Introduction to Tuner-Based Measurement and Characterization

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Abstract: *This paper is a discussion of tuner-based RF device characterization and measurement. A rational for automated tuner-based measurement and automated tuner-based device characterization is given, followed by a discussion of the factors that drive the choice of tuner architecture. These factors include repeatability, impedance range, tuner speed, power capability, tuner resolution, bandwidth, and the size, level of integration, and ease of integration that are characteristics of various automated tuners. Detailed explanations of how tuners synthesize impedance, when and how tuner resolution is important, and why tuner repeatability is critical, are also given. System configuration examples are given and a discussion of advanced capabilities of automated tuner-based measurements is included. A glossary of terms related to these subjects is provided.*

Why Do We Need Automated Tuner Measurements?

RF and microwave transistors amplify voltage, current, and power, so it is natural to characterize transistors with respect to a parameter that relates these three quantities. That parameter is impedance. Automated tuner measurements enable rapid and accurate characterization of deembedded transistor characteristics, such as noise figure, gain, optimum linearity, and PAE, each with respect to impedance. Application of automated tuner measurements is diverse, from extraction of noise parameters to ACPR characterization optimization of power LDMOS transistors to mismatch ruggedness characterization of handset PAs.

What is Automated Tuner-Based Characterization?

Tuner-based characterization refers broadly to those applications where transistor performance is established by varying source and load impedance. Automated tuner-based characterization refers specifically to presenting an a priori known impedance in a precisely controlled fashion.

From establishing the noise figure of a highly linear low-noise CMOS transistor for a GPS receiver to optimizing the ACPR and PAE of a 90 W LDMOS transistor for a WCDMA base-station, tuner-based measurements are an integral component of the characterization and design process. In each of these examples, optimum performance is found by varying source and load impedance, along with frequency and bias, to rapidly and accurately establish conditions under which optimum performance can be obtained. Automated tuner measurements are also an integral part of linear and nonlinear model verification and semiconductor process tracking.

A common method of distinguishing tuner-based characterization architectures is the fashion in which impedance is synthesized. Measurement and characterization requirements and goals will constrain which type of architecture is most suitable. Impedance range, tuning speed, power handling capability, tuning resolution, tuner bandwidth, and tuner size are important considerations in choosing what type of tuner architecture to choose. Passive solid-state, passive-mechanical, and active-injection are the three basic architectures for synthesizing arbitrary impedances. Passive solid-state and passive-mechanical are the most common, while active-injection can be found primarily in mm-wave applications where cabling and wafer-probe losses are high.

Applications in which performance can be extrapolated over a broad range of impedances from a small number of impedances, such as determination of minimum noise figure, can be done easily and quickly using Maury's solid-state tuners. Here, tuner speed and tuner size are important, since most noise characterization is done over a broad range of closely spaced frequencies and varying bias in an on-wafer environment.

Requirements for high-power characterization, roughly 1 W or more, place different demands on the tuner architecture. The ability to synthesize impedances in the neighborhood of 1 Ω are necessary for establishing conditions under which optimum power, gain, PAE, and linearity can be established. Maury's passive-mechanical line of tuners, coupled with dynamic pre-matching or distributed pre-matching networks, provides a repeatable and accurate solution for synthesizing sub 1 Ω impedances over a broad range of frequencies.

- Maury passive solid-state tuners are ideal for characterization where speed and tuner size are important, such as on-wafer noise measurements
- Maury passive mechanical tuners are ideal for characterization where impedance range and power handling capability are important, such as power and linearity measurements for wireless PAs
- With the exception of very high power applications, passive solid-state and passive-mechanical offer similar capabilities for most applications

What Really Matters in Choosing Tuners for a Tuner-Based Measurement and Characterization System?

How does one choose between passive solid-state and passive-mechanical tuner architectures? What really matters in choosing an automated tuner-based measurement system? It depends. While certain tuner characteristics are important for both types of tuner systems, such as repeatability, the priority of other characteristics depends on how specific tuner attributes meet the needs of a specific measurement and characterization application. For example, while a passive-mechanical tuner system can be used for both noise and power characterization, a passive solid-state system might be a better choice for high-speed on-wafer lot-tracking of a low-noise CMOS process, due to its speed and size. Similarly, a passive-mechanical tuner system is necessary for very high power applications, roughly over 1W or so, due to its power handling capability.

Important tuner characteristics

- Repeatability

  Passive automated tuner systems rely on *a priori* characterization of tuner impedances. Tuner repeatability is therefore an important characteristic to ensure accurate and meaningful data with respect to optimum impedance.

- Impedance range and distribution

  Impedance range, often called matching range or mismatch range, refers to the impedance range a tuner can present. This is a critical characteristic for high-power applications, where sub 1 Ω impedances are often encountered. Impedance distribution refers to coverage of impedance points over the Smith chart and the distribution of those points within that region.

- Tuner Speed

  Tuning speed refers to the time of a tuner to move from one impedance state to the next. This is a critical characteristic when collecting, for example, lot-tracking data for a low-noise process. Total measurement time, at each impedance, is a function of measurement equipment and the type of measurements being made, in addition to tuner speed.

- Power capability

  Power capability refers to both the maximum rms and peak power that can be delivered to a tuner without any appreciable change in tuner impedance or any damage to the tuner. A high tuner insertion loss results in heating of tuner elements, which can perturb the calibrated impedance seen by the transistor. An improperly designed tuner, along with certain classes of RF connectors, can exhibit corona discharge or arcing, resulting in damage to the tuner or the transistor.

- Tuner resolution

  Tuner resolution refers to the resolution of impedance points that can be synthesized by the tuner. Solid-state tuner systems are usually composed of two individual cascaded tuners, each with a few

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hundred points, resulting in over 500,000 tuning points. Passive-mechanical tuner systems typically exhibit 10,000 points using one tuner. This can be expanded to millions of points using cascaded tuners or interpolation.

- Tuner Bandwidth

  Tuner bandwidth usually refers both the frequency range of the tuner and also the instantaneous bandwidth of the tuner. Tuner frequency range refers to the bandwidth of the tuner over which it is able to present its specified impedances. Both solid-state and passive-mechanical usually exhibit at least a decade of operating range. Instantaneous bandwidth refers to the modulation envelope bandwidth over which group delay is constant. This is an important parameter for wideband modulation formats, such as WCDMA.

- Tuner size, level of integration, and ease of integration

  Tuner size can be important in certain instances, as is level of integration and ease of integration. These are most often a concern when doing on-wafer measurements in a high-speed environment where *insitu* calibration is used and acoustic vibrations may be a concern.

How Do Tuners Synthesize Impedance?

Impedance synthesis is broadly classified as either passive or active. Passive impedance synthesis is done with either a solid-state network or an electro-mechanical network. Active-injection is done by injecting a signal toward the transistor to emulate a reflected wave by a termination.

Passive solid-state tuners synthesize impedance by varying the impedance state of a number of shunt connected p-i-n diodes placed in a precise fashion along a transmission line. Depending on the design, the diode impedance state can be varied continuously or toggled discretely between on and off states. The number of states achievable with a practical number of p-i-n diodes leads to the requirement of cascaded tuners to exhibit a sufficient number of impedance states for adequate tuning resolution. This configuration is transparent to the user, so the cascaded tuners behave one tuner unit.

Passive-mechanical tuners are based on a slab transmission line loaded by a shunt sliding short. A precision stepper motor controls the distance of the sliding short from the center conductor, while another precision stepper motor controls the distance of the sliding short assembly from the load. Modern passive-mechanical tuners usually have two sliding shorts to increase operating bandwidth to over a decade. The physical resolution of current stepper motor technology used on Maury passive-mechanical tuners, coupled with advanced interpolation algorithms, enable millions of impedance points to be synthesized.

The principle of active-injection impedance synthesis is based on injecting a signal, whose amplitude and phase can be precisely controlled, toward the transistor. Active-injection can further be classified as either open-loop or closed-loop. Since any loss between the tuner and transistor contracts the impedance range, an attractive theoretical advantage of active-injection is the ability to compensate for loss, such as that due to wafer-probes. In practice, however, active-injection is much slower than passive synthesis, can require large reference PAs to overcome injection loss, and can be difficult to control over a wide range of operating and frequency conditions. The advantages are further diminished when modulated signals are used. Presently, pre-matching networks or pre-matching tuners, coupled with passive-mechanical tuners, provide an impedance range nearly identical to active-injection, at far lower cost and complexity.

Why is Tuner Repeatability Important?

Measurements made in an automated tuner-based characterization system are with respect to the impedance presented by *a priori* calibrated tuners. Tuner repeatability is defined as the vector difference in the initial tuner impedance, made with a VNA during calibration, and a subsequent tuner impedance measurement. Being able to repeat tuner impedance states is an important tuner characteristic. Subsequent use of the impedance data in matching network synthesis or model verification will lead to differences in measured or simulated performance with respect to performance reported by the automated tuner system.

Maury passive-mechanical tuners and passive solid-state tuners typically exhibit better than -60 dB and -70 dB repeatability to 50 GHz, respectively. This number exceeds VNA calibration uncertainty by a wide margin, showing that Maury's automated tuners are essentially transparent.

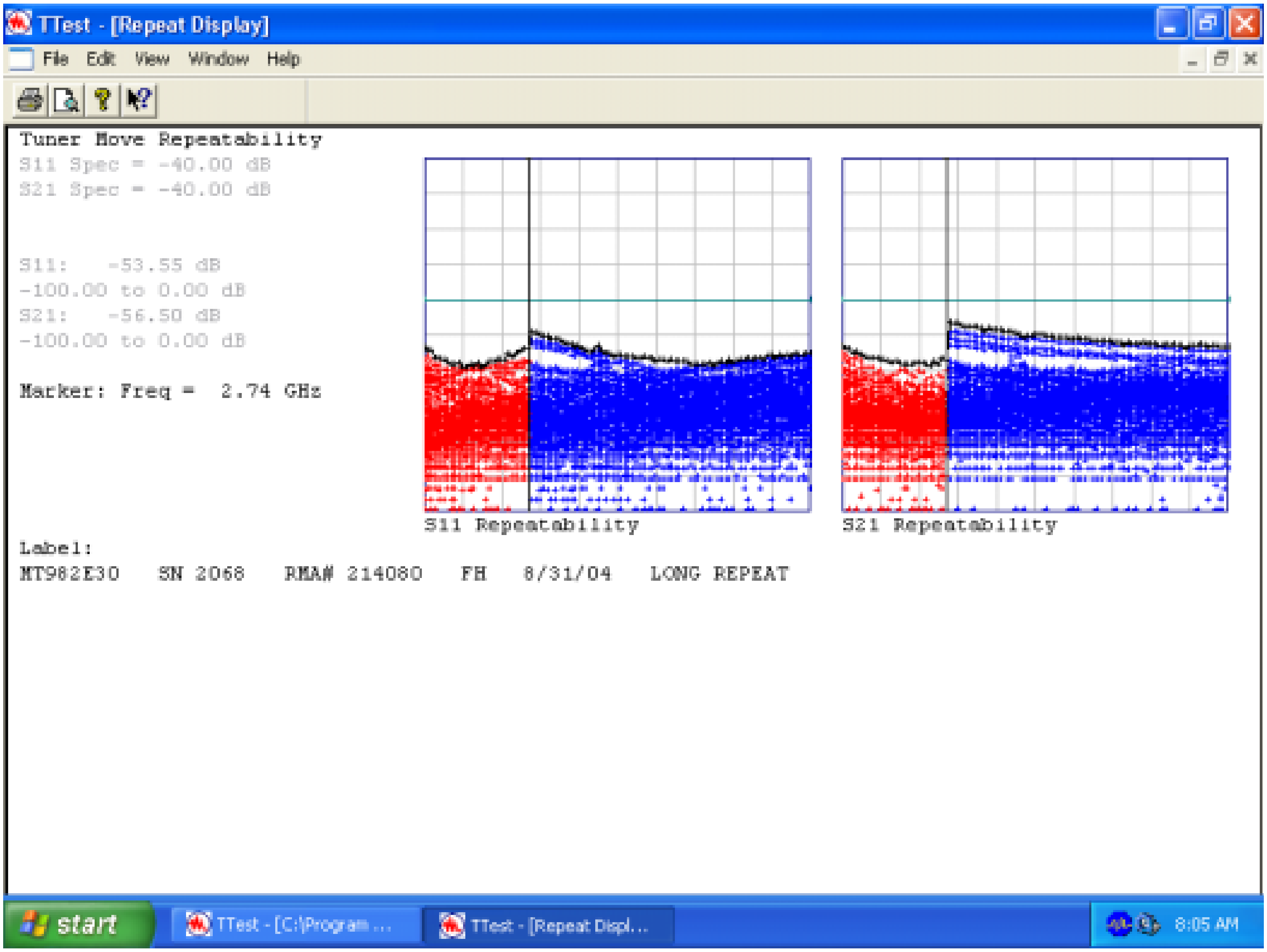

Figure 1. Tuner Repeatability as displayed by the Maury MT993 SNP Software

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When and Why Is Tuner Resolution Important?

Noise characterization of transistors is based on linear analysis from which general performance versus impedance can be extrapolated from a widely-spaced set of impedance measurements. The same is not true for power measurements, precluding extrapolation of performance outside of the impedance-domain presented by the source and load tuners. Although interpolation is possible within the tuner impedance-domain, it is desirable to be able to perform measurements at candidate optimum impedances during the characterization process. Therefore, resolution is an important parameter for power characterization, since an exact impedance state may be necessary in order to obtain the desired performance.

How much resolution is enough? It depends. Obviously, there are realizability and manufacturing constraints that minimize the importance of being able to present an impedance with resolution to 4 or 5 decimal places. Nevertheless, there are some practical guidelines.

For example, consider a typical transistor used as a final-stage for a 3.2 V GSM PA. The load impedance for this transistor to deliver 35 dBm is typically in the neighborhood of 2 Ω. Based on normal manufacturing targets for supply voltage changes over battery charge-time would give a required impedance resolution, $\Delta|\Gamma|$, of about 0.009. Even in the extreme case of uniform coverage in the gamma-domain, this tuning resolution requires only 50,000 impedance states, which is easily achievable by Maury's passive solid-state and passive-mechanical tuners.

Advanced Capabilities of Automated Tuner-Based Measurements

This note has provided an introduction to basic aspects of automated tuner-based characterization. Advanced methods provide additional insight to device behavior, enabling additional optimization. References are provided for the interested reader to learn advanced methods of transistor characterization.

- Harmonic load pull

  The amplitude and phase of harmonics present at the input and output of a transistor have a significant effect on performance, influencing parameters such as power, PAE, and linearity. Maury offers a complete solution for harmonic load pull.

- Large-Signal Network Analysis

  Large-signal network analysis is vector analysis, at a user-defined reference-plane, of arbitrary signals under nonlinear conditions. For example, using LSNA technology, the phase of intermodulation mixing products can be characterized to optimize PAs for minimum distortion. In addition, the transistor loadline, common to designers of low-frequency PAs, can be examined. Only Maury has LSNA technology.

- Fixture Analysis and Characterization Software

  At frequencies where wavelength is on the order of the physical dimensions of the electrical network, impedance is no longer position independent. Precision measurements, based on impedance, therefore require an ability to characterize the hardware that connects automated tuners to the transistor. The hardware can be as simple as a 50 Ω microstrip line or a 50 Ω wafer-probe to complex as a multi-section quarter-wave transformer. Maury offers software to enable rigorous characterization of fixtures, including impedance re-normalization and two-tier fixture calibration.

- Real-Time Thermal Imaging

  Management of heat is a significant concern all designers face, particularly those involved in PA design and high-power transistor design. Maury has recently integrated high-performance thermal imaging hardware with Maury's automated tuner system, allowing real-time thermal analysis versus source and load impedance, frequency, and bias.

Glossary of Common Terms Commonly Associated With Automated Tuner-Based Measurements

ACPR Adjacent channel power ratio is a commonly used metric for characterizing linearity of nonlinear devices when excited by a digitally modulated signal. The ratio is usually expressed as the total power over some frequency band adjacent to the main channel to the total power in the main channel.

AM-AM Conversion refers to modulation of the amplitude transfer characteristic versus input signal level. For example, gain compression is a form of AM-AM conversion. Memory effects are easily identified using variable-rate swept AM-AM tests. Amplitude distortion is a form of AM-AM conversion.

AM-PM Conversion refers to modulation of the instantaneous phase transfer characteristic versus input signal level. Transistors exhibiting AM-PM are referred to as quasi-memoryless, since the phase modulation is a result of quasi-static nonlinearities present, such as nonlinear charge. As with AM-AM conversion, memory effects can also be identified with variable-rate swept AM-PM tests. Phase distortion is a form of AM-PM conversion. Note that the elements with linear charge functions and nonlinear conductance functions will exhibit AM-PM, since the instantaneous phase angle will change as the signal level modulates the instantaneous conductance.

Bandwidth can take on many definitions. In the context of automated tuner-based measurements, it usually means either operating frequency range of the tuner, over which it meets certain performance specifications, or the instantaneous BW, referring to modulation bandwidth.

Instantaneous Bandwidth refers to the bandwidth of a tuner over which its impedance remains constant within some specified range. This metric is critical when using wideband signaling formats, such as WCDMA or OFDM.

Modulation refers to the process of changing a characteristic of a signal in response to some other signal. Generally, amplitude, frequency, and phase can be modulated, although the last two are essentially the same. Note that access method and modulation are often confused with one another. Thus, TDMA is not a type of modulation. Rather, it refers to the manner in which users share a common resource, in this case time. Common TDMA systems, such as GSM and IS-136, use different modulation methods. GSM uses GMSK whereas IS-136 uses π/4-QPSK. Modulation is also critical for identifying various forms of memory when performing automated tuner-based measurements of transistors.

Active-Injection is a method of impedance synthesis using a reference amplifier with variable gain and phase. This method can be either open-loop or closed-loop, and injects a signal toward the transistor to emulate an arbitrary impedance based on the amplitude and phase of the output signal. In principle this architecture can create $|\Gamma = 1|$ although the relative higher cost, complexity, and increase in measurement time are significant disadvantages.

Bias generally refers to the quiescent drain/collector voltage and current of a transistor.

Center Conductor in a slab-line or coaxial-line refers to the center conductor.

Air line is usually a coaxial-line used to provide a known delay or a precise reference impedance. An air line with a short termination or a load termination can also be used to measure VNA source match and effective directivity. A beadless air line usually offers the most precise impedance standard.

Effective directivity refers to the residual directivity of a VNA after calibration. Identical to the physical meaning of directivity, it characterizes to the ability of the VNA signal separation hardware to discriminate forward and backward waves after calibration. This parameter is significant when characterizing networks with small reflection coefficients.

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Source Match is the apparent corrected impedance looking into the source-port of a VNA. Often described in terms of return-loss with respect to the calibration impedance, this parameter is critical when characterizing tuners, since very high reflection coefficients are encountered. Generally, a source match better than -45 dB is necessary, implying that TRL calibration be used.

Load Match is the apparent corrected impedance looking into the load-port of a VNA. Often described in terms of return-loss with respect to the calibration impedance, this parameter is critical when characterizing tuners, since very high reflection coefficients are encountered. Generally, a load match better than -45 dB is necessary, implying that TRL calibration be used.

VNA Calibration colloquially refers to removal of systematic errors present in a VNA. Generally, these are directivity, source match, load match, tracking, and isolation. It is important to note that a VNA must provide impedance measurements with respect to a standard whose value is either assumed or known. Hence, calibration methods that enable precise specification of reference impedance are preferred, such as TRL. While other methods, such as SOLT, can have the load standard characterized a priori to enable precise knowledge of the reference impedance, this still requires that an additional calibration be done, such as TRL.

VNA Verification colloquially refers to quantification of systematic errors present in a VNA. Generally, these are directivity, source match, load match, tracking, and isolation. Various specialized standards are used to quantify these errors. See sliding short, offset short, sliding load, and offset load.

TRL Calibration is generally the preferred VNA calibration method due to the precision in which the reference impedance is specified. TRL stands for Thru-Reflect-Line, where the Line standard sets the calibration reference impedance. Since this impedance can be precisely determined, TRL generally yields the best effective directivity, source match, and load match. Maury recommends that all tuner characterization be done with a VNA calibrated by TRL.

LRM Calibration stands for Line-Reflect-Match and is a special case of TRL, with the Delay standard replaced by a lumped termination. Due to parasitics associated with the fabrication of the Match standard, LRM does not provide the same level of precision as TRL.

SOLT Calibration is a common VNA calibration method when accuracy is not a priority. SOLT refers to Short-Open-Load-Thru, where the Load standard sets the calibration reference impedance. Due to parasitics associated with the fabrication of the Load standard, SOLT does not provide the same level of calibration precision as TRL, particularly with respect to source match and load match.

LRRM Calibration stands for Line-Reflect-Reflect-Match and is a special case of SOLT, with the Delay standard replaced by a lumped termination. A significant improvement with LRRM is the ability to extract parasitic inductance of the Match standard as part of the calibration procedure. In addition, LRRM requires the Match standard to be measured at one port only. The ability to remove the reactive part of the Match standard gives a more precise calibration reference impedance, although not as precise as TRL. LRRM finds wide application in on-wafer applications, where TRL standards are difficult to fabricate.

CMOS stands for Complimentary Metal Oxide Semiconductor. CMOS is based on the field-effect, and was initially conceived due to its relative processing simplicity. Due to cost, there is considerably interest in developing high-performance RF functions using CMOS technology, including high-Q inductors for VCO's and low-noise transistors for LNAs.

Corona Discharge is breakdown of a dielectric, usually air, due to ionization. Corona discharge usually occurs in regions of high electric field intensity as a result of physical dimensions exhibiting high curvature. Corona discharge is a primary failure mode for improperly designed slab-line tuners, such as those with contacting shorts. Some automated tuner manufacturers still use tuner technology based on sliding contacting shorts.

Current is the time-rate of change of charge.

Voltage is the potential energy per unit charge.

Power is the work done per unit time, and equals the product of voltage and current.

Impedance is the ratio of voltage to current and is in general a complex quantity. Nearly every performance metric of a transistor is directly related to impedance, so it plays a central role in automated tuner-based characterization.

dBm represents 10x log ratio of power with respect to 1 mW.

dBW represents 10x log ratio of power with respect to 1 W.

dB represents 10x log ratio of one power with respect to another power. When comparing ratios of voltage or current, then the expression simplifies to 2 blog.

Deembedding is the process of moving a reference-plane forward from the initial reference-plane. Often, deembedding refers colloquially to removing the effects of known parasitic elements. For example, when one speaks of deembedding wafer-probe pads, it is meant that the effect of the wafer-probe pads is removed from the measurement.

Embedding is the process of moving a reference-plane backward from the initial reference-plane.

Distortion is a broad term which in general means the presence of undesirable corruption of a signal as it interacts with a network. There are many types and manifestations of distortion. See Delay Distortion, AM-AM, AM-PM, and Nonlinear Distortion.

Delay Distortion occurs when the group delay of a network is non-constant over a bandwidth similar to the signal bandwidth. Delay distortion can result in amplitude or phase distortion of a signal, depending on the spectral composition of the signal and the severity of the delay distortion. Note that although nonlinear distortion can also produce amplitude distortion, delay distortion is a linear distortion, and hence will not produce new frequencies, whereas, in general, nonlinear distortion will. This is a distinguishing feature of amplitude distortion due to delay distortion, and amplitude distortion due to amplitude nonlinear distortion.

Nonlinear Distortion occurs when a linear relationship no longer exists between the output and input signals of a system or network. Although this broad definition can include nonlinear delay distortion, a major distinction between nonlinear (amplitude-based) distortion as implied here and nonlinear delay distortion is the former produces spectral components that were not present in the input signal, whereas the latter does not. Nonlinear distortion will yield spectral regrowth, for example, while nonlinear delay distortion will yield asymmetry in spectral regrowth. A significant motivation for adopting automated tuner-based measurements is precisely due to the mathematical complexity of describing nonlinear distortion and the ease in which nonlinearity can be characterized using automated tuner measurements.

Envelope Bandwidth see instantaneous bandwidth.

Harmonic Load pull refers to the method of varying reflection coefficient at the harmonics of a signal, at both the input-port and output port of the transistor. Generally, the reflection coefficient is close to unity, and only the phase is varied. This results in a substantial reduction in hardware complexity and cost for harmonic load pull. Harmonic load pull can affect power, gain, PAE, and linearity of a transistor.

Impedance Domain refers to expressing a ratio of voltage to current in the frequency-domain. Ratios expressed in the impedance domain are related to ratios expressed in the gamma domain by the bi-linear transformation and characteristic impedance. (In VNA calibration nomenclature, characteristic impedance is often called reference impedance.)

Gamma Domain refers to expressing the ratio of reflected to incident waves in the frequency-domain(or time-domain). Ratios expressed in the gamma domain are related to ratios expressed in the impedance domain by the bi-linear transformation and characteristic impedance. (In VNA calibration nomenclature, characteristic impedance is often called reference impedance.)

GSM is the world's most common digital wireless standard, and is generally referred to as a second-generation wireless standard. It is based on GMSK modulation and TDMA/FDMA for resource sharing. GSM is a French acronym for Group System Mobile.

NADC is the North American Digital Cellular Standard, now know as IS-136. It is based on p/4-QPSK

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modulation and TDMA/FDMA for resource sharing. It is generally referred to as a second-generation wireless standard.

EDGE is a third-generation wireless standard (sometimes called 2.5 G) using 3π/8-PSK modulation and TDMA/FDMA for resource sharing.

In Situ Calibration is a method that enables two-port characterization and VNA calibration directly within a fixture or on-wafer. This method is usually done with passive solid-state tuner systems intended for on-wafer noise characterization. A dedicated VNA is necessary. When done as part of a two-tier calibration, fixture files can be generated as well.

Insertion Loss refers to the loss of a two-port network due to internal dissipative losses. For a two-port network loaded by a matched source, insertion loss equals the available loss, which is a primary figure of merit for characterizing passive tuners. Insertion loss and tuner mismatch are intimately related. See available loss.

Reflection Loss, also called **return loss**, is the power carried away from a transmission line interface with a load due to reflection.

Available Loss is a measure of dissipative losses taking into account the effect of mismatch between the source and the two-port.

Two-Port Network is a general term applied to a linear or nonlinear network consisting of two independent terminals each referenced to a common node, often ground.

Large-Signal Network Analysis refers to vector analysis of general nonlinear networks with arbitrary stimulus. The method is based on time-domain capture of incident, reflected, and transmitted waves under arbitrary conditions. Fourier transformation is used to analyze data in the frequency-domain.

LSNA refers to Large-Signal Network Analyzer. An LSNA is an instrument capable of performing large-signal vector measurements. See large-signal network analysis.

LDMOS refers to Laterally Diffused Metal Oxide Semiconductor. The diffusion underneath the gate enhances the transport properties of the electrons in the channel, resulting in enhanced high-frequency performance. LDMOS technology is widely used for base-station PAs due to its linearity and ruggedness superiority over Si BJT technology.

Loadline is the instantaneous trajectory of the load current versus load voltage at the output terminals of a transistor (and also at the input terminals). Parameterized to time, this trajectory gives a direct indication of voltage clipping and current clipping as well as other useful data, such as the effect of reactance and harmonics on voltage and current.

Matching Network is the general term given to a network whose primary function is to transform impedances. While matching may be a goal, the primary motivation of a matching network is most often to present impedances determined from automated tuner measurements to exhibit the target performance observed during measurement. Frequently a matching network may not be conjugately matched to a source or load in order to enable some other performance goal to met, such as ACPR.

Maximum Available Gain is the gain realized when an unconditionally stable two-port is conjugately matched at both ports. The conditions under which MAG occur under small-signal operation are far different than when they occur under large-signal operation, and is a primary motivation for adopting load pull.

Transducer Gain is the ratio of power delivered to a load from a network to power available from source driving the network.

Power Gain is the ratio of power delivered to a load from a network to power delivered to the network. Power gain equals transducer gain when the source is conjugately matched to the input of the network.

Available Gain is the ratio of power available from a network to power available from the source. Available gain equals transducer gain when the network output impedance is matched the load impedance. Note that available gain and available loss differ by a sign.

Microstrip is a commonly used planar waveguiding structure.

PAE is power-added efficiency. It is defined as:

$$\eta_{PAE} = \frac{P_{LOAD} - P_{DEL}}{P_{DC}} = \eta_T \left(1 - \frac{1}{G_P}\right)$$

where P_{DEL} is the power delivered to the transistor and G_P is power gain, and is collector/drain efficiency. Note that contrary to claims made by some manufacturers of automated tuner systems, η_{PAE} can be measured in an automated tuner system. All Maury automated tuner systems are capable of measuring PAE.

Passive-Mechanical Tuner is a system composed of a slabline loaded by a shunt sliding-short and various computer-controlled motors. The motors control the position of the carriage, which houses the shunt element, and the position of the shunt sliding-short. To increase frequency range, some tuners will have two shunt sliding-short's mounted on the carriage. Using interpolation, passive-mechanical tuners can synthesize millions of impedance points.

Passive Solid-State Tuner is a system composed of a microstrip line slabline loaded by a precisely placed computer-controlled shunt p-i-n diodes. Cascaded passive solid-state tuners can synthesize several hundred thousand impedance points.

Slab Transmission Line is waveguiding structure composed of two parallel plates for ground and a circular center conductor. Its structure is amenable to insertion of probes for altering the impedance of the line. Slab transmission line is often called slab-line.

Reference-Plane refers a defined location from which measurements are referred to with respect to amplitude and phase. While the reference-plane is usually physical in the sense it can be associated with a specific location, it can also be abstracted to exist in a mathematical sense only.

Noise Figure of a network is defined as the ratio of output SNR to input SNR. An alternative, but equivalent, definition, is the ratio of noise power available at the output of a network to noise the power available by the source driving the network.

Pre-Matching Network is a network designed to transform impedance, usually in order to extend the impedance range of a tuner. Pre-matching network's can be based on single-section, multi-section, or tapered microstrip lines. Wafer-probe's can also have internal pre-matching. Currently, pre-matching networks give the lowest impedance possible, with impedance's as low as 0.1 Ω at 2 GHz having been designed.

Pre-Matching Tuner is a tuner composed of cascaded tuners with one of the tuners acting as a pre-matching element. This style of tuner offers broad coverage over the Smith chart, compared to microstrip pre-matching, but does not offer as low of impedance.

Interpolation is a method for estimating the value of a function between two, or more, known points on the function. Automated tuner systems use Interpolation algorithms in many areas, from increasing the number of available tuner impedance states to generating data contours.

Sliding Short is a waveguide terminated in a short whose position can be moved axially up and down the guide. A certain class of harmonic tuners use sliding short's, as do various VNA calibration and verification methods.

Sliding Load is a waveguide terminated in a load whose position can be moved axially up and down the guide. It is used primarily for VNA calibration.

Offset Short is a waveguide terminated in a short. It is used primarily to provide a ripple pattern from which can be derived equivalent source match as:

$$E_{sf} = 10\log \frac{1-10^{\frac{\text{peak to peak ripple}}{10}}}{1+10^{\frac{\text{peak to peak ripple}}{10}}}$$

Offset Load is a waveguide terminated in a load. It is used primarily to provide a ripple pattern from which can be derived equivalent directivity. Best case directivity would be 6 dB less than the peak ripple.

Stepper Motor is a precision computer-controlled motor used to control the position of both the carriage and the sliding shunt short in a slabline tuner.

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Shunt Sliding-Short is an element in the slabline used to control the impedance of the slabline. The closer the short is to the center conductor, the lower the line impedance, and higher the mismatch presented. Often a shunt sliding-short is referred to as a probe.

P-I-N Diode is a special type of pn junction diode whose RF resistance can be controlled by the DC current through the diode. P-i-n diodes are used to set the impedance in a passive solid-state tuner.

Real-time Thermal Imaging is a general term referring to integration of a high-resolution IR camera with an automated tuner system to observe the effects of source and load impedance on thermal characteristics of a transistor.

Tuner Repeatability is a measure of the vector difference of the impedance states of a tuner from an initial calibration to a subsequent measurement. Passive mechanical tuners typically exhibit -60 dB repeatability and passive solid-state tuners typically exhibit better than -70 dB repeatability.

Two-Tier Calibration is a general VNA calibration method consisting of a primary calibration, usually referred to as the outer-tier calibration, and a secondary calibration, usually referred to as the inner-tier calibration. The method is often applied to fixtures, such as those with 7 mm outer-tier connectors and microstrip inner-tier, for extracting a two-port s-parameter description of the fixture. This is necessary to move the reference-plane from a tuner, for example, to the transistor reference-plane. The method is often applied to characterization of wafer-probes as well.

VNA refers to Vector Network Analyzer, and is an instrument capable of measuring s-parameters, usually with built-in error correction routines, such as SOLT and TRL.

Test-Fixture is a general term that usually refers to a structure capable of making electrical and mechanical and thermal contact with a transistor and providing suitable connections to mate with a waveguiding element, such as a 7 mm coaxial line. Test-fixture's are often designed to mate with transistors with microstrip leads, and therefore have microstrip to coaxial transitions. Fixture loss is a critical parameter that can affect apparent tuner impedance range.

Wafer-Probe is a special structure designed to make electrical contact with metalized pads on a wafer (or, often times, a substrate of some sorts, such as alumina). The most common configuration is Ground-Signal-Ground (GSG) coplanar, although GS or SG can be used at lower frequencies.

CDMA also know as IS-94 or cdmaOne. It is based on QPSK and OQPSK modulation and CDMA/FDMA for resource sharing. It is generally referred to as a second-generation wireless standard.

WCDMA refers to wideband CDMA and is generally referred to as a third-generation wireless standard. There are presently two major standards for WCDMA, the 3GPP standard and edma2000 standard.

Peak-Average Ratio refers the ratio of peak instantaneous power to average power. It is an often-used metric for characterizing the difficulty of amplifying a signal with a time-varying envelope. While commonly used, it can also be misleading, since it does not directly indicated the dwell time of the peak instantaneous power. A far more useful metric is the envelope distribution function (EDF). See envelope distribution function.

Envelope Distribution Function is a measure of the probability of a specified instantaneous power occurring with respect to some normalization power, often average power or minimum power. This metric is far more useful than peak-average ratio, since it provides an estimate of how often an instantaneous power will occur over the normalization variable.

Intermodulation Distortion results when two or more spectral components are applied to a nonlinear system. The resultant mixing of the spectral components yield so-called intermodulation mixing products, whose spacing is related to the spacing of the original spectral components.

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