

# Pulsed-Bias Pulsed-RF Harmonic Load Pull for Gallium Nitride (GaN) and Wide Band-Gap (WBG) Devices

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**Abstract** — For the first time ever, a commercially available pulsed-bias pulsed-RF harmonic load pull system is being offered for high power and wide band-gap devices. Pulsing DC bias in conjunction with pulsing RF reduces slow (long-term) memory effects by minimizing self-heating and trapping, giving a more realistic observance of transistor operating conditions. IV, S-Parameter and Load Pull measurements taken under pulsed-bias pulsed-RF conditions give more accurate and meaningful results for high-power pulsed applications.

**Index Terms** — Microwave measurements, impedance matching, tuner, load pull, pulse measurements, power amplifiers, modeling.

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## I. Gallium Nitride and Wide Band-Gap Devices

Gallium nitride (GaN) is a wide band-gap material that has been used for LEDs since the 1990s. In recent years, its usage has spread to the microwave community as an enabling technology for high power amplifiers. Originally, GaN was not cost effective for non-military programs, but material maturity, yield improvement, expansion to 4" wafers, and inclusion of lower cost substrates have driven down the cost. Discrete devices, as well as MMICs, are now commercially available using GaN from many foundries worldwide.

GaN offers several advantages over GaAs, including higher operating voltage (over 100V breakdown), higher operating temperature (over 150°C channel temperature), and higher power density (5-30W/mm). Mechanically, the material is durable and resists cracking. Although most GaN devices are commonly grown on silicon carbide (SiC) substrates, lower cost GaN devices are also popular on sapphire and silicon wafers.

Even though GaN is ideal for high efficiency amplifiers, the large output power capability presents a great deal of heat dissipation. SiC has an impressive thermal conductivity, but for large periphery GaN devices, it is not sufficient for eliminating thermal effects. GaN HEMTs can also suffer from the effects of trapping in the surface passivation along the gate width. Electrical performance degradation over time, including a decrease in the threshold voltage and an increase in the gate leakage current, can be caused from electron trapping after driving in saturation or hole trapping after driving near breakdown. Self-heating, usually modeled by a thermal resistance ( $R_{th}$ ) and capacitance ( $C_{th}$ ), is an issue for these devices often leading to current collapse, a reduction in output power, and a limitation in the operating frequency.

For the reasons previously discussed, GaN is usually found in high power pulsed applications. Since device characterization should be performed under realistic operating conditions, it is essential to use pulsed IV, pulsed S-parameters, and pulsed load-pull techniques to obtain accurate and meaningful results.

Maury Microwave offers turnkey pulsed-bias harmonic load pull systems designed specifically for wide band-gap transistor and amplifier designers (Figure 1).

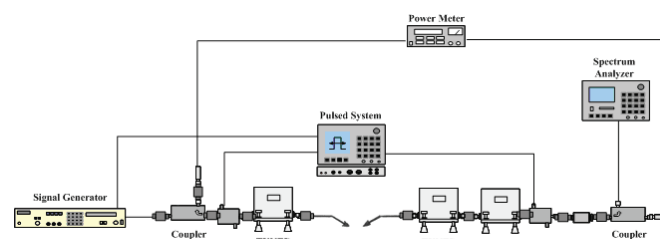


Figure 1. Pulsed-IV Pulsed RF Harmonic Load Pull System

## II. Pulsed Measurements

Current-voltage (IV) measurements are used to describe the relationship between the input and output currents and voltages of a device. Standard GaN Field Effect Transistors (FETs) are characterized by measuring the output current as a function of output voltage for swept input voltages. Because GaN devices tend to self-heat and are susceptible to trapping effects, it is important to pulse voltages between a quiescent and hot value and define appropriate pulse-widths. Pulsing the voltage will result in a lower average power being delivered to the device



and reduced self-heating. Such a measurement allows for near-isothermal performance.

During device characterization, it is important to test a variety of pulsing condition to find a suitable testing environment. If the pulse duration is too long, the device will experience temperature swings which defeat the purpose of pulsed testing. If the pulse duration is too short, any initial “ringing” in the pulse will affect the measurement accuracy. In most cases, a range of suitable pulses can be determined. Typical values include pulse widths of 200nS-1mS, duty cycles between 0.001%-10%, voltages and currents up to 200V and 30A. The result is a more stable current reading as voltage increases, without the normal drop we see in high-power devices at high voltages caused by self-heating [1]. A comparison of DC- and Pulsed-IV curves can be seen in Figure 2.

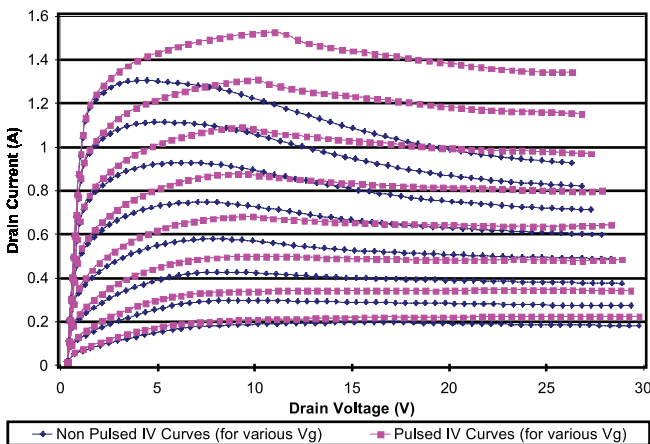


Figure 2. Comparison of DC- and Pulsed-IV Curves

### III. Pulsed-Bias Load Pull

Load pull consists of varying or “pulling” the load impedance seen by a device-under-test (DUT) while measuring the performance of the DUT. Source pull is the same as load pull except that the source impedance is changed instead of the load impedance. Load and source pull is used to measure a DUT under actual operating conditions. This method is important for large signal, nonlinear devices where the operating parameters may change with power level or impedance [2].

Load pull results are taken as a function of power, bias and impedance, among other things; therefore changing any one of these will affect the measurement results. Because the device will operate differently under DC and pulsed- bias

conditions, a difference in load pull contours is expected. Since commercial and military pulsed applications are being considered, the load pull setup and results should perfectly describe the application.

Notice the ideal impedance range on the source-pull contour shown in Figures 3(a) and 3(b).

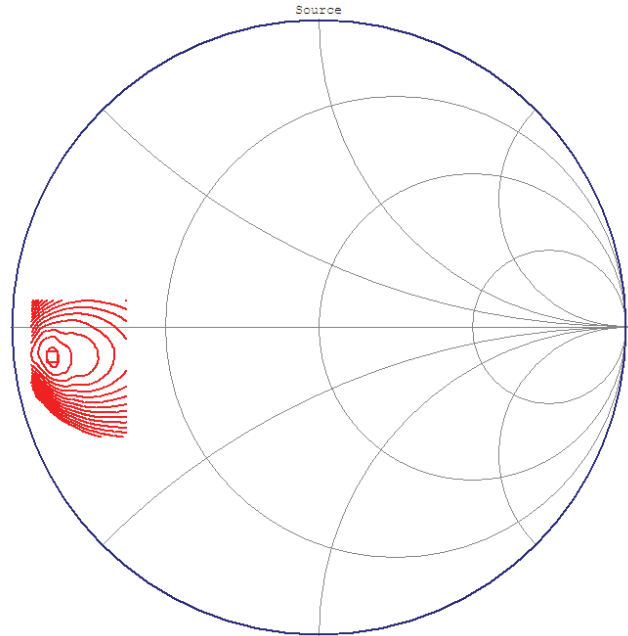


Figure 3a. Pulsed Source Pull Contour

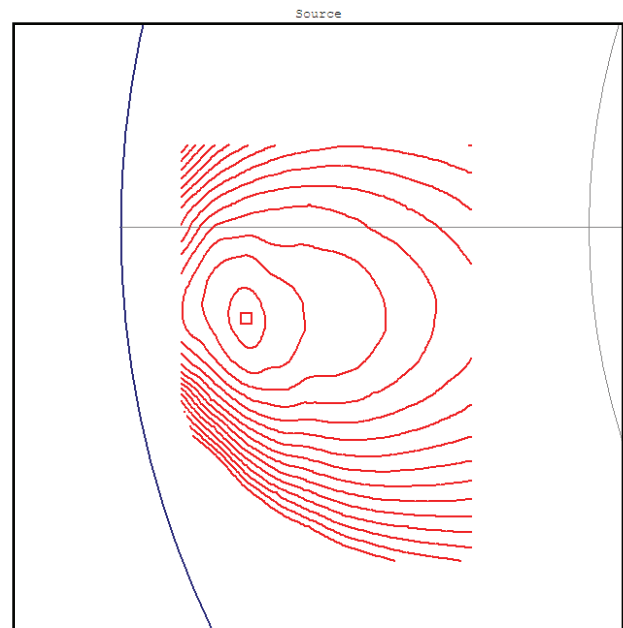


Figure 3b. Pulsed Source Pull Contour (zoomed area)



Many higher-power GaN devices have source impedances around or below  $1\text{-}3\Omega$  because of their large peripheries. Achieving these impedances at the DUT reference plane (taking into account the losses of a fixture, adapters, cabling, probes...) requires a tuner, or a combination of tuners, capable of presenting a VSWR in the range of 100:1 – 200:1. Load matching requirements are not as high due to the output geometry of the device designed specifically for higher current operation, and a 15:1 – 20:1 VSWR is often enough to meet matching requirements, as shown in Figure 4.

Harmonic load pull consists of tuning the source and/or load impedance at a harmonic frequency while

maintaining the impedance at  $F_0$  and measuring device performance. Harmonic load pull tends to greatly influence device efficiency and linearity, and in cases can lead to efficiency improvements of 15 – 20%. With specific regards to GaN, harmonic load tuning at  $2F_0$  is extremely important when dealing with high-power amplifiers. The following is an example of a 10W-linear power GaN device operating under compression at 25W where the fundamental impedance was kept constant at  $Z_{F_0} = 3\Omega$  and the second harmonic impedance  $Z_{2F_0}$  was swept across the entire Smith Chart. A variation of ~25% drain efficiency was observed while tuning  $2F_0$ , as shown in Figure 5.

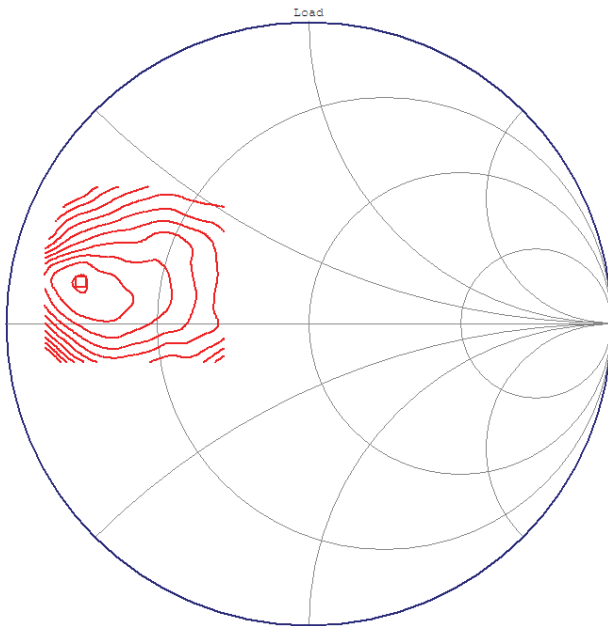


Figure 4. Pulsed Load Pull Contour

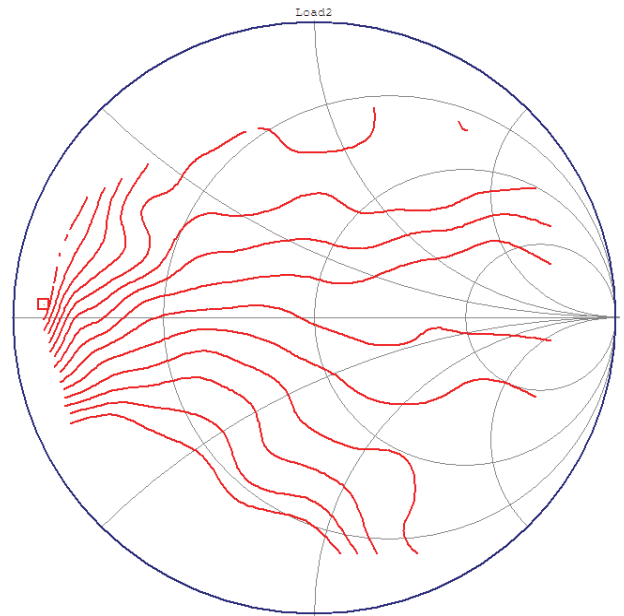


Figure 5. Drain Efficiency as a Function of  $2F_0$



## IV. Pulsed-Bias Considerations

It is important to properly consider the components and instruments that go into a pulsed-bias load pull measurement setup.

First, bias-tees must be properly defined for pulsed applications. Standard bias-tees make use of inductors that can influence the pulse performance, causing a delay in the rise and fall of the pulse, a “rounding off” of the square pulse. This can be overcome by using bias-tees with fast rise-time created specifically for pulsed applications, or using the back-to-back hybrid-coupler approach.

The selection of power meters is quite important when considering pulsed applications with very low duty cycles. Because the average power of a 1% duty cycle might be extremely low, a standard CW power meter with accuracy of 1% might introduce unwanted errors. It is therefore recommended to use a peak power meter designed specifically for pulsed applications.

Standard sequencing normally dictates that the bias of a device is turned on before the RF power is introduced. It is therefore important to consider the triggering of external instruments and the sequence in which each is engaged. Maury’s solution makes use of the triggering that is native to the pulsed-IV controller to trigger both the signal generator and power meter for accurate and reliable results.

## V. Pulsed-Bias X-Parameter Model

Traditionally, S-parameters are used to measure the complex magnitude and phase relationship between small signals at the same frequency at different ports, but don’t account for additional spectral components generated by the DUT under large-signals, or the interaction among different frequency signals incident on a device whose state is time-varying due to large-signal stimuli. X-parameters include harmonics and intermodulation frequency components, and also the relationships between all those frequencies for a given drive amplitude and frequency, enabling the complete waveforms – including those corresponding to strongly compressed conditions – to be measured at the device terminals [3]. Recent advances allow X-Parameters to be taken with various bias settings and load impedances. As such, the device model relies heavily on biasing, and pulsed-biasing plays an essential role in proper amplifier performance as discussed. The resulting load-dependent pulsed-bias X-Parameter file can be imported directly into circuit simulation software such as Agilent ADS. A pulsed-bias load dependent X-Parameter measurement system is shown in Figure 6.

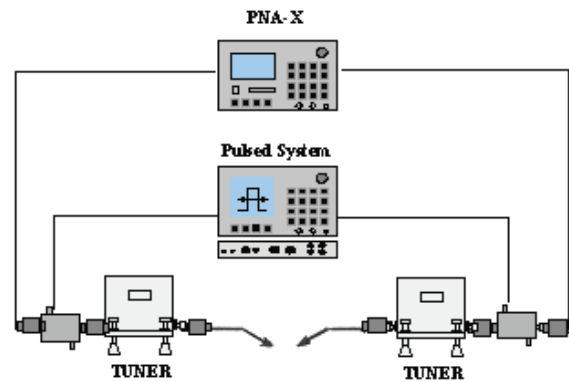


Figure 6. Pulsed-Bias X-Parameter Setup

## VI. Conclusion

Maury Microwave Corporation offers solutions tailored for all pulsed applications including the study and design of gallium nitride transistors and amplifiers for commercial and military applications. Turnkey systems include Maury-manufactured High-Gamma Tuners™ for sub-1Ω source pull, cascaded wideband tuners for harmonic load pull and ATS software for automated on-wafer measurements. Channel partners complete the systems by supplying state-of-the-art industry-proven pulsed-IV measurements systems, network analyzers, power meters, thermal infrared microscopes, probe stations and associated components.

## Acknowledgement

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## References

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