Q&A With Gary Simpson, Chief Technical Officer, Maury Microwave

Microwaves and RF

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JJD: How were you first introduced to load pull and impedance tuning, and how were you using these techniques to solve the challenges at the time?

I was introduced to load pull and impedance tuning at Motorola Semiconductor Product Division in Phoenix, Arizona; it was my first job out of college and my first foray into amplifier design and validation. We had a project to develop a 10 Watt microwave power transistor and the tools of the time were not ideal for quick and efficient design success.

My role was to test each iteration of the transistor design which included manually tuning the source and load impedance, measuring the output power, gain, and efficiency, and determining the source and load impedance match which gave the best performance. Thanks to load pull, the project succeeded with only a few transistor design iterations, first at 1 GHz and then at 3 GHz. The year was 1973.

JJD: What load pull tools did you use to complete that project?

I built a microstrip fixture to hold the device, and used two tunable capacitors to change the impedance. After tuning for the best power, I then took the fixture apart and used an HP 8410 network analyzer to measure the source and load impedances at the DUT plane. The fixture had limited phase tuning range, so if the best impedance was at the edge of the tuning range. I then built another microstrip substrate to shift the tuning range, and repeated the test.

JJD: What were the dynamics in your career path that brought you to Maury Microwave, and how have you been involved with load pull and impedance tuning within Maury?

In my early years, I had designed calibration standards and wrote 12-term error correction software to automate an HP8410 network analyzer. Funny enough, when I joined Maury in 1982, it had nothing to do with impedance tuners or load pull. My job was to work on network analyzer calibration standards! Maury was in the process of working with HP to supply calibration kits for the upcoming 8510 VNA.

In the 1970s, Maury designed a family of manual slide-screw impedance tuners based on precision slablines and metallic tuning probed/slugs (these same manual impedance tuners are still sold today). After joining Maury, we decided to automate our manual tuners to create a computer-controlled automated load pull system. The idea was to remove the uncertainties due to manual tuner movements and repeatability, reduce the timely delays caused by lengthy hand-tuning, and speed up testing by automating the measurement and communication with instruments.

Pre-characterization/pre-calibration also meant that the VNA used to measure the impedances presented to the DUT was now used only once to calibrate the system, and not required for iterative measurements of the tuner.

performance parameters could now be plotted at the DUT reference plane without manual mathematics and embedding of each tuned point.

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Having performed manual load pull with tunable capacitors, and having used manual slide-screw and double/triple stub tuners, as well as having an advanced knowledge of calibration techniques and “modern” VNAs, I was selected to manage the project. The Automated Tuner System (ATS), the first commercial automated load pull system based on slide-screw tuners, was first introduced for sale in 1987. Ironically, nearly all of my time was spent on developing the hardware and software of the automated tuner system and I had to transfer my responsibilities related to calibration standards and techniques to other engineers.

Since then, I have been actively involved with the evolution and development of all load pull software and hardware at Maury Microwave.

JJD: How have impedance tuners evolved since that memorable day in 1987?

Impedance tuners have evolved in three main categories: tuner control, frequency range, and number of controlled frequencies.

In the 1970s and 1980s, the most popular commercial tuners were manual slide-screw and double-stub/triple-stub tuners. That all changed when Maury released the first commercial automated slide-screw impedance tuner in 1987. In 1987, the main automation interface in most microwave labs was the General Purpose Interface Bus (GPIB) then known as the Hewlett Packard Interface Bus (HPIB), and the motor control boards filled a 19-in instrument case. Tuners were originally controlled externally, with internal carriage and probe motors connected via cable to external GPIB controllers.

USB technology allowed us to embed motor-control inside the tuner, while the mathematics and automation was handled by ATS (Automated Tuner System) software residing on an external computer. LXI technology allowed us to move the mathematics and automation inside the tuner with the addition of embedded microprocessors and dual USB/Ethernet control, even adding a web-enabled interface!

At first, automated impedance tuners were offered only with 7mm connectors and limited to a maximum frequency of 18 GHz. Over the years, tuners were fitted with 3.5-mm, 2.4-mm, and 1.85-mm connectors and were offered to 26.5 GHz, 50 GHz, and 67 GHz. Waveguide tuners were designed to operate at frequencies above 100 GHz.

And while engineers are still mainly concerned with tuning the impedance presented to the DUT at the fundamental frequency, some applications benefit from higher-order harmonic frequency impedance tuning as well, and standalone multi-carriage tuners have been developed to meet this need.

And of course general mechanics and motor technology has evolved as well.

JJD: Have the applications that benefit from load-pull techniques been advancing? How have load pull techniques improved to compliment these trends?

Early load pull systems made use of passive impedance tuners which controlled the impedance by moving

ces of metal (probe/slugs). Only three primary performance parameters were of interest: output power, gain, l efficiency. In addition to the tuners, a basic load pull setup comprised of an RF source, a power meter, and bias supplies. A network analyzer was a general lab instrument, and only used to characterize the tuners. The goal was to characterize transistors and design simple amplifiers using a CW signal.

When the cell phones and other wireless devices began to evolve, there was a push to do load pull with modulated signals. The desire at the time was to use the actual modulation signal in the load pull setup for target amplifier design. To achieve this goal, digitally modulated sources and vector signal analyzers became part of the load pull setup. Linearity, as it applies to a particular modulation type, became an important parameter. This is sometimes referred to as “mixed-signal” load pull, since it includes an RF signal and modulation signal.

With the emergence of wide bandgap device technologies, such as GaN, pulsed load pull has become extremely important (true for any device technology with high power densities). Pulsed load pull lowers the average power seen by the DUT and the test system and allows power devices to be measured on-wafer, which saves a lot of cost and turn-around time compared to packaging the devices for test. It can also prevent self-heating which normally leads to performance degradations. And the quiescent bias can be pulsed to non-0 Volt states to study trapping effects.

Another recent trend involves using vector receivers to measure the a- and b- waves of the DUT at a calibrated DUT reference plane. The measured ratio a2/b2 is the reflection coefficient (or gamma load) presented to the DUT and is now measured with the DUT in place instead of relying on tuner pre-characterization and mathematical de-embedding.

The a- and b-waves are used to calculate parameters such as delivered input power, gain, output power...as well as phase information which results in am/pm... It is also convenient to measure the a- and b-waves independently at each frequency of interest in order to calculate the impedance presented at each frequency, the power at each frequency, including harmonics or intermodulation frequencies.

When an impedance tuner is used to passively reflect energy back towards the DUT, the reflected a2 signal is always lower than the incident b2 signal. However, a signal from a separate RF source can set a2, and therefore control the load impedance presented to the DUT; this is known as active tuning (or active load pull). Hybrid-active tuning (or hybrid-active load pull) combines passive and active tuning together. The passive tuner can reflect a large share of the signal, so the required injection signal for the active tuning can be much smaller.

For high power devices, this is much more economical than active tuning alone. Active and hybrid-active load pull have many benefits over purely passive load pull systems (even vector-receiver systems): active and hybrid-active load pull simplifies block diagrams by replacing mechanical tuners with active tuners, eliminates mechanical challenges associated with larger mechanical tuners and wafer prober (probe station) integration, easily allows for the expansion to harmonic load pull, and allows for high gamma tuning by overcoming losses associated with probes, cables and fixtures.

And when paired with more advanced vector-receivers, such as the Keysight Technologies PNA-X VNA, active and hybrid-active load pull solutions can be upgraded with nonlinear VNA (NVNA) and X-Parameters behavioral modeling capabilities.

Active and hybrid-active load pull systems are based on the injection of active a2 signals, and rely on a vector receiver to analyze those signals in real-time. Commercial solutions most often make use of a vector network analyzer (VNA) as the vector receiver, and in addition VNAs conveniently contain one or more RF source(s). This configuration is usually limited to CW or pulsed-CW measurements single-tone measurements, or several independent tones for intermodulation measurements.

there are now mixed-signal active load pull solutions, which can do mixed-signal load pull with active or hybrid tuning over a full modulation bandwidth to 240 MHz. That removes the biggest limitation of vector receiver based systems and allows for active load pull on realistic modulated signals such as WCDMA, LTE, 802.11ac...

Load Pull Trends

JJD: What trends do you see in the industry that may inevitably effect the load pull and impedance tuning market?

The load pull and tuner market follows the evolving industry trends. We are seeing a push for higher frequency measurements, with IEEE papers being published on MMICs at 500-1000 GHz! It will be exciting to see what type of load pull solutions, if any, will be suitable at those sub-THz frequencies.

Modulated signals and modulation bandwidths are increasing with every generation of mobile communications. What started off as a "pulsed" signal has grown to 5 MHz, then 10 MHz, then 20 MHz and now 60 MHz! We don't see this expansion in modulation slowing anytime soon, and load pull systems will need to catch up. How will the next generation of load pull systems handle transistor characterization under realistic modulated signals?

Amplifiers are becoming more complex, circuits and systems are becoming more complex, and load pull data and modeling are beginning to converge. What will be the most efficient method of using load pull data for amplifier, circuit or system design? Will behavioral modeling using load pull data bridge the measurement/modeling gap?

JJD: What industry advances would dramatically change the way load pull measurements are performed?

Load pull solutions exist to serve industry needs, and we have adapted and continue to adapt as transistor and amplifier technologies change. There are a number of hypothetical advancements that would disrupt current load pull offerings.

The emergence of hypothetical transistor technologies with extremely low impedances (as we see today in some cases) would lessen the effectiveness of passive tuners with their limited gamma capabilities and force a mass movement towards active and hybrid-active load pull solutions.

The possibility of wideband (multi-octave/decade) radio designs using a single matching network would prove challenging, as the possibility of performing harmonic load pull would be replaced by the requirement of properly matching all fundamental frequencies. For example, matching a chip between 50 MHz and 500 MHz for maximum power and efficiency across the entire band, simultaneously, without possibility of harmonic terminations (harmonic of one frequency can be another fundamental frequency).

The trend to wider modulation bandwidths will also make passive tuners less effective, as the electrical delay cause by the load pull system and tuners can distort a wideband signal and lower its performance, independently of the actual device performance. It will be exciting to see what load pull technologies are developed to overcome these challenges.

And of course auto-tuning circuits used inside of radios would improve the robustness of matching network designs by adjusting for spontaneous or by-design mismatches, making load pull less necessary (although in that case, load pull would be used to challenge the auto-tuning circuits and test their robustness).

D: How would you recommend for an engineer looking for education on load pull and pedance tuning techniques?

Formal education on load pull and impedance tuning is hard to find. Most engineering colleges and universities do not cover load pull in undergraduate programs, or if they do, only at a very basic level. Some graduate programs do cover load pull, of which Georgia Tech, University of Southern Florida, TU Delft, and KU Leuven immediately come to mind. The two best places, in my opinion, to find resources on load pull theory, techniques, practice...is in the IEEE database and from load pull companies.

There are dozens of papers published each year by academia and industry on advanced load pull techniques and using load pull for advanced characterization and design. Because these are peer-reviewed technical papers, they most often concentrate on the technical and do not "market" to the reader.

Load pull companies are also excellent sources of information. Most provide in-depth application notes and technical papers, and can point readers to relevant industry papers. At Maury, we have an extensive application note database which we make publicly available. We also offer individual and group training courses tailored for any level (from the novice to the experienced). Courses can be customized around theory or practical hands-on training.

Be sure to check out Gary Simpson's column for Microwaves & RF, "Impedance Testing 101."

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