Beyond Fundamental Load Pull: Unlocking Next-Generation Device Performance Through Harmonic Control

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Abstract

For engineers characterizing next-generation RF/microwave devices, the central question is not simply which fundamental load maximizes performance, but how that optimum changes with harmonic termination. Continued advances in compound semiconductor technologies, particularly GaN and other wide-bandgap materials, increase the demands on characterization as frequency, power density, and efficiency requirements rise. Fundamental-frequency load pull remains essential, but alone it cannot fully reveal nonlinear behavior, harmonic interactions, or the optimum operating conditions.

A fundamental load-pull optimum is conditional on the harmonic terminations present during the measurement. For nonlinear power amplifiers, those terminations affect drain or collector waveforms, voltage-current overlap, dissipation, output power, gain, and distortion. The practical question is whether the selected fundamental load remains useful when harmonic impedances are deliberately varied and the resulting combination is translated into a realizable matching network.

Harmonic load pull involves the controlled termination of the device at frequencies such as $2f_0$ and $3f_0$, making it possible to analyze the effects of harmonic interactions on device performance. The Maury Microwave multi-harmonic tuners enable impedance control at several frequencies through the use of multiple tuning carriages within a slide-screw tuner. This paper discusses the application and limitations of harmonic tuning for nonlinear device characterization, as well as how Maury multi-carriage tuners can support a disciplined characterization workflow.

What Fundamental Load Pull Leaves Out

Under nonlinear excitation at a fundamental frequency f_0, the drain or collector current and voltage can contain components at f_0, $2f_0$, $3f_0$, and higher harmonics. For periodic steady-state operation, these waveforms can be represented by a DC component and a Fourier series of harmonic components:

$$V(t) = V_0 + \sum_{n=1}^{\infty} V_n \cos(n\omega_0 t + \varphi_{\vartheta,n}) \qquad \textit{Equation 1}$$

$$I(t) = I_0 + \sum_{n=1}^{\infty} I_n \cos(n\omega_0 t + \varphi_{i,n}) \qquad \textit{Equation 2}$$

At each frequency, the load influences the harmonic components of the voltage and current waveforms at the device plane. Load pull at the fundamental frequency changes the impedance $Z_L(f_0)$ and measures the device performance in terms of its output power, gain, drain efficiency, or power-added efficiency (PAE). However, for nonlinear power transistors, the fundamental frequency impedance $Z_L(f_0)$ is not the only impedance experienced. Harmonic currents experience impedances $Z_L(2f_0)$, $Z_L(3f_0)$, and so on, as seen in Figure 1.

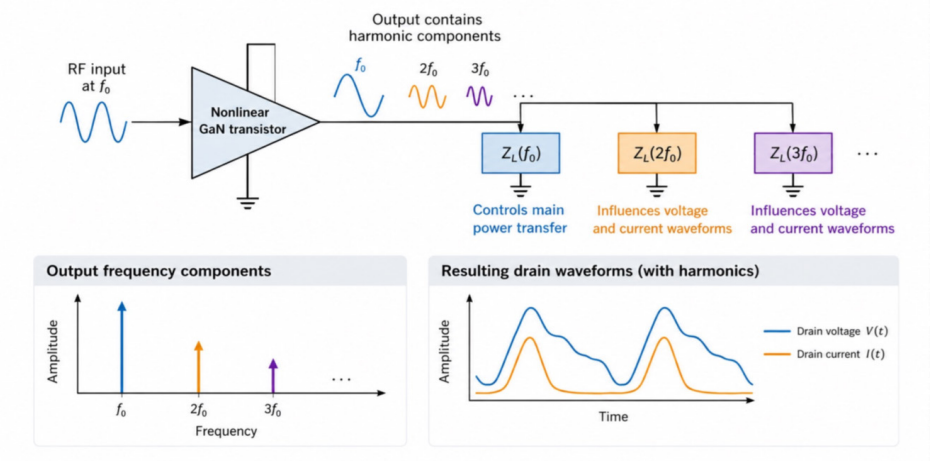


Figure 1: Effects of fundamental and harmonic load impedances on a GaN transistor.

For a near-linear device, higher-frequency termination may not have much effect. However, in the case of a nonlinear power transistor, harmonic components may affect the waveform substantially. Designing based solely on the optimum fundamental-frequency impedance can result in missing important operating regions or selecting an optimum point that cannot be achieved with a practical matching network.

Harmonic load pull involves varying the impedance at one or more harmonic frequencies and measuring the same performance metrics. Harmonic load pull can be described as an extension of traditional fundamental load pull in which both fundamental and harmonic impedances are controlled. To understand how harmonic terminations affect device performance, let's first consider waveform shaping and voltage-current overlap (Figure 2).

The instantaneous power at the transistor is:

$$P(t) = V(t) * I(t) \qquad \textit{Equation 3}$$

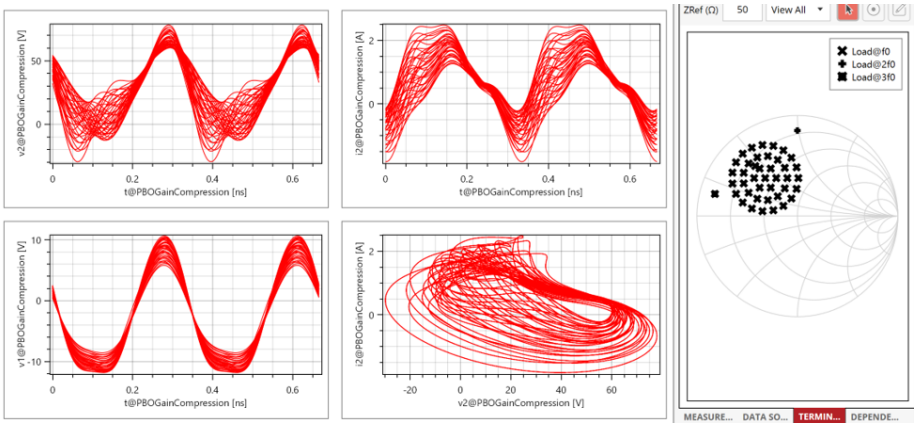


Figure 2: Comparison of drain voltage and current waveforms under different harmonic termination conditions.

The average power delivered by the supply is divided among RF output power, losses, and other energy flows. In a simplified saturated power amplifier, efficiency improves when the voltage and current waveforms overlap less during the active part of the RF cycle. Harmonic impedances influence that overlap by setting the amplitude and phase of voltage and current harmonics. The fundamental load sets the main voltage swing and power transfer, while harmonic loads can reshape the peaks, shoulders, and zero-crossing regions of the waveforms.

The second harmonic is often a practical starting point because it can produce a meaningful waveform change without requiring control of many higher-order components. Third-harmonic control can add further freedom.

Output Efficiency and Power

Drain efficiency is commonly defined as:

$$\eta_D = \frac{P_{RF,out}}{P_{DC}} \qquad \textit{Equation 4}$$

while PAE includes the RF input power:

$$PAE = \frac{P_{RF,out} - P_{RF,in}}{P_{DC}} \qquad \textit{Equation 5}$$

Changing harmonic terminations can improve efficiency by reducing voltage-current overlap, or reduce it by increasing device dissipation or power dissipated in the surrounding network. Electrical stress is a separate operating constraint. A high-efficiency state is useful only if it also meets the required output power, gain, and linearity targets, so these quantities must be evaluated together.

Gain and Gain Compression

At a specified RF input drive level, harmonic terminations can change the fundamental-frequency voltage and current components and therefore alter output power and gain. The direction of the change depends on the device and operating conditions: gain may increase, remain approximately constant, or decrease. Any efficiency or output-power benefit must therefore be evaluated alongside gain and gain compression, rather than treated as a guaranteed improvement.

It is for this reason harmonic load-pull measurements must record multiple parameters over the same impedance search. Parameters include output power, gain, drain efficiency, PAE, and even linearity parameters such as adjacent-channel power ratio (ACPR) or error-vector magnitude (EVM), which can be measured if a device is driven under modulated signals. Optimal values for one parameter may not necessarily be optimal for others.

Figure 3 illustrates the harmonic and intermodulation distortion components associated with device compression.

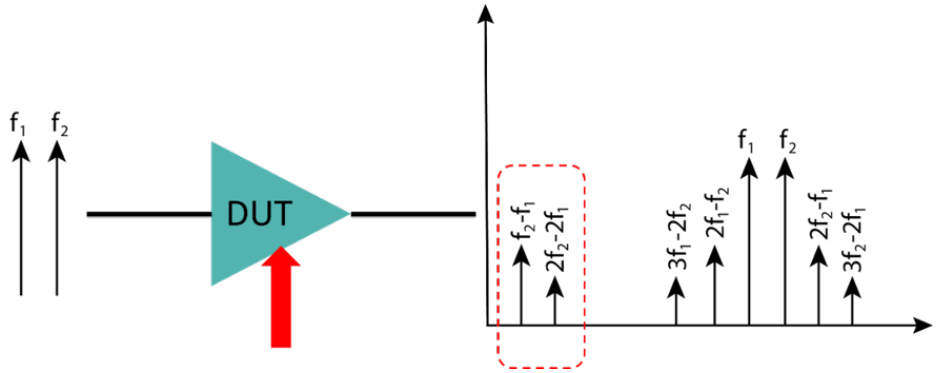


Figure 3: Diagram relating harmonic and intermodulation spectral components as a result of device compression.

Linearity and Spectral Behavior

Harmonic terminations can improve or worsen spectral regrowth and distortion, depending on the device architecture and signal conditions. Different metrics may favor different impedance regions (Figure 4), so a CW optimum cannot by itself establish modulated-signal performance. Verify the selected impedance combination using the intended waveform, bias, thermal conditions, and operating back-off. For this validation, the Maury MT2000 supports modulated-signal characterization and wideband impedance control up to 2 GHz.

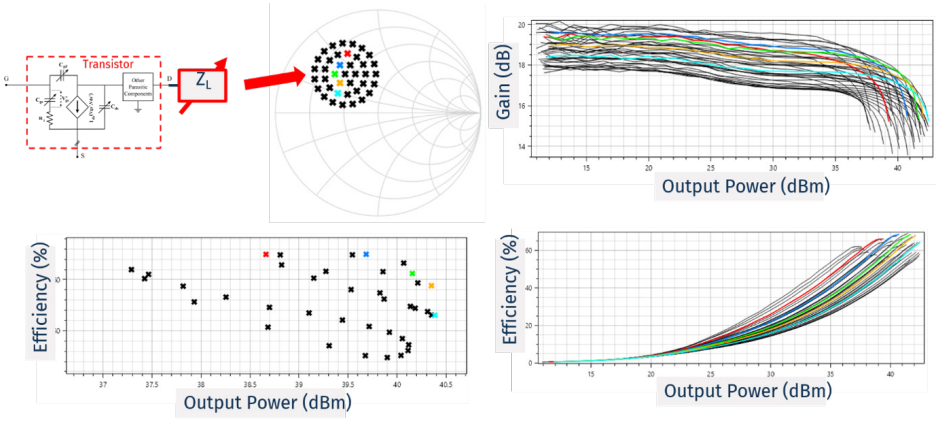


Figure 4: Different optimum impedance regions of output power, gain, drain efficiency, and PAE.

Multi-Carriage Harmonic Tuners

The measurement challenge is to vary harmonic terminations while preserving a known fundamental load at the device plane. Multi-carriage harmonic tuners provide additional mechanical degrees of freedom for this multi-frequency impedance search, using passive slide-screw tuning in a common RF path.

A passive slide-screw tuner presents a controllable impedance by perturbing the electromagnetic field in a slabline. Probe depth primarily controls reflection magnitude, while longitudinal position controls reflection phase. The structure of a Maury harmonic tuner (Figure 5) uses multiple motor-driven carriages for multi-frequency tuning. Each carriage contains probes covering segments of the operating frequency range; the selected probe responses combine to determine the impedances presented at the fundamental and harmonic frequencies.

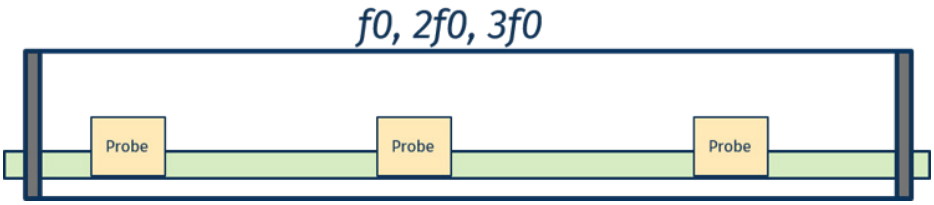


Figure 5: The Maury multi-carriage harmonic tuner architecture.

A multi-carriage setup enables tuning of controlled impedances at multiple frequencies in the same RF path. Those frequencies are generally fundamental (f_0) and one or more harmonics of f_0 in the case of harmonic load pull. Additional adjustable degrees of freedom are provided by carriages, although the impedance at each frequency is determined by the combination of all carriages. The tuner must first be characterized by a VNA so that the control software can calculate carriage positions required to provide the desired impedances at selected frequencies.

A carriage position is a mechanical setting, not a harmonic impedance specification. Tuner characterization establishes the frequency-dependent electrical response of each combined carriage state; measurement-system calibration and de-embedding then establish the impedances presented at the chosen device reference plane.

Frequency Coverage and Tuning Range

A three-carriage tuner may offer greater frequency-tuning configurability than a tuner with fewer carriages. However, it does not ensure that every combination of $\Gamma(f_0)$, $\Gamma(2f_0)$, and $\Gamma(3f_0)$ with an equal reflection magnitude value will be accessible. Configurability depends on tuner model, operating frequency, losses, probe configuration, reference plane, and the configured combination of impedances.

For example, the Maury XT982ML03 (Figure 6) has a frequency range of 0.6 to 18 GHz for both fundamental and harmonic frequencies. Depending on frequency and configuration, matching ranges include SWR of 100:1 for single-frequency tuning at the lower end as well as 10:1–100:1 for two- and three-frequency tuning. Other specifications include 50 W CW and 0.5 kW peak-envelope-power capacity at maximum VSWR, and up to 1.0 dB insertion loss with probes fully retracted. These specifications are model-specific and should not be interpreted as the general limits of harmonic tuners.

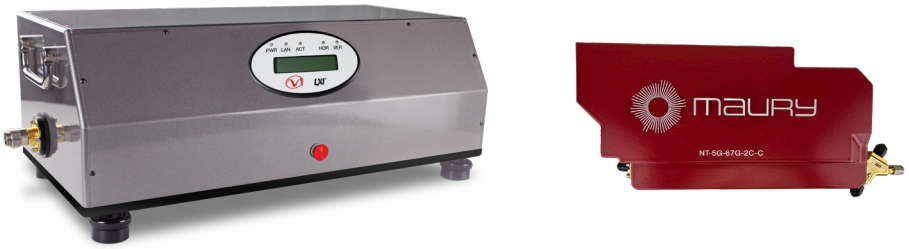


Figure 6: The Maury XT982ML03 and NT-5G-67G multi-harmonic automated tuners.

Harmonic Load Pull Workflow

Define the Device Plane and Measurement Objectives

Begin by selecting the device, packaged/wafer type, biasing, frequency, drive level, and performance targets. Then, establish the reference plane from which impedances will be measured, typically the device package plane or probe tips. Cabling, fixture, bias tee, and interconnect losses can significantly affect impedance and power. Calibration and de-embedding should put the impedances at the reference plane.

Next, determine which frequency components need to be controlled. For a typical characterization, one might start with f_0 and $2f_0$ and later possibly add $3f_0$ if there is justification based on the device harmonic power and waveform-shaping goals. It must be ensured that the tuner, couplers, bias network, and measurement receiver are adequate for those frequencies (Figure 7).

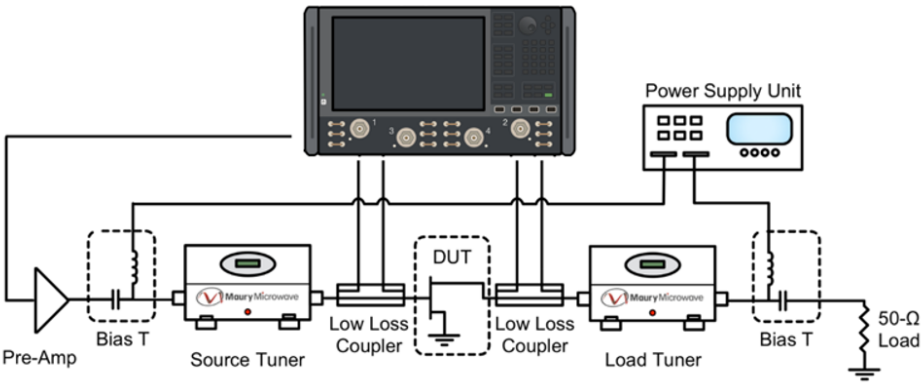
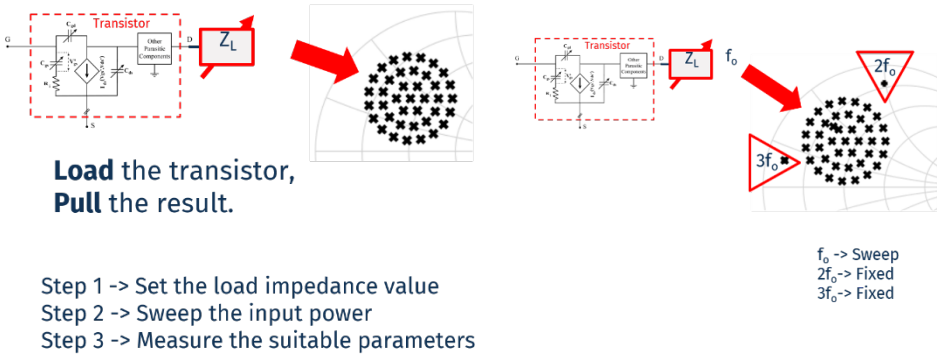


Figure 7: Diagram of a harmonic load pull setup.

Characterize and Verify Tuner States

The tuner must be characterized over the desired frequency range such that carriage positions yield the required impedance values at the device plane. Tuner states required for measurements should be verified through the measurement system, with repeatability confirmed prior to device characterization. If interface cables, fixture, or bias tees are changed, calibration must be re-verified at the reference plane. Figure 8 illustrates a typical search process, beginning with a fundamental-frequency load search and followed by a second-harmonic impedance sweep.



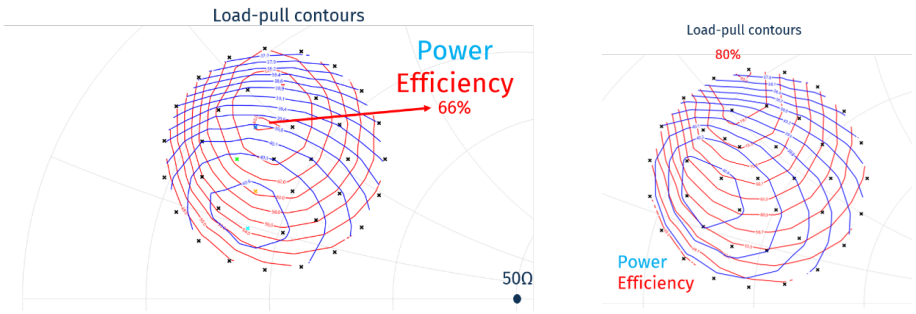


Figure 8. Fundamental load search and second-harmonic sweep.

Search Efficiently

An efficient search usually proceeds in stages as follows:

1. Find a promising fundamental-frequency load point under the required bias and RF drive conditions, and record the harmonic terminations present during that baseline search.
2. Sweep the second-harmonic impedance while maintaining and verifying the selected fundamental-frequency impedance at the device plane; record the other harmonic terminations for each state.
3. Measure output power, gain, efficiency, and any linearity metrics.
4. Repeat the harmonic sweep at several promising fundamental load points, then revisit the fundamental search under the selected harmonic terminations to determine whether the preferred ZL(f_0) changes with ZL($2f_0$).
5. Add third-harmonic tuning where needed and map only the reachable impedance combinations.
6. Repeat measurements at promising states to verify repeatability and thermal stability.

A full Cartesian sweep over all carriage states may prove inefficient. Contour searches, coarse-to-finer sweeps, and optimization techniques can help reduce measurement time, provided they preserve coverage to reveal multiple local optima and tradeoffs.

Distinguish Measured Behavior from an Assumed Operating Class

The measured device may not be operating in an ideal textbook class due to parasitic effects of the package, nonlinear capacitance, finite harmonic content, dispersion, and losses (Figure 9). Treat the impedance contours as the measured results and explain through waveform or nonlinear models the cause for a particular region's behavior.

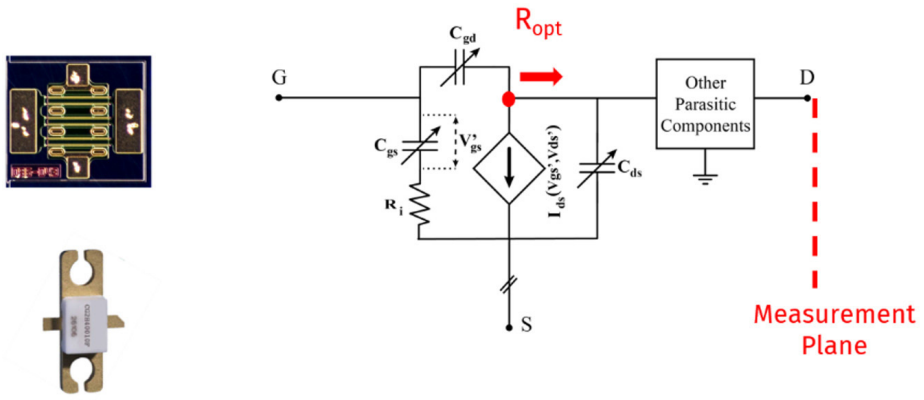


Figure 9. Device parasitic effects between the intrinsic transistor and measurement plane.

Practical Considerations and Limitations of Harmonic Load Pull

Losses, Power Handling, and Compression

Passive tuner and fixture losses limit the reflection coefficients achievable at the device plane and must be included when referring power measurements to that plane. Source-path loss reduces available RF drive, while output-path loss separates device-plane output power from power measured farther along the load path. Electrical stress and thermal effects can also change device behavior. Keep the tuner and all interposed components within their model-specific operating limits, especially at high mismatch, and measure or control bias and temperature under the intended pulsed measurement conditions.

Harmonic Power is Not Always the Objective

Low net power at a harmonic does not, by itself, establish that its termination is irrelevant to waveform shaping; the harmonic voltage and current components must also be considered. Conversely, observing harmonic power does not establish that its termination improves device performance. The engineering objective is useful fundamental-frequency output with the required efficiency, gain, and linearity, not maximum harmonic output power.

For a broadband amplifier, harmonic targets cannot be chosen independently of the required fundamental-frequency response across the band. A harmonic of a lower-band operating frequency may fall within the amplifier's fundamental operating band, where an open- or short-like termination can conflict with the required power transfer. Harmonic load-pull results therefore need to be evaluated as a set of realizable broadband matching requirements, not only as optimum impedances at one carrier frequency.

Beyond Fundamental Load Pull

The outcome of harmonic load pull is not a universally better load point, but a measured set of fundamental and harmonic impedance combinations that meet the required output power, gain, efficiency, and linearity targets. The useful question is whether controlling the terminations at $2f_0$, $3f_0$, and higher frequencies reveals operating regions that a fundamental-only search would miss, and whether those regions can be realized in the output network.

Multi-carriage tuners help answer this question by enabling automated tuning of passive terminations at several frequencies via a slide-screw structure characterization. The importance of these devices is in their ability to make controlled comparisons between harmonic and fundamental termination states.

The design handoff is a set of repeatable, reachable impedance combinations with their measured output power, gain, efficiency, and linearity, all referred to a stated device plane and operating condition. Select a usable region rather than relying only on the best laboratory point, and evaluate that region against tuner and fixture losses, power limits, calibration, and practical output-network realization. The workflow identifies what must be demonstrated; the benefit for a particular device must be established by its measurement results.

References

1. Maury Microwave. *A Beginner's Guide to All Things Load Pull, or Impedance Tuning 101* (Application Note 5A-062).
2. Maury Microwave. *Understanding the Relevance of Harmonic Impedance Matching in Amplifier Design* (Application Note 5A-060).
3. Maury Microwave. *XT981-571 Automated Tuner User Guide*.
4. Maury Microwave, *Automated Impedance Tuner Multi-Harmonic Datasheet*.
5. Maury Microwave, *Device Characterization with Harmonic Source and Load Pull* (Application Note 5C-044).

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