. 7 **Uncorrected 40 kW pulse.**

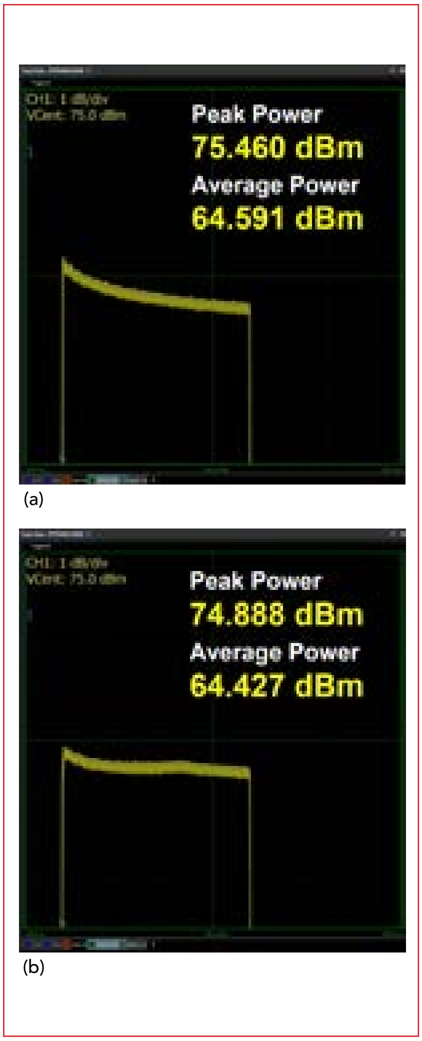

Fig. 8 **Response with overshoot correction applied (a). Response with slope droop correction applied (b).**

step of correcting the droop of the pulse.

Fig. 9 Response of the optimized result.

SUMMARY

The power output measured over the duration of the 500 µsec pulse is shown in ***Figure 10***. This output demonstrates a flatter response with less overshoot that results from applying both droop and overshoot correction. In addition to providing more uniform power throughout the pulse, the amplifier can also generate higher average power. This is a result of higher system gain without fear of the overshoot activating the limiter and a pulse with less droop.

CONCLUSION

Using these techniques increased the average pulse power by 0.9 dB, which is close to the amount of pulse correction. This is as expected since the maximum transmitter output can be increased by the amount that the pulse variation is reduced. The result represents more than a 20 percent increase in average power, which also improves SWaP, cost and MTBF. The transmitter power density improves by 20 percent. The MTBF and cost improve since the component count in the RF chain would have been higher and the transmitter would have operated at a higher temperature to produce the 20 percent output power increase that would have been required without the pulse correction. In addition, the radar performance improves as roughly 1 dB of increased transmit power extends the range of the radar by 6 percent. ■

MEASUREMENT CONSIDERATIONS

Measuring pulsed radar signals requires a peak power sensor. For fast pulses, the rise time of the power sensor is important. The Boonton RTP5006 has a rise time of ≤ 3 ns. This means that a pulse rising edge of 5 ns can be comfortably measured. The rise time display of a representative pulse is shown in ***Figure S-1***.

Fast real-time and equivalent-time sampling provide fine resolution on narrow pulses. The RTP5000 real-time peak power sensors, with 100 MSa/s real-time and 10 GSa/s equivalent-time sampling, can make measurements on 10 nsec pulses with 100 psec resolution.

When measuring amplifier droop, automated measurements become important. Droop is one of the 16 automated pulse measurements available from the RTP5000 family. ***Figure S-2*** shows the effects of droop on a reference signal.

RTP5000 power sensors may be used with a PC running the Boonton Power Analyzer Software or with the PMX40 power meter for a benchtop instrument experience. Either way, they provide an ideal tool to characterize radar and EW signals.

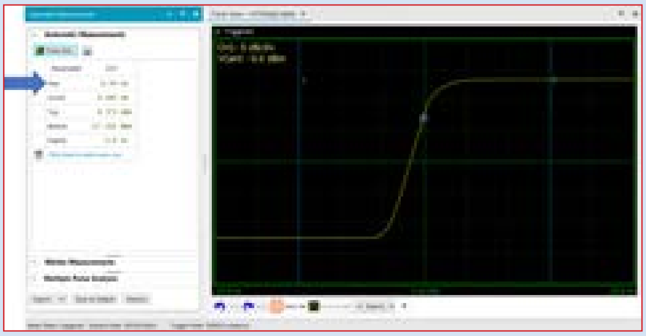

Fig. S-1 Pulse rising edge with automated 10/90% rise time measurement shown by the blue arrow.

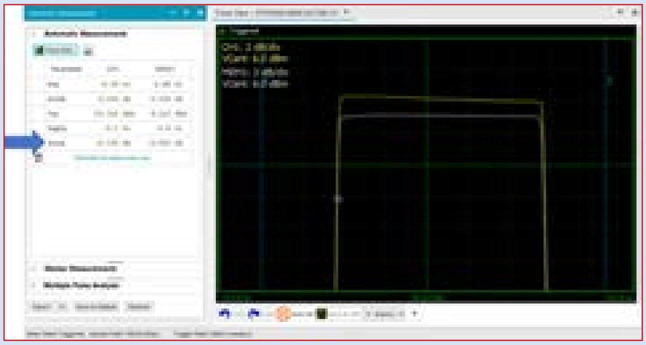

Fig. S-2 Comparison of live trace with memory to see the effect of signal changes on droop.