Power Pull: An unconditionally stable active Load-Pull measurement system

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ABSTRACT

For today's communication circuits optimum operational conditions for almost every Tx power amplifier is one of the most important parameters. Only this will offer maximum power added efficiency and output power. For the experimental determination of these conditions load-pull measurements are the best solution. To compensate losses of the setup for on-wafer measurements an active load-pull measurement system is required. The **Power Pull** load-pull system combines all advantages of active load-pull measurements with an absolute stable configuration. It prevents oscillation of the measurement setup as well as of the transistor under test for large signal operation. Therefore, this configuration easily allows the complete characterization of transistors for optimum matching within power amplifiers.

INTRODUCTION

Today, limited DC power consumption is one of the most important restrictions in mobile communication techniques. In combination with maximum output power of the Tx amplifier these parameters determine the commercial success. For this reason the optimum output, and also associated input, matching network has to be designed. If an accurate nonlinear model for the transistor is available this is no problem. But in most cases the quality of nonlinear models near saturation is not sufficient for this purpose or the accuracy has at least to be checked experimentally. These nonlinear measurements for the characterization of the device properties for different load impedances and input power levels are called load-pull. By the variation of the load impedance and simultaneously measuring output power and input impedance (as well as other parameters like gain and harmonic power) an optimum load impedance (together with all associated parameters) can be determined for specific criteria. This may be a combination of power added efficiency (PAE), output power, and gain. One of the commercially available solutions for such measurements is the **Power Pull** system. It offers all the possibilities of active load-pull measurements while preventing the problems of oscillation. The differences between load-pull measurement methods will be explained in the following chapters.

PASSIVE LOAD-PULL MEASUREMENTS

There are two main principles for load-pull measurements: passive and active load-pull. There are two or three basic methods for the realization of passive tuners:

1. Attenuator / phase shifter combination (Figure 1)
2. Stub tuner (Figure 2)
3. IQ modulator (similar to method 1).

For the first setup magnitude and phase of the reflected wave is controlled separately by attenuator and phase shifter. This separation makes the understanding and control easy but the sum of the insertion losses of both elements is relatively high.

Stub tuners can almost cover the complete unit circle but the setting is complicate. For this purpose a pre-calibration is required to select load conditions which cover the load region of interest in a homogeneous manner. Mechanical stub tuners require high mechanical reproducibility (due to the pre-calibration) but usually have lower losses and almost no limitation in power. Electronical stub tuners are utilizing PIN switches. This causes higher losses and limits the power handling capability. Real high power applications can hardly be measured using a passive load-pull measurement system.

Passive load-pull can easily be used if losses of the measurement setup together with the losses of the passive tuners do not restrict the measurement capabilities. This is only valid at low frequencies (below 1 GHz) if on-wafer power devices have to be characterized. Even for such transistors the determination of the load impedance for maximum output power may fail. For high power transistors the optimum load reflection is very large (about 0.95, Figure 3). In Figure 4 the power dependence of input impedance, output power, and gain is shown. Here is input match is strongly related to the power. Such high load reflections required for power transistors can not be realized if losses are too high. Losses are caused by the probe tips (Figure 5) and bias tees (Figure 6). Furthermore, passive tuner systems inherit losses due to interconnections and movable terminations (mechanical tuners) rsp. PIN switches (electronical tuners). These losses of the passive 1-port tuners are in the order of 0.45 dB according to [7], [9]. For a frequency of 1.8 GHz the sum of losses is:

$$\alpha_{Sum} = \alpha^2_{ProbeTip} \cdot \alpha^2_{BiasTee} \cdot \alpha_{Tuner} = 2 \cdot 0.05dB + 2 \cdot 0.1dB + 0.45dB = 0.75dB = 0.917 \qquad (1)$$

In the above formula the bias tee is located between DUT and load. In a different setup the bias tee is behind the load. This reduces the RF losses (about 0.2 dB) but increases the DC losses (about 1 Ω). The influence of these losses has to be taken into account for voltage control and PAE calculation.

Other losses due to cables and interconnections are not taken into account. Referring to Figure 3 a maximum achievable reflection factor of 0.9 may not be sufficient to characterize a high power device. To overcome this problem active load-pull setups are required. For this purpose 1-port or 2-port active load systems can be used while passive loads may be realized by using 1-port tuners.

ACTIVE LOAD-PULL MEASUREMENTS

The active 1-port load (Figure 7) works like a passive tuner with additional amplification. The main problem of this setup is the danger of oscillation. Together with the output reflection of the DUT (S_{22}) and the internal reflections of the load there is a closed loop (attenuator, phase shifter, amplifier, DUT output reflection). If the loop amplification is larger than 1 oscillation will start. This can occur at almost arbitrary frequencies. To prevent oscillation an additional YIG filter (not shown in Figure 7) is introduced which reduces the off-band loop amplification. But there is still the possibility that the active load may oscillate either in-band or outside the reject band of the YIG filter. Furthermore, the losses of YIG filters are very high and have to be compensated by an additional amplifier. Drift of the YIG has to be prevented by an appropriate hardware setup (frequency and temperature dependent current control).

All above mentioned 1-port tuner systems can be pre-characterized. That means that the reflection factor is directly measured at calibration time (for passive as well as active tuners). For the active load this of course requires that the load amplifier always operates in the linear region (magnitude and phase). Furthermore, the setting of amplitude and phase has to be reproducible. If mechanical parts are used this requires very accurate fabrication, as well as a good motion strategy (e.g. setting always in the same direction). Additionally, thermal stability is required. This not only includes the tuner itself but also all connection cables.

Another method for an active load is shown in Figure 8: the active 2-port load. This load is directly driven by the RF source. It does not depend on the DUT's output signal. Therefore, there is no closed loop and oscillation is not possible. Now a little bit more about the functionality of this configuration: The main part of the RF source output signal is amplified and then sent to the input of the DUT. A minor part is coupled out, modified in amplitude and phase (like for the passive 1-port load in Figure 1) and then amplified. This load amplifier is always necessary to guarantee the required load reflection factors. The isolator will protect this amplifier against over-load conditions enforced by the DUT's output signal. Due to the fact that the DUTs' output signal and the load amplifier signal are coherent this setup works like every other more conventional passive or active load. For the DUT the load reflection (2) is only determined by the relation of power waves at output side (Figure 9):

$$\Gamma_{Load} = \frac{b_2}{a_2} \tag{2}$$

Because the power wave b_2 is controlled by attenuator and phase shifter as described above and a_2 depends on the DUTs' gain it is easily possible to control the load impedance in an predictable manner.

THE *POWER PULL* MEASUREMENT METHOD

The active 2-port load can not longer be pre-characterized due to the fact that the load reflection factor now depends on the DUTs' output power. Therefore, the measurement system has to determine all four power waves (Figure 8 and Figure 9). This method is used for the **Power Pull** and **Power VNA** measurement systems ([11], [13], [15]). Both systems are based on an VNA as free running receiver which can measure not only at fundamental frequency but also at higher order harmonics. The **Power Pull** system is the load-pull extension of the nonlinear **Power VNA**. Utilizing this measurement strategy allows the easy determination of input reflection, load impedance (for fundamental frequency and higher order harmonics), gain, output power (again for fundamental frequency and higher order harmonics), bias parameters, and PAE. Because the load condition is measured on-line, linearity as well as reproducibility of the load is not longer a problem. Therefore, very high mechanical or electronical accuracy is not required and less expensive tuners can be used.

To achieve accurate parameter extraction for nonlinear models stable thermal conditions are necessary. The self-heating effects of high power transistors normally not only depend on the bias parameters but also on the RF conditions. This results from different temperatures for each measurement. To overcome this problem pulsed measurements are used. This means bias as well as RF power are only switched on with such a duty cycle that heating can be neglected. This feature is available for both **Power VNA** and **Power Pull** measurement systems.

To achieve the best PAE the optimum load condition has to be realized not only for the fundamental frequency but also at higher order harmonics. Harmonic load-pull can easily be added to a **Power Pull** system by introducing another load path including a frequency doubler. This active harmonic load-pull system can again easily be controlled because fundamental and higher order harmonic load impedances are individually controlled. This procedure guarantees that the complete Smith chart can be covered even at higher frequencies. This is not possible if passive load-pull measurement systems are used. According to (1) the losses for the first higher order harmonic (3.6 GHz) will be in the following order:

$$\alpha_{Sum} = \alpha^2_{ProbeTip} \cdot \alpha^2_{BiasTee} \cdot \alpha_{Tuner} = 2 \cdot 0.1dB + 2 \cdot 0.2dB + 0.91dB = 1.51dB = 0.84 \tag{3}$$

Because the optimum load condition for the harmonics is normally at very high reflection levels the result for passive harmonic load-pull systems according to (3) will not be sufficient. This impressively demonstrates the necessity for active harmonic load-pull measurements.

POWER LIMITATIONS

It is important to check the power handling capability of load-pull measurement systems before every measurement. Otherwise the measurement stand can easily be destroyed (at little bit expensive) or the measurements will not deliver the required results (you have wasted time). From small signal considerations and the expected maximum output power the power waves within the measurement system (Figure 9) can be calculated. Let us assume that the transistor will deliver a maximum output power of $P_{2c}=5W$ at a load reflection factor of $|\Gamma_{Load}|=0.9$. Analog to the assumption in (1) the losses of probe tip and bias tee are $\alpha=0.15dB$. With

$$P_{2c} = |b_2|^2 - |a_2|^2 \tag{4}$$

and (2) the power wave b_2 results as

$$|b_2| = \sqrt{\frac{P_{2c}}{1-|\Gamma_{Load}|^2}} \tag{5}$$

what is for the given values $|b_2|=34.2dBm=2.6W$. To perform a successful measurement the Test-Set and tuner need to handle this enormous amount of power which is much higher than the usable output power of the transistor without destruction. Furthermore, for such high load reflection factors passive load-pull measurements are very difficult. Therefore, active load-pull is required (for saturation the optimum load reflection factor is normally higher than under small signal conditions). In this case the power wave a_2 results as:

$$|a_2| = |\Gamma_{Load}| \cdot |b_2| = \sqrt{\frac{|\Gamma_{Load}|^2}{1-|\Gamma_{Load}|^2} \cdot P_{2c}} \tag{6}$$

what is $|a_2|=33.3dBm=2.1W$. To calculate the maximum load amplifier output power P_{Load} the measurement setup losses have to be taken into account:

$$P_{Load} = \left(\frac{|a_2|}{\alpha}\right)^2 \tag{7}$$

This results a minimum required power of $P_{Load}=33.7dBm=2.3W$. The **Power Pull** load-pull measurement system is available for real high power applications. Selecting appropriate couplers and load amplifiers the characterization of almost every device is possible.

CONCLUSION

In this paper the advantages of the **Power Pull** measurement system concerning absolute stability of the measurement setup as well as power handling capabilities have been shown. This gives a short introduction into the requirements for the measurement setup needed for the characterization of high power devices. But only by using such advanced method for the characterization of transistors the designers have access to the data required for the development of modern communication circuits. These measurements will directly deliver the information about optimum load and input impedance, output power, gain, and power added efficiency. The measurement system can be extended for pulsed measurements (to compensate heating effects), harmonic load-pull (to achieve the last few percent of PAE), and ACPR optimization (for CDMA amplifiers).

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FIGURES

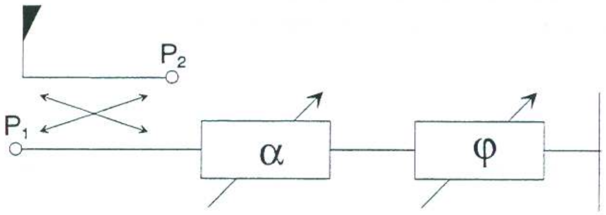

Figure 1: Passive 1-port load: Attenuator / phase shifter combination

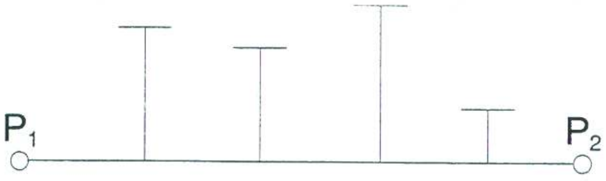

Figure 2: Passive 1-port load: Stub tuner

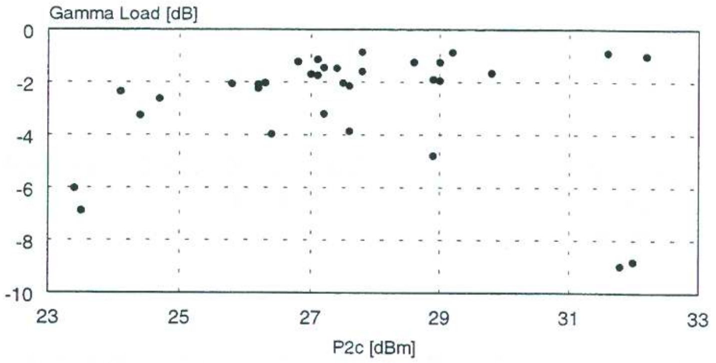

Figure 3: Load reflection factor of GaAs HBTs and SiGe BJTs

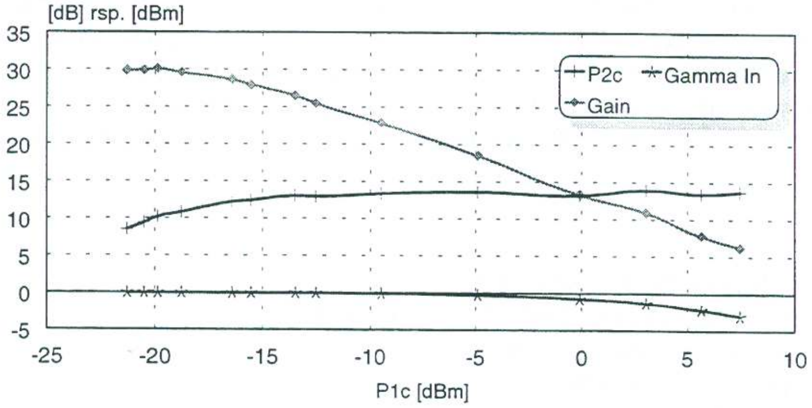

Figure 4: Input power dependence of output power, input reflection factor, and gain.

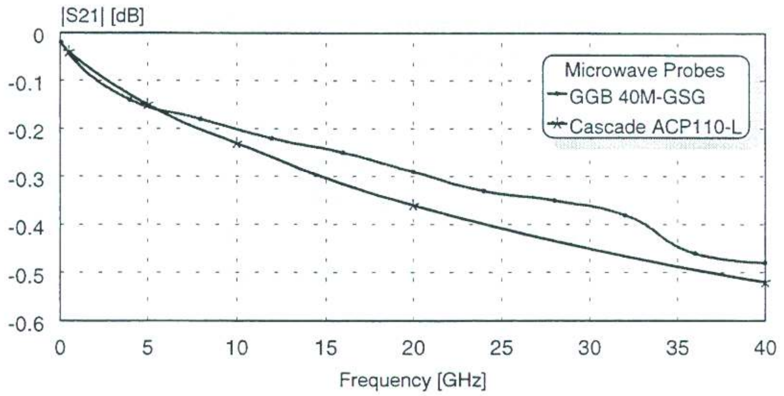

Figure 5: Losses of RF probe tips according to [1], [2]

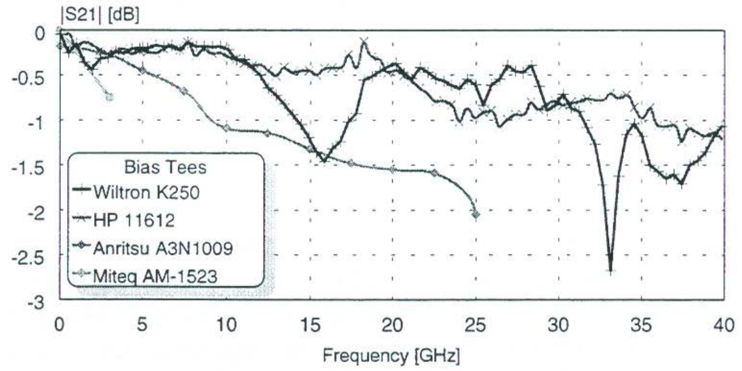

Figure 6: Losses of bias tees according to [3], [4], [5], [6]

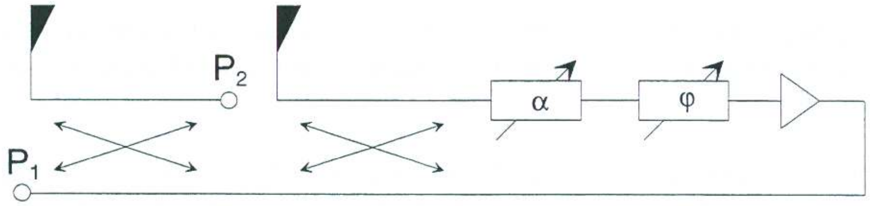

Figure 7: Active 1-port load: Attenuator / phase shifter combination with amplifier

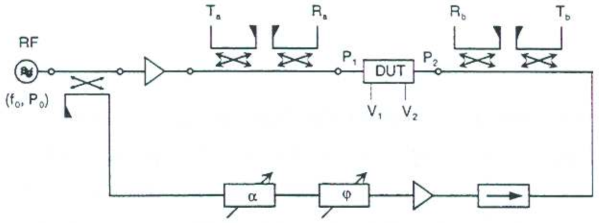

Figure 8: Active 2-port load

Figure 9: Definition of power waves