INVITED PAPER

On-Wafer, Large-Signal Transistor Characterization from 70–110 GHz Using an Optimized Load-Pull Technique

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The ability to benchmark the performance of semiconductor technologies using small periphery devices, quickly and accurately, can reduce development cost and expedite time to market. This can now be achieved using hybrid-active vector receiver load-pull measurements that enable E- and W-Band device characterization up to gamma magnitudes of 1 at the device-under-test (DUT) reference plane.

Much of the next generation of wireless technologies for mobile, satellite, automotive and radiolocation are being designed to operate in the upper mmWave bands of 70 to 110 GHz. For mobile and satellite, this means 10× to 100× more available unlicensed spectrum compared to the sub-10 GHz bands, leading to increased data bandwidth, transmission rate and data throughput. For automotive applications and radiolocation, mmWave frequencies provide higher imaging resolution and improved intra- and inter-vehicle communications. This enables applications such as automotive radar, collision avoidance and traffic information exchange between vehicles.

Designing solutions to work effectively and efficiently in these frequency bands is not a simple task. It is especially challenging to design mmWave circuitry, such as transmitters and receivers, which include amplifiers to boost signal power levels. Active components are critical to achieving the required performance. Some of the biggest challenges to overcome are the low gain, output power and efficiency of transistors at these frequencies. To address these limitations, multiple technologies have been developed (see ***Table 1***). While these semiconductor technologies offer good performance for applications in the 20 to 40 GHz range,[5] i.e., the 5G FR2 range, transistor performance

TABLE 1
TRANSISTOR TECHNOLOGY MMWAVE PERFORMANCE

Technology	fmax (GHz)	Frequency (GHz)	Power-Added Efficiency (%)	Power (dBm)	Reference
InP HBT	580	76	26.9	26.4	1
SiGe HBT	360	76	12.4	27.3	2
CMOS SOI	410	77	18	19.6	3
GaN HEMT	400	76	10	32.4	4

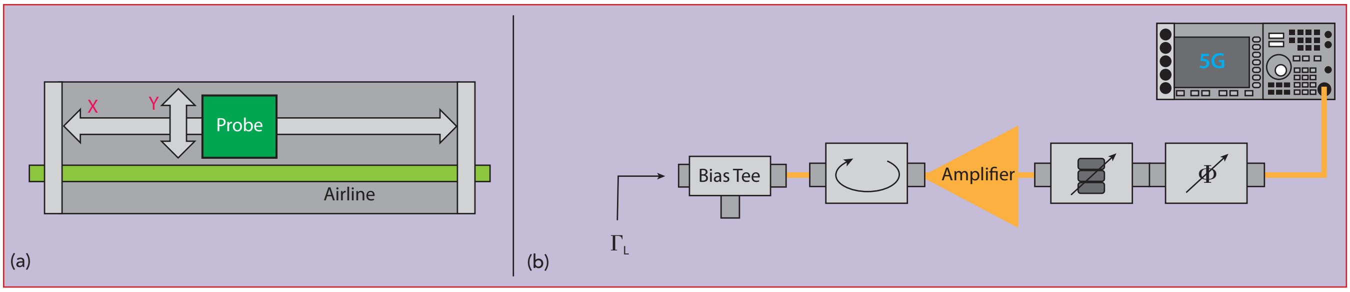


Fig. 1 **Mechanical tuner (a) and active loop (b) load-pull measurement.**

drops as frequency increases, limiting their use for applications over 70 GHz. This is due to the device parasitics becoming significant at E- and W-Bands. The cutoff frequency (f_t) of a device should ideally be about 10× the target operating frequency for the device not to become one of the major limiting factors in a high efficiency power amplifier design. So it is critical to optimize the circuit design to squeeze out every last tenth of a dB of gain, dBm of output power and percent of efficiency.

Optimal circuit design can only be realized with accurate device models or fully characterized transistors. While a robust mmWave device model is often available for a mature device technology, newer modeling approaches can use accurate device reference plane measurements to develop device models for less mature technologies.[6] mmWave device models based on neural networks, for example, may offer an advantage compared to the current modeling paradigm.

Load-pull, the technique of systematically varying the reflection coefficient (Γ_L) at the output of a DUT and measuring changes in its performance, is a practical method for extracting and validating models and for performing small- and large-signal device characterization.

A common consideration when performing load-pull at E- and W-Band is choosing the size of device to characterize. Performing load-pull on devices with small peripheries—less than four fingers—results in lower fabrication costs and time and contributes to faster time to market and higher profitability.[7] The small periphery, however, usually has high device S_{11} and S_{22}. This makes characterization challenging because $\Gamma_L > 0.9$ at the DUT reference plane is required to fully characterize the device. Conventional tuner-based load-pull setups struggle to achieve $\Gamma_L = 0.7$ at the DUT reference plane, limited by high insertion loss of the RF probes connecting the test system to the DUT. As such, designers tend to fabricate larger devices with more than four fingers[8] or include pre-matching circuitry[9] to lower the Γ_L required to characterize DUTs. This, however, increases fabrication cost and time, which can delay technology development and time to market.

Recent advances in measurement technology and instrumentation have enabled hybrid-active vector receiver load-pull for high-power, mmWave device characterization, including the 70 to 110 GHz bands discussed here.

HYBRID-ACTIVE LOAD-PULL

Consider a two-port network where the waves incident to and reflected by the network are denoted as a_x and b_x, respectively, where x denotes the network port. This network has an input reflection coefficient $\Gamma_{in} = b_1/a_1$ and a load reflection coefficient defined as $\Gamma_L = a_2/b_2$. Load-pull characterization enables the user to systematically vary Γ_L presented to the DUT while measuring a multitude of device parameters versus drive power at each impedance state. Passive load-pull[10] uses mechanical impedance tuners to change the magnitude and phase of the reflected signal a_2 and vary the Γ_L presented to the DUT. This is accomplished by moving a probe up, down, left and right along a 50 Ω airline (see ***Figure 1a***). $|\Gamma_L|$ will always be < 1, since a_2 will always be smaller due to losses between the output of the DUT and the tuner. Open-loop active load-pull systems[10] do not rely on a mechanical tuner to reflect part of b_2 back as a_2. Instead, they use active signal injection with magnitude and phase control to create a new signal a_2 (see ***Figure 1b***). When amplified by an external amplifier, any a_2 and any Γ_L can be achieved.

Active tuning has several advantages over passive tuning, including faster speed and increased coverage of the Smith chart. This is because there are no mechanical moving parts, and the actively generated a_2 wave can be used to set $|\Gamma_L| > 1$. The challenge with active tuning is the availability of driver amplifiers to boost the a_2 signal. Typically, they are required to have 5× to 10× higher output power than the DUT due to the mismatch between the DUT output impedance and the nominal 50 Ω impedance of the driver amplifier. A modified approach, hybrid-active load-pull, overcomes this challenge by pre-matching the DUT impedance with a passive impedance tuner, which lowers the driver amplifier output power required to deliver the same signal a_2 to the output of the DUT (see ***Figure 2***).

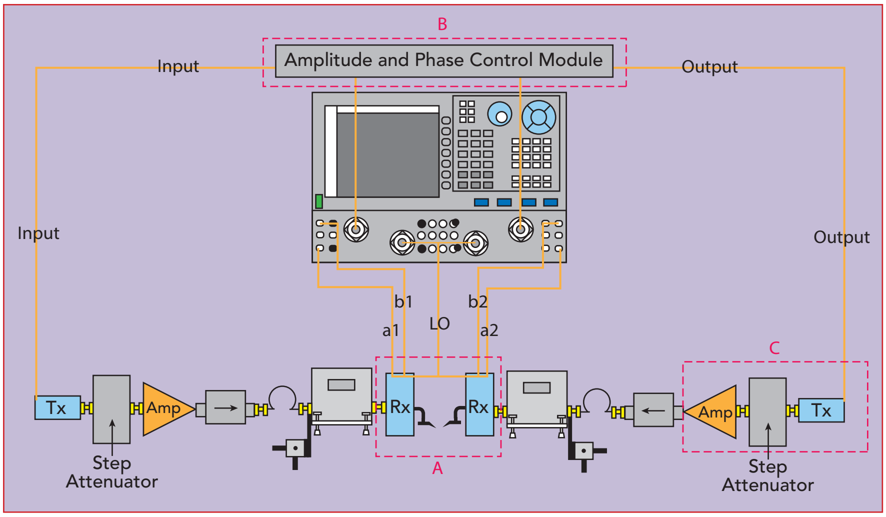
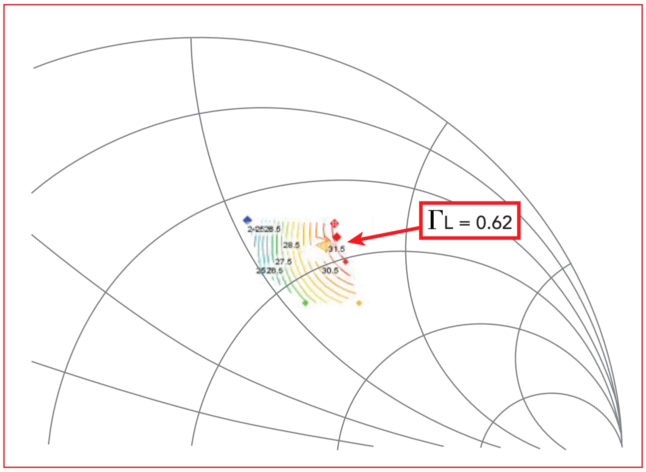


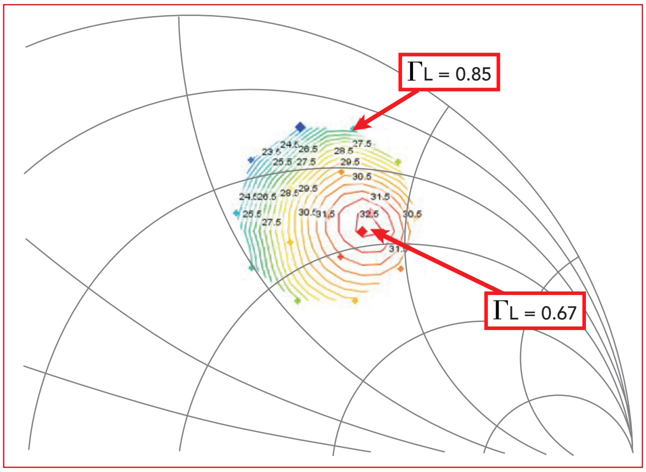
Fig. 2 W-Band hybrid-active load-pull measurement system.

To date, active and hybrid-active load-pull have been limited to coaxial measurements in commercially available systems because of the impracticality of measuring and controlling the magnitudes and phases of the a and b waves using waveguide frequency extenders. To overcome this limitation, Maury Microwave has introduced custom low-loss couplers with integrated down-conversion (see block A in Figure 2), which extend VNA-based load-pull measurements to 110 GHz, and a source control unit (see block B in Figure 2) enables accurate amplitude and phase control to 110 GHz. The custom couplers enable direct a and b wave measurements at the vector calibrated DUT reference plane, increasing system measurement accuracy and providing critical device performance—output power, power gain, input Γ and power-added efficiency (PAE)—for each input power level and load impedance state. The amplitude and phase controller with the frequency multiplier and step attenuator on the load loop (see block C in Figure 2) enable 0.01 dB magnitude and 0.1 degree phase control of the a_2 wave.

This hybrid-active load-pull solution enables W-Band VNA-based load-pull measurements, reaching $|\Gamma_L| = 1$ at the probe tip reference plane for DUTs with output power on the order of 1 to 2 W. These



▲ Fig. 3 **Device drain efficiency measured using a traditional load-pull setup, showing a maximum drain efficiency of 31.5 percent at 75 GHz. The traditional setup can't obtain closed contours.**



▲ Fig. 4 **Device drain efficiency measured using a hybrid-active load-pull setup, which provides closed contours. At 2 dB compression, the maximum drain efficiency is 32.5 percent at 75 GHz.**

capabilities enable measurements of highly mismatched devices previously impossible to characterize due to system limitations. The implementation of active load-pull using waveguide frequency extenders is possible up to 1.1 THz, frequencies where commercial automated impedance tuners are unavailable or impractical.[11]

DEVICE MEASUREMENTS

To demonstrate this solution, a small periphery, two finger, GaN HEMT was characterized at 75 GHz using passive and hybrid-active load-pull systems. A traditional waveguide passive load-pull system could only achieve a maximum $|\Gamma_L| <$ 0.62. Without closed contours (see ***Figure 3***), the best device performance may be missed, leading to incorrect conclusions about the optimum DUT impedances. As noted, this is problematic when characterizing small periphery active devices, where the output impedance is typically close to the edge of the Smith chart. The same device PAE characterization using a hybrid-active load-pull system is shown in ***Figure 4***. Much higher magnitude Γ_L is achieved at the DUT reference plane, enabling closed contours and providing confidence the correct load impedances are identified to maximize DUT performance.

Other benefits of hybrid-active vector receiver load-pull include real-time measurements of the a and b waves at the input and output of the DUT, which enable characterizing power gain variation and input reflection coefficient versus available input power and load impedance. ***Figure 5*** shows the measured gain variation with load impedance of the GaN HEMT. The characterization of input impedance variation is important when optimizing the power gain at a particular DUT input power level, to optimize the design of the input and output matching networks. Due to the low device gain at these frequencies, designers must consider the tradeoffs among power gain, drain efficiency, PAE and output power.

CONCLUSION

During the initial stages of device technology development, timely feedback to device develop-

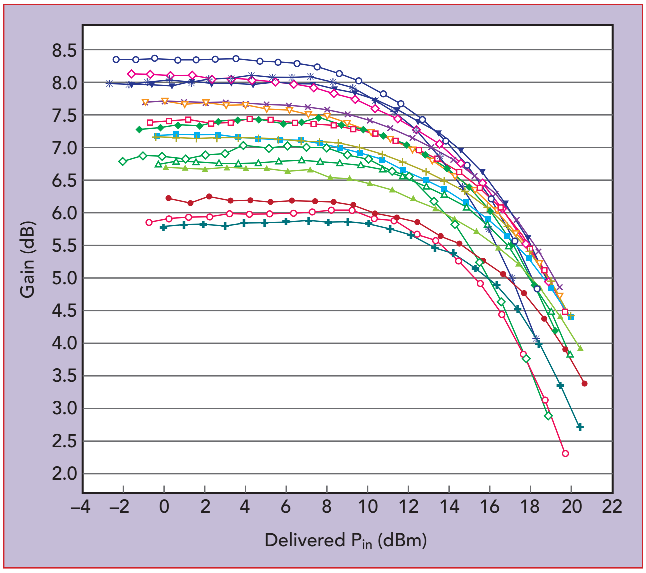


Fig. 5 **GaN HEMT power gain vs. load impedance measured with the hybrid-active vector-receiver load-pull system.**

ment engineers is important to accelerate the development process. Quickly and accurately benchmarking the performance of various semiconductor technologies using small periphery devices contributes to reducing development costs and expediting time to market. This can be achieved using hybrid-active vector receiver load-pull systems providing $|\Gamma_L| = 1$ at the DUT reference plane at E- and W-Band frequencies. The measured vector a and b waves enable the characterization of various DUT parameters, such as delivered input power, output power, power gain and PAE that are not normally available from scalar measurements. This enables higher device characterization accuracy, facilitating more accurate device parameter extraction for better model fidelity.■

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