Overcoming the Challenges of Passive On-Wafer Load Pull Measurements at Millimeter Wave Frequencies for 5G Applications.

APPLICATION NOTE / 5A-074

Maury Microwave Inc. — Feburary 2024

Introduction

5G, short for fifth-generation wireless technology, is the latest evolution of mobile network technology that aims to provide faster and more reliable connectivity for mobile devices and other internet-enabled devices. It builds upon the capabilities of previous generations but offers significant improvements in terms of data speeds, latency, and capacity.

Advantages of 5G at millimeter wave frequencies:

- High data speeds: Millimeter wave frequencies, typically in the range of 30 to 300 GHz, can support much higher data transfer rates compared to lower frequencies used in previous wireless generations. This enables faster download and upload speeds, making it possible to download large files and stream high-definition videos with minimal delay.
- Low latency: 5G at millimeter wave frequencies can reduce latency, the time it takes for data to travel between devices and the network. Low latency is crucial for applications that require real-time responsiveness, such as online gaming, virtual reality, and autonomous vehicles.
- Increased capacity: Millimeter wave frequencies provide a broader spectrum for data transmission, allowing for more devices to connect to the network simultaneously without causing congestion. This increased capacity is especially beneficial in densely populated urban areas where large numbers of devices are in use.
- Enhanced user experience: The combination of higher data speeds and lower latency results in a smoother and more responsive user experience. Activities like video conferencing, cloud-based applications, and online gaming can be more enjoyable and seamless.

However, it's important to note that there are also some challenges with millimeter wave frequencies. They have shorter range compared to lower frequencies, and their signals can be more easily blocked by obstacles like buildings and trees. To address this, each element in 5G infrastructure must be optimized for maximum performance. An essential component of the infrastructure necessary to unlock the advantages of 5G millimeter-wave technologies is the power amplifier (PA). The PA's design plays a crucial role in ensuring optimal performance, where the primary goals are to maximize power and efficiency while maintaining appropriate linearity and a small size. During the design phase, PA engineers must carefully consider these expectations. To aid in achieving optimal performance, PA engineers have a valuable tool in their arsenal known as Load Pull.

There are over 3,000 entries on IEEE Xplore regarding load pull at the time of publishing, many of which cover the methodologies and applications of load pull. This solutions brochure will concentrate on a specific type of load pull referred to as passive on-wafer load pull and will concentrate on measurements at 5G FR2 frequencies of 28 GHz and 39 GHz.

The Challenges

There are typically two grand challenges when performing passive on-wafer load pull measurements at millimeter-wave frequencies:

- The tuning range at the device-under-test (DUT) reference plane may be reduced due to the insertion loss of components placed between the automated impedance tuner and the DUT.
- The measured performance of the DUT may be degraded due to the phase skew of the impedances presented to the DUT over the bandwidth of the signal.
- The ability to perform low-temperature measurements with minimum insertion loss without any enclosures to seal the measurement environment and achieve repeatable and accurate probe placement at all temperatures.
- A typical passive on-wafer load pull system with impacted tuning range and phase skew is shown below, and consists of:
- FormFactor Summit 12000 200 mm probe station
- MT984AL01 automated impedance tuner
- MT902-series probe mount (or cable assembly as shown on the output of the DUT)
- FormFactor coaxial Infinity probe
- Positioner and probe arm connected between probe station platen and automated impedance tuner

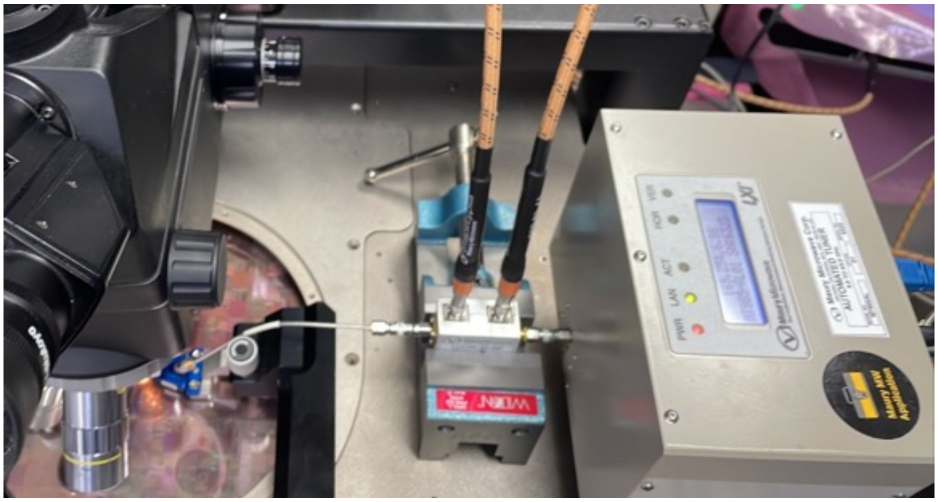

Figure 1: Typical on-wafer setup for load pull at 39 GHz.

We will first introduce the solution, then compare the measurement results of the typical passive on-wafer load pull system pictured above, and the one described in the solution.

The Solution

Maury developed its Nano™ automated impedance tuner series to overcome the challenges of passive on-wafer load pull measurements at millimeter-wave frequencies. The Nano5G™ model was optimized for performance at 5G FR2 frequencies of 28 GHz and 39 GHz, however, it works continuously between 18-50 GHz.

The Nano™ series has been miniaturized using state-of-the-art actuator technology which allows it to be integrated on FormFactor's angled probe arm and connect directly to a probe, thereby eliminating the probe mount, or cable, typically placed between the tuner and DUT. In addition, every component of the tuner was optimized, including the development of low-profile RF connectors. Models are available with integrated low-loss high-directivity couplers, further eliminating sources of insertion loss. The movement of the semi-rigid cables between the coupler and the test equipment (typically a vector network analyzer) is minimized, thanks to a cable management bracket placed on the probe arm.

The engineering probes used to contact the wafer are also a determining factor when performing load-pull measurements. The insertion loss of the FormFactor probes is less than 0.8 dB @40 GHz across multiple probe families – Infinity, InfinityXT, ACP, |Z| probes. For the Infinity and |Z| probes, special attention the probe is designed to have minimum and repeatable contact resistance to ensure that long-duration load-pull measurements are unaffected by tip-to-pad contact variation during the tuning cycle.

The FormFactor IceShield platen insert solution addresses the RF cold measurement load-pull application for which the device under test does not require any enclosure for EMI shielding or light tightness. The positive partial pressure surrounding the wafer creates an airwall and enables frost-free operations down to -60°C. With the IceShield solution the cables between the tuner and the DUT, typically required when utilizing an enclosure, can be avoided, thus minimizing another source of insertion loss.

The repeatability and accuracy of the probe placement at all temperatures is ensured by the Contact Intelligence automation technology, which employs digital-imaging software to automate the realignment process required to synchronize the probe tips with the target pads on the wafer surface.

The Nano5G™ and an integration on common FormFactor probe station configurations are shown in the following images.

Figure 2: Nano5G™ automated impedance tuners with and without integrated low-loss coupler.

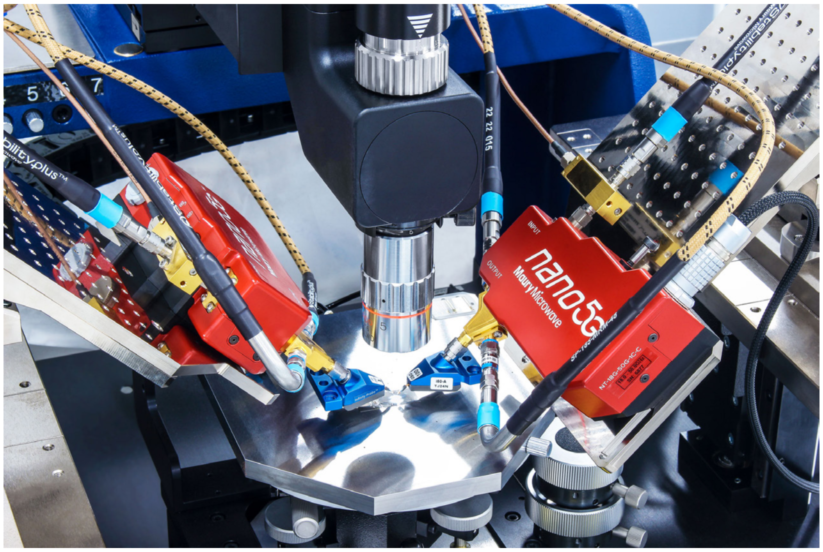

Figure 3: Optimized integration of Nano5G automated impedance tuners on FormFactor manual probe station.

Tuning Range

The tuning range, or the maximum magnitude of reflection that can be presented to a DUT, can be calculated from the formula $RL_{tuner} + RL_{coupler+cable+probe} = RL_{dut}$ where

$$RL_{tuner} = -20Log\left(\frac{VSWR_{tuner}-1}{VSWR_{tuner}+1}\right) \text{ and } RL_{coupler+cable+probe} = 2(IL_{coupler+cable+probe})$$

In the typical on-wafer load pull system pictured above,

- RL tuner = -1.16 dB (VSWR = 15:1, $|\Gamma|$ = ~0.9)
- RLcoupler+cable+probe = -2.4 dB (insertion loss = -1.2 dB)
- RLdut= -3.56 dB (VSWR= ~4.95:1, $|\Gamma|$ = ~066)

Therefore, even though the tuner can achieve a tuning range of VSWR=15:1, the maximum tuning range at the DUT reference plane is VSWR=4.95:1.

Using the Nano5G with optimized on-wafer integration on FormFactor probe stations, the tuning range can be recalculated as

- RL tuner = -0.43 dB (VSWR = 40:1, $|\Gamma|$ = ~0.95)
- RLprobe = -0.8 dB (insertion loss = -0.4 dB)
- RLdut= -1.23 dB (VSWR= ~14:1, $|\Gamma|$ = ~0.87)

With the Nano5G's optimized tuning for 5G FR2 frequencies resulting in a 40:1 VSWR, and its elimination of external coupler and cable insertion loss, the maximum tuning range at the DUT reference plane is increased to VSWR=14:1.

Smith Chart coverage at 4.95:1 and 14:1 are shown on Figure 4.

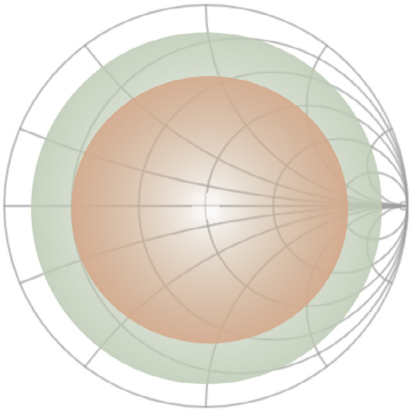

Figure 4: VSWR at DUT reference plane at 39 GHz for typical and optimized on-wafer load pull systems.

The Smith Charts in Figure 5 show the load pull iso-contours for a maximum tuning range of (a) VSWR=4.95:1 achieving a PAE of 63% at Pout of 24 dBm at 39 GHz, and (b) VSWR=14:1 achieving a PAE of 64.4% at Pout of 24 dBm at 39 GHz. Notice the first set of iso-contours are not closed, and therefore, we cannot know with confidence whether we have achieved the maximum power and/or PAE, while the second set are closed, thereby assuring us that maximum performance has been achieved.

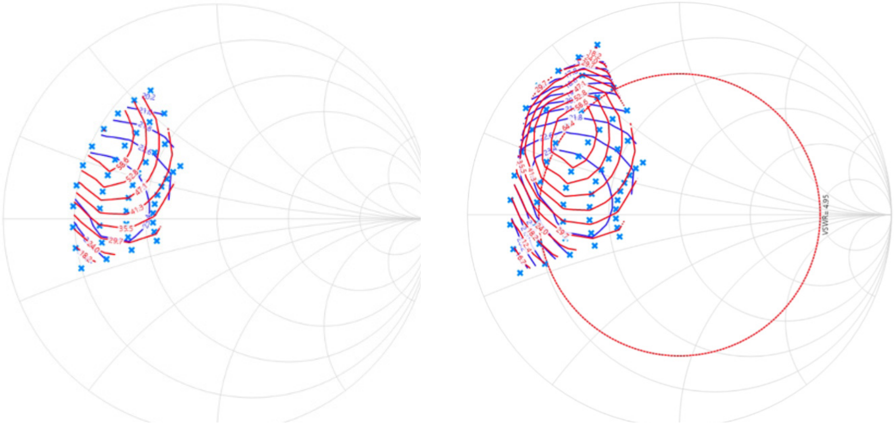

Table 5: Max Pout (blue) and Max PAE (red) iso-contours at 39 GHz with maximum tuning range of (a) 4.95:1 and (b) 14:1.

Phase Skew

The phase skew, also known as phase delay or phase shift, of the impedance presented at the DUT reference plan is influenced by the length of the transmission line between the tuning element (probe inside the tuner) and the DUT. Longer lengths result in greater phase skew, while shorter lengths lead to smaller phase skew.

Consider the following 5G FR2 signal 64QAM 160 MHz BW 8 dB PAR at 39 GHz with a modulated bandwidth of 160 per channel.

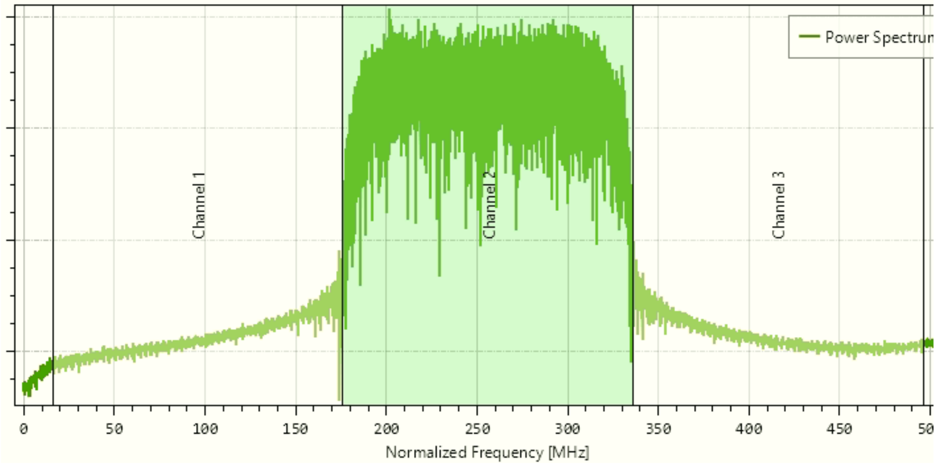

Figure 6: 64QAM 160 MHz signal 3 channels for a total of 480 MHz bandwidth.

In the typical on-wafer load pull system, the phase skew is 0.9 degree/MHz and will result in a phase skew of 144 degrees in the main channel and 432 degrees if we also consider the adjacent low and high channels.

The Nano5G™ integration eliminates the need for external probe mounts/cables and coupler and brings the tuning element closer to the DUT, thereby minimizing the length of the transmission line. This results in a reduced phase skew of 10X, achieving 0.12 degrees/MHz and 22 degrees of phase skew within the main channel. Figure 7 shows the phase skew from the target impedance for 144 degrees and 22 degrees.

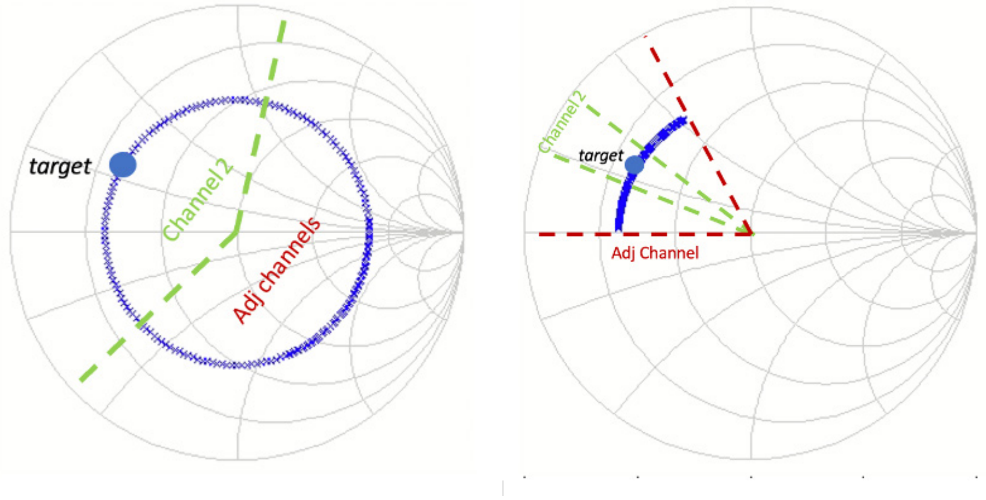

Figure 7: Phase skew from the target impedance for (a) 144 degrees and (b) 22 degrees

The plots in Figure 8 show PAE and EVM at a fixed impedance of -0.50 + 0.35i with a phase skew of (a) 144 degrees achieving a PAE of 23% and EVM of -28 dB at Pout of 15 dBm at 39 GHz, and (b) 22 degrees achieving a PAE of 25.5% and EVM of -32 dB at the same Pout of 15 dBm at 39 GHz. The reduced phase skew resulted in a PAE improvement of 2.5% and an EVM improvement of 4 dB for the same impedance and same output power.

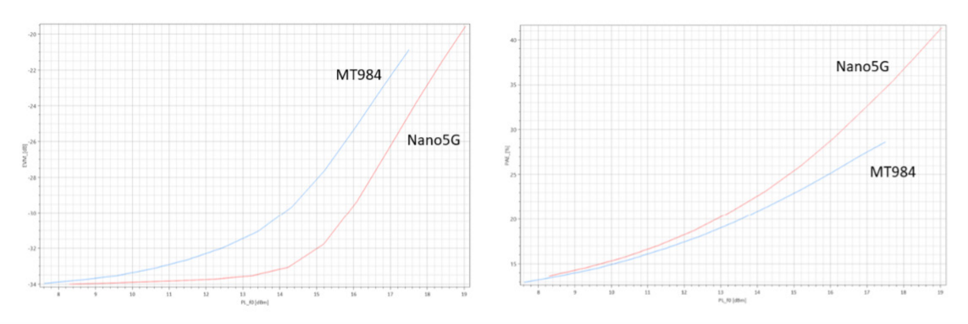

Figure 8: Power sweep measurements for (a) EVM and (b) PAE, using typical (blue) and optimized (red) on-wafer load pull systems.

Conclusion

The benefits are clear; 5G at millimeter wave frequencies will bring higher data speeds, lower latency, increased capacity, and result in enhanced user experience. To realize these benefits, telecommunications infrastructure will need to be optimized, with special attention on PAs and ICs. PA developers and circuit designers using load pull will need to pay special attention to tuning range and phase skew, both critical considerations for on-wafer load pull measurements needed to maximize the performance of their designs. Maury Microwave has developed its Nano5G™-series of miniaturized tuners which allow for direct-probe connection, and when used in conjunction with FormFactor's low-loss Infinity, InfinityXT, ACP, |Z| probes and optimized probe station integration, result in maximized tuning range and minimized phase skew. Together, Maury Microwave and FormFactor offer solutions that overcome the challenges of passive on-wafer load pull measurements at millimeter wave frequencies for 5G applications.

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