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Application Note 8

Basics on Load Pull and Noise Measurements

Please notice that some of the information in this document is not any more accurate. This concerns especially the Harmonic Load Pull topics. For more information please contact our office.

This note is a practical review of terms, applications and techniques used for Load Pull and Noise Measurements. It describes Focus' tuner systems and compares to other possible solutions, such as Active load pull, non-linear Model and other vendor's systems. It includes an Index and list of Keywords on page 8.

Introduction

Load Pull and Noise Measurements are **Impedance** related measurements. This means that the **main independent parameter** of the measurement is not Frequency, Power, Bias or even Temperature, Vibration or Pressure but the **Source or Load Impedance** (or Reflection Factor) at the fundamental or any Harmonic frequency, presented to the Device Under Test (DUT).

These Impedances are normally generated using a TUNER, which is a passive component that changes the Impedance, at a given frequency, as a function of the position of its internal components. This method is called **Passive Load Pull.**

The method of generating the impedance virtually, i.e. by re-injecting at the output of the DUT the signal after modifying its amplitude and phase using 'active circuits' ie. circuits with gain, has first been proposed in the 70's and is generally called **Active Load Pull**.

Tuner measurements have been used from the beginning of the microwave technology, it was however not possible to **visualize** the Impedance conditions **during the measurement** until the mid 70's, where the first Automatic Load Pull System became available at RCA David SARNOFF Research Laboratory in N. Jersey. This system operated using a model to compute the impedance of the tuners as a function of their geometry and position. Many other Laboratories have developed and published semi-automatic or automatic tuner systems, but RCA's was the first one to become really commercialized in the early 80's.

Three other companies have introduced Load Pull and Noise Measurement systems in the market since:
ATN Microwave, which uses electronic (PIN diode) tuners.

MAURY Microwave, which uses mechanical slide screw tuners with two slugs mounted in the same airline.

FOCUS Microwaves uses mechanical sliding screw tuners with a single slug.

In all cases the tuner positions (=Impedances or States) are set by a controlling computer, which also talks to GPIB instruments, collects and processes the data and generates printouts.

Some other Laboratories, including Universities, have developed their own Measurement setups, mostly using Active Load Pull and make the services available to outside customers.

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Terminology

This section explains the basic terms used in Load Pull or Noise measurements.

Active/Passive: An active device is one that generates more power (at a given frequency) than it absorbs. If we also consider the DC bias, then it is obvious that pure active devices do not exist. A transistor biased and tuned to produce Gain>1 is an Active Device. At a higher frequency or wrong tuning the same transistor may become passive (Gain<1). All non-transistorised devices, such as diodes, attenuators, isolators etc are passive.

Load Pull: Is a measurement technique in which the load impedance is modified using a tuner (pull the stub of a tuner). Part of the signal generated by the device (transistor) is returned with a modified amplitude and phase and interacts with the departing signal, modifying this way its operation (and Gain). The most usual tuning condition is 'matching', in which case the returned power is zero (the transistor is power matched).

Gain: Is the ratio (at a given frequency) of the power leaving the DUT to the power injected? The term Gain alone does not define anything. There are several 'Gains' used, according to the different powers involved:
Power Gain = The ratio of the power delivered to the Load and the power delivered to the DUT
Insertion Gain =The ratio of the output power after and before inserting the DUT in the chain
Transducer Gain =The ratio of the power delivered to the Load to the power injected (=available) at the DUT's input
Available Gain = The ratio of the power injected (= available) at the Load to the power injected (= available) at the DUT's input.
Maximum Available Gain (MAG) = The ratio of output power to input power when input and output are **simultaneously** matched.

The Load Pull Systems of FOCUS Microwaves deal with **Transducer Gain** only.

GPIB: General Purpose Interface Bus (HP uses the term HPIB) is a communication protocol between 'programmable' instruments. A 24-pin cable with 8 data lines (8 bit = 1 byte) and 8 shielded bus control lines establishes the communication between the different instruments. **One** of the instruments (one of the computers) is the System Controller. All other instruments are Peripherals. Any computer (HP, IBM-PC, Apple etc) can be used as a Controller as long as it is equipped with the proper GPIB Interface. The GPIB interface itself is a Microprocessor chip that receives and transmits data and sets the control signals. FOCUS Microwaves uses such an interface with the 7210 chip of NEC (or TMS 9914 of TI). Other, more sophisticated interfaces use VLSI microprocessor chips, such as National Instruments' AT card and others.

GPIB Driver: This term is used twofold:
1- It is a memory resident program, that is loaded when we boot the computer and makes the communication via the GPIB interface possible. The name of the driver for the FOCUS system is GPIBDRV.COM
2- It is a program code that is sent by the application program via the GPIB card to the instruments in order to configure them, trigger and read their response. We use also the term **Instrument Driver** for this later item.

Tuner Controller: Is an electronic circuit that communicates with the main computer and sets the electrical conditions (motor positions or PIN diode states ON/OFF) for different Impedances. MAURY, SARNOFF and ATN use external boxes in 19" racks that drive the tuners. **FOCUS** uses a PC Interface Card, which is inserted in the computer and drives the motors directly using proprietary drivers. This simplifies maintenance and possible points of failure.

Vibrations: For On-Wafer operation vibrations of mechanical tuners may be important. The tuners of **FOCUS** use timing belts between motors and axis. This attenuates the Vibrations during movement and initialisation. The total Peak Amplitude of the vibration of FREE MOVING tuners of FOCUS has been measured to be less than 1μm! If the tuners are fixed the vibration is even smaller. Vibrations can cause MICROPHONISM, i.e. a jitter of RF Impedance. The tuners of **FOCUS** use slotted slugs that always stay in spring-contact with the walls of the slab line. This eliminates Microphonics.

Power Contours: Are the loci of Load (or Source) impedances for constant Output Power. For small signal these contours are circles (Gain Circles) and can be computed from S-parameters of the device. The higher the power the larger the deviation of the Power Contours from circles.

Large Signal S-parameters: Scattering (S) parameters are defined for **small signal and 50Ω load/source impedances**. Small signal is the condition at which the behaviour of the device does not change during the signal raise and fall as it follows the sinusoidal excursion. For bipolar transistors small signal stops at 20mV input Voltage. Beyond this value the transistors become **Non-Linear.** FETs are more linear since the input section is a reversed diode, whereas in bipolars it is a forward biased diode. We can define Large Signal S-parameters at a given power level as the ratio of reflected and transmitted to injected power. But when we tune the device to increase Pout or Gain with Zs,ZL ≠ 50Ω then large signal S-parameters become invalid, since the device changes its behaviour as a function of the source and load impedances.

P1dB: Is the Output Power of a transistor at which its Gain has dropped (compressed) by 1dB as compared to the small signal case. Since the small signal Gain changes with load impedance, also P1dB changes with load impe-dance.

To accurately measure the P1dB contours a load pull system has to sweep the input power starting with small signal for each new load impedance so the real 1dB Gain Compression can be determined for each load. By consequence the input power is different each time. This is what FOCUS' software does. Other systems perform load pull measurements using the input power required to compress Gain by 1dB at Pmax or 50Ω. This does not provide accurate information.

Gain Expansion: Normally Gain should drop as we increase the input power. The impedances of a transistor however also change as we modify the input power. If in the course of increasing the input power the DUT's impedances come closer to the complex conjugate source and load impedances of the setup, then we may observe a higher Gain at medium power than at small signal, especially if we were not fully matched. This phenomenon is called Gain Expansion.

Small Signal Model: The microwave behaviour of a transistor can be described by equivalent circuits, i.e. networks that include R, L, C and controllable current or voltage sources. Between 10 and 15 such elements are sufficient to describe a FET's behaviour up to 20GHz quite accurately. The values of the elements are found by "curve fitting", i.e. modifying their values until a set of measured S-parameters is simulated in a frequency range. Small Signal Models are used by Universities for scientific reasons, i.e. in order to understand the transistor behaviour and optimised the processing to improve it. They are used in Industry mostly in order to scale devices, and to predict the RF behaviour of larger or smaller structures before making the processing masks.

Nonlinear Model: These are small signal Model that include internal components, essentially voltage controlled current sources and capacitors, which depend on the applied voltages to the transistor. Different techniques have been used in the 80's to simulate the non-linear behaviour of transistors, such as the Volterra equations and the Harmonic Balance method.

Non-linear Model are quite useful for understanding the physical behaviour of the transistors and scaling analysis.

Used in Amplifier or Mixer design however, the data provided by non-linear Model are valid for light compression only. At 2 or 3 dB Gain compression, the results provided by a Non Linear Model are rather inaccurate.

They have been used, however quite often in the past for a number of reasons some of which are:

- Unavailability of adequate Large Signal measurement setups
- High expectations created by scientific publications and Marketing strategies
- Convenience for the Operators
- Easy to modify "modelling conditions"
- A relatively lower investment compared to a full setup (including Load Pull System, Power Meters, power Sources, Network Analysers etc)
- Easy to be operated by Junior, Computer oriented Engineers.
- Model Libraries

Meanwhile more and more laboratories realize that **Design Data** should be generated by, now available, **Load Pull setups.** However it still has to be considered as a competitor to the Load Pull systems as such.

The most well known Non Linear packages are:
- Libra (EESOF)
- MDS (HP)
- Harmonica (COMPACT)

Tuning Resolution: This is the number of independently setable states (impedances) a tuner system can realize. Manual tuners have infinite resolution: Each point on the Smith Chart can be tuned. Automatic systems have resolutions between a few million impedances (FOCUS) and a few hundred (ATN). For an automatic system, it is very important to know the S-parameters of the tuners for each tuned impedance. This can be done either by calibration (ATN, MAURY), by Model (SARNOFF) or by Calibration and subsequent numerical Interpolation (FOCUS). The result is the number of points that can be tuned and measured upon.

Typical Tuning Resolutions:
1. SARNOFF (100,000 or more)
2. ATN (300 to 1000)
3. MAURY (200-400)
4. FOCUS (500,000 to 10,000,000)

Is Fine Tuning Important?

Fine-tuning is not important for Noise Measurements, because Noise is a linear phenomenon, simply described by one formula.
Fine Tuning is very important for Load Pull, because the transistors have to physically "see" the source and load impedances required to generate an actual Gain or Output Power. The more points that can be tuned the more accurate the characterization of the devices.

However: If we only increase the number of calibrated points without introducing numerical interpolation techniques, then the time and the computer memory required to calibrate such a system will increase proportionally.

How do we Interpolate?

In order to interpolate effectively and accurately we have to fully understand the physical behaviour of the tuners. This has been done by FOCUS and SARNOFF: both systems include efficient interpolation algorithms.
Because SARNOFF system is based exclusively on a model, it's inherent accuracy is limited to about 0.02 to 0.05 reflection factor error. This performance is not always sufficient.
FOCUS tuners are calibrated at distinct impedance points regularly distributed over the Smith Chart and then a second order Interpolation between adjacent points is being carried through. This provides accuracy of about 0.001 reflection factor units.

How Much Tuning Resolution is Required?

Many tests with high power transistors have shown that we should be able to tune accurately within 0.5 Ω or less in the 3 to 6 Ω area of the Smith Chart. This corresponds to $\Delta\Gamma \approx 0.017$ and $\Delta\_ \approx 1°$ and requires a minimum tuning capability of 21,000 impedance states. As it can be seen from previously listed data, only SARNOFF and FOCUS tuner systems are capable to generate such a tuning capability, the FOCUS system being, in addition, about five times more accurate than the SARNOFF system.

Measurement Techniques

Noise Characterization

Noise Parameter: These are four numbers that fully describe the Noise behaviour of a noisy device (two port) at a given frequency. For practical reasons we use the following quantities as Noise Parameter:
1- Minimum Noise Figure **NFmin:** This is the smallest Noise Figure that the device can reach at a given frequency and bias, if it is optimally matched at the source.
2- Equivalent Noise Resistance **Rn:** This is a number with the dimension Ohm (Ω) that indicates how fast the Noise Figure increases when we mismatch the input (source).
3-4 Optimum Noise Reflection Factor **Γopt**, is often used also as Optimum Admittance **Yopt:**
Is the source admittance required for the DUT to have NFmin.
The Noise Figure does not depend on the Load impedance presented to the device. It only depends on the Source Impedance. A simple relation exists between the four Noise Parameters

$$\text{Noise Fig}(Y_s) = NF_{min} + \frac{R_n}{G_s} \left| Y_s - Y_{opt} \right|^2 \quad [1]$$

where $Y_s = G_s + jB_s$.

$$\text{Since} \quad Y_s = \frac{1 - \Gamma_s}{1 + \Gamma_s} * Y_0 \quad [2]$$

[1] can be expressed also in the form NF (Γ_s).
This is the equation of a set of Circles on the Smith Chart (**Noise Circles**) for which the value of the Noise Figure is the Level on each Circle.
This Circle Representation is only possible because the **Noise behaviour** of transistors is a **Small Signal Phenomenon.**

Measurement of the Noise Parameter:
The 4 Noise Parameters can be determined if we measure the Noise Figure of a device at 4 different source impedances (4 unknowns).

Because of errors associated with the extremely low level noise measurements (the typical noise power of a transistor is about -110 dBm in 1 MHz bandwidth = the Noise Power is directly proportional to the Bandwidth) in general we measure at more than 4 impedances and average the measured data. 7 to 10 impedances are typically sufficient for the determination of the noise parameter at each frequency. The setup required to measure the Noise Parameter includes:

- A Noise Analyser (HP 8970 A/B)
- A Noise Source
- A Programmable Tuner
- A mixer and Local Oscillator (for f>1.8GHz)
- Isolators, bias tees etc.

Contrary to Load Pull measurements, it is not absolutely required to **pre-calibrate** the Tuner used in Noise Measurements. It can be set to a number of positions and readings can be taken, both of the Noise Figures and the Tuner positions. If the tuner is then characterized at those positions using a Network Analyser, the 4 Noise Parameter can be calculated. This is only possible because of equation [1].
If the tuner is pre-calibrated, of course this facilitates a lot the operation and the result can be computed immediately. Again, a non pre-calibrated tuner will **not permit to tune** to the minimum Noise Figure; it will only permit to **compute it**.

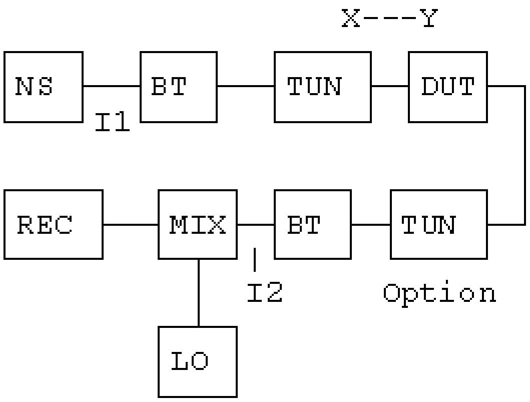
Important Remark:
In Large Signal (Load Pull) an equation like [1] does not exist, because the behaviour of the devices is non-linear, i.e. the gain of the transistor changes during the excursion of the sinusoidal signal. Consequently we need to know, during the measurement, what the loss of the tuner is; otherwise we cannot find the optimum Gain (or Power).
NS=Noise Source (Solid State)
BT=Bias Tee
TUN=Programmable Tuner. Output Tuner can be omitted
DUT=Device Under Test with Test Fixture. Includes Wafer Probe stations
MIX=Mixer
LO=Local Oscillator
REC=Receiver, typically HP-8970 or HP-8970/71

Effect of Second Stage on Noise: The Noise Figure of a chain of amplifiers mostly depends on the first stage, especially if this has high gain.
The effect of the following stages is divided by the gain of the preceding stages.
The formula of FRIIS describes this as follows:

$$NFtotal = NF1 + \frac{NF2-1}{G1} + \frac{NF3-1}{G1*G2} \ldots \quad [3]$$

Here G1, G2 is the Available Gain of each stage.

In a Noise Measurement setup we measure NFtotal and have to correct for the second stage (receiver) effect using calibration techniques.



Noise Temperature Tn: Is the temperature (in Degrees Kelvin) of a resistance connected at the input of the device, that will generate as much noise power at the output of the device as the device itself.

$$NF = 1 + \frac{Tn}{T0} \quad \text{where } T0=290K\ (17°C) \quad [4]$$

Example: 1dB Noise Figure corresponds to 75.1K
0.5dB NF corresponds to 35.4K.

A Noise Measurement setup

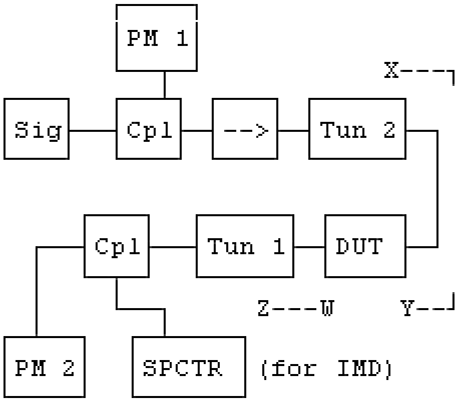
It is advisable to use isolators directly after the noise source (I1) to eliminate the ON/OFF change in source impedance.
If only an input tuner and no output tuner is used (classical FOCUS approach) then a second isolator (I2) is **required** after the output bias tee.

The **CRITICAL SECTION** of a noise measurement setup is the **area between the RF slug of the tuners and the DUT (X--Y).** The reflection and **insertion loss** of this section has to be **MINIMIZED by all means and expenses**.

Cold Noise Source Technique: This is an alternate measurement technique, which does not use a Hot/Cold noise source to set the reference noise level at the source. Instead it uses a passive 50Ω load at T0=290K and measures the variation of the noise power at the output of the receiver as a function of source impedance. This technique has the advantage of being independent of the tuner losses as a calibration quantity. ATN (and recently TWIN software of FOCUS) use this method, ATN because of the high loss of their tuners and FOCUS to improve accuracy for noise figures smaller than 0.7dB

Load Pull Characterization

Why do we NEED Load Pull Measurements?
Any setup including a transistor can be optimally matched at a single frequency using molytabs, or manually adjustable tuners.
This however does not mean that the transistor itself is optimally matched; only the **combination of transistor and tuning circuitry** is matched. We do not know if the transistor would perform better at another load, where the tuner itself would have more loss and would over compensate the excess gain of the transistor.



In order to find this out we **need** a tuner that has been **pre-calibrated.** An automatic tuner alone is not enough. The **Calibration of the Tuner** has to be done **previous to the measurement**, or the search for the maximum. Only this way, we can display during the measurement, the net Gain or Pout referenced to the transistor terminals.
This is not a detail. It may make differences of more that 1 dB (possibly 2 dB) in amplifier performance, especially if we have to **Design an equivalent matching network**.
Another advantage of Load Pull measurements is the fact that we can easily sweep the frequency and collect data over a wide frequency range in order to be able to design wide band matching networks.

Why do we Need Automatic Load Pull?

Automatic Load Pull is **needed**

1. To solve a **theoretical problem** =separation of tuner Loss from Gain of the transistor **during** the measurement
2. To solve a **practical problem**
   = collect accurate data automatically over a frequency range in order to design amplifiers, oscillators etc.

During Automatic Load Pull all Impedance and Gain (Power) data are DE-EMBEDDED back to the DUT reference plane, so all results shown are NET-DUT data.

A Load Pull Setup

PM 1,2	GPIB Power Meter
Sig	Signal Source (2 needed for IMD)
Cpl	Directional Coupler
SPCTR	Spectrum Analyser

The **CRITICAL SECTION**S of a Load Pull measurement setup are the **areas between the RF slug of the tuners and the DUT (X--Y, Z--W).** The reflection and **insertion loss** of these sections has to be **MINIMIZED by all means and expenses**.

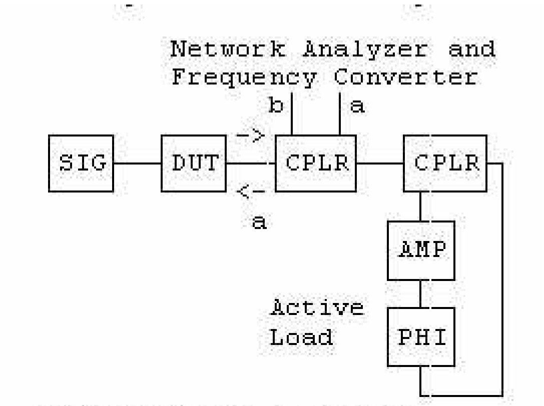
Active Load Pull

This is a measurement technique that permits to generate a "virtual load" to the DUT by injecting in the output terminals a signal synchronized with the signal flowing thru the DUT and not by reflecting it on a passive load (tuner). There are two ways of generating this injected signal:

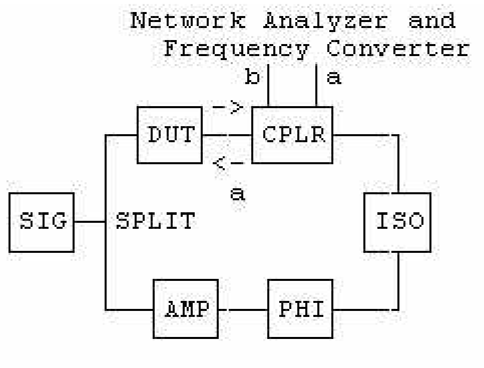
1. By splitting the source signal before it enters the DUT, amplifying and de-phasing it and injecting it at the output via a bypass ("Takayama" method)

2. Using an "active one port load", i.e. an amplifying loop which receives part of the outgoing signal modifies its amplitude and phase and re-injects it into the output port of the DUT.

In both cases by changing the gain (AMP) and phase (PHI) of the feedback we re-inject to the output of the DUT the controllable power wave a. Since the load reflection factor Γ_L = b/a we have control over the load.



"Active Load" load pull



"Takayama" active load pull

Takayama's method has the advantage of relative simplicity, since the loop cannot oscillate. It has the disadvantage that if input power is increased (power sweep) the load has to be re-synthesized since b changes independently if the DUT saturates (gain of DUT changes, whereas gain of bypass loop is constant). In the case of the active load method this is not a problem, as long as the AMP is linear. However the setup is more complex and requires filters and other precautions to avoid oscillations.

Why Active Load Pull?

There are two reasons:

1. Active load pull permits to generate a reflection factor up to 1 or higher independently on the losses of the test fixture. This is most important for "on wafer" operation, because of the (still) relatively high losses of the probes.
2. It is possible to extend an active load pull setup to "harmonic load pull", i.e. re-inject signal power at harmonic frequencies and control this way the load impedance at harmonic frequencies.

Both features are practically impossible to accomplish using passive tuners only.

What is the Price?

The price is high! Both in $, complexity of operation and convenience (speed):

1. There is a much more complex setup to realize. On top of adjustable phase shifters, attenuators, YIG filters and associated electronics a simple Network Analyser is not enough to run the system. It requires separate access to both the injected and reflected signals at the output of the DUT (Frequency Converter).
2. Impedance setting cannot be pre-calibrated. Each time we need to tune the output we have to run a Search Routine, which will adjust AMP and PHI as a function of the actual a and b in order to generate the desired ΓL. This is time consuming.
3. There is no such a system commercially available.

What are the Alternatives?

The alternative for generating high Reflection Factors, despite losses of the test fixture is to use impedance transformers. Using transformers limits the instantaneous bandwidth of the setup but generates very high reflection factors and improves measurement accuracy. This technique however cannot be applied for "on wafer" tests.

In the case of "on-wafer" the only alternative is to lower the loss of the probes and the cables to the tuners. At this point both CASCADE and GGB offer probes with losses in the few tenths of a dB up to 40 GHz.

With high reflection tuners used, a reflection factor of 0.82 (10:1) at DUT reference level is possible (Z=5 Ohms) for wafer tests.

There is no practical alternative for Harmonic Load Pull. This test would require high quality tuners coupled to wideband very low loss frequency multiplexer, which is technically practically impossible. Any lossy component such as YIG filters to control signal components independently will reduce the tuning range to unacceptably low level of reflection factors.

Index and Keywords