

# LOAD PULL TECHNIQUES FOR MILLIMETRE-WAVE DEVICE CHARACTERISATION

U. Pisani, A. Ferrero, G.L.Madonna  
Dipartimento di Elettronica  
Politecnico di Torino  
Corso Duca degli Abruzzi, 24, Torino, Italy  
e-mail: pisani@polito.it

## ABSTRACT

*Load-pull experimental characterisation of active devices under non linear operation is a well proved technique still used in designing power amplifiers. When applied to the MMIC, this technique shall require special solutions to be extended to on-wafer devices up to millimetre waves. The paper presents an overview on the traditional load pull measurement techniques focusing the attention on millimetre wave application. An example of a fully automatic on-wafer system is described along with the more useful calibration techniques. By means of this test set a very detailed characterisation of devices can be carried out in short time, by setting the loads either at the fundamental or at the harmonic frequencies with independent controls.*

## INTRODUCTION

The load pull approach is widely used to characterise microwave transistors in large-signal operations for microwave power amplifier design and non linear model validation. The load pull technique consists on measuring the device performances at a single frequency under different loading conditions. Typical measured quantities are: power gain, gain compression, input impedance, efficiency and so on. The constant level contours of these quantities, drawn on the load impedance complex plane, give a detailed description of the transistor behaviour and allow to synthesise the matching networks to accomplish the desired specifications.

The measurement presents several problems:

- the need for a variable load with sufficient resolution covering the widest area of the Smith chart,
- the accurate knowledge of the set load, which can be obtained by a previous load calibration or by real time measurements, possibly without disconnecting it from the device output,
- the ability to measure, for each load, all the most significant device parameters

To get a variable load, mainly two groups of techniques can be used:

- passive networks with variable elements ( slug tuners, switch controlled loads and so on) [1, 2, 3]
- active load where the reflection coefficient is obtained using an auxiliary signal, locked to the input signal generator, injected into the output port of the device [4,5].

Millimetre wave load pull measurements are mainly devoted to on-wafer devices. The increase of probe connector mismatches and cable losses makes the use of passive networks, as variable loads, unfeasible. In fact the passive load has intrinsic losses which prevent from exploring the high reflectance region of the Smith chart and in particular the low impedance area generally interesting for the device behaviour. To overcome this problem an impedance adapter has been proposed between the tuner and the D.U.T. reference plane, but this solution is unfeasible for on-wafer measurement unless such adapter is integrated into the probe [20]. The active load is the solution to

the loss problem since, by controlling the amplitude of an auxiliary signal injected into the device output, the magnitude of the load reflection coefficient can be set beyond unity, so compensating for losses introduced by the measuring systems.

## TWO SIGNAL TECHNIQUES

The original "two-signal" technique, as proposed in [4], is sketched in figure 1. A power divider is used to split the source test signal into two parts: the first one drives the input port of the device which generates the waves outgoing from the output port  $b_2$ . The second one, properly amplified and phase shifted, injected into the device output port as  $a_2$ . The load reflection coefficient  $a_2/b_2$  can be changed by varying the amplitude and the phase shift of the auxiliary signal  $a_2$  playing on the variable gain amplifier and the phase shifter.

The main drawback of this technique consists in the difficulty to keep the load constant when the input power changes. Since  $a_2$  is independent from the outgoing travelling wave  $b_2$ , when the latter changes, due to a different device behavior, the *active load* moves and consequently affects the transistor performances. An automatic procedure based on a successive approximation which keep the load constant has been proposed in [6].

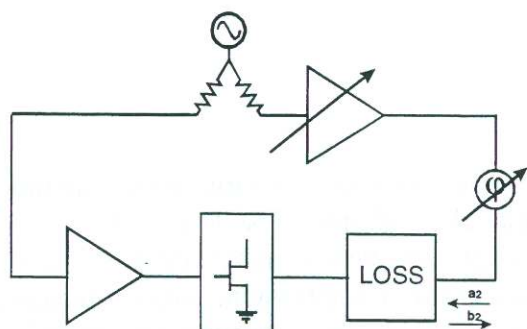


Figure 1. Block schematic of the two signal Technique

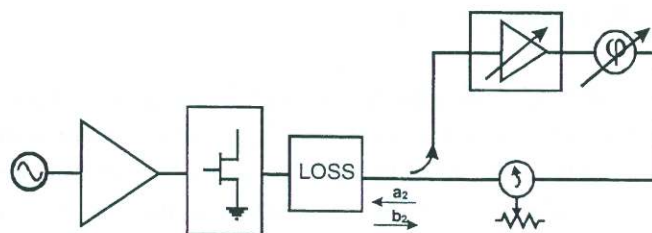


Figure 2. Block schematic of the active load loop

## THE ACTIVE LOAD LOOP

The active load loop, originally proposed in [5] and sketched in figure 2, simplifies the load setting procedure. A sample of  $b_2$  from the directional coupler is properly amplified, phase shifted and injected back in the transistor output port by a circulator as  $a_2$ . It can be easily demonstrated that the load reflectance magnitude, set at the transistor output, ideally depends on the loop gain, while the load phase depends only on the loop phase shift. This technique allows to change the amplitude and the phase of the load reflectance independently from each other and independently from the behaviour of the transistor under test. An high selectivity filter has to be introduced in the loop to avoid possible instabilities due to the relative broad band of the loop components and it makes the active load frequency selective (see figure 3).

At microwave frequencies an ordinary solid state amplifier can be used [14] with a variable attenuator and pin diode phase shifter, but for millimetre wave applications an high power, high gain TWT amplifier, waveguide attenuator and phase shifter are mandatory. Such components rises the overall system cost far above the one at microwave frequencies.

## LOAD PULL TEST SETS

Several test set has been proposed for automatic load pull measurements, from computer controlled tuners up to six-port based test set [2,7]. We will focus on those systems which have been used up to millimetre bands. A block diagram of the main components of such systems, based on the active load loop and a network analyzer is shown in figure 3.

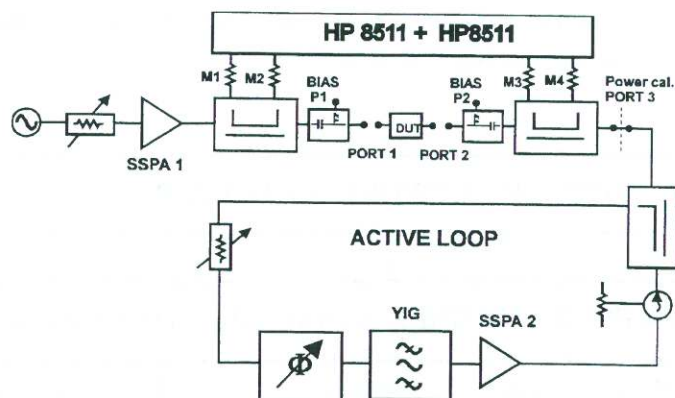


Figure 3. Block schematic of the load pull test set using the active load loop

The vector network analyser performs a real time measurement of all the d.u.t. load pull parameters by means of dual directional couplers and a four channel harmonic converter which sample the input and output device waves.

The loop gain recovers the losses between the output port and the active load loop and allows for setting up to unitary reflection coefficients at the probe tip. Since the load can be electronically controlled a computer can completely automate the measurement process. Particular calibration procedures were developed to de-embed the raw data from the mismatches introduced by the probes itself and the directional couplers. This test set allows for automatic input power sweeps along with load pull contouring.

This solution has been evolved from its basic development [8] to more sophisticated systems which includes harmonic capabilities [9], 50-60 GHz bandwidth [10,11], intermodulation and ACPR measurement [12], integration of load pull and S-parameter measurement capabilities [13].

Since the harmonic terminations can contribute to the device performances, recent development focus on the harmonic load pull techniques [3,7,10]. The active load loop technique has been extended to set different loads at the harmonic frequencies, by adding other loops with the pass-band filter tuned on different harmonics [9, 14].

## SYSTEM CALIBRATIONS

The test set, shown in figure 3, allows to measure, by means of a network analyser, the large signal vector quantities at the device ports, and the direct and reverse gains. Furthermore absolute power levels have to be measured to define the input and output powers. No power meters are used for this task, but the same NWA, after a proper calibration, acts as an absolute power level receiver [16].

Figure 4 sketches the power waves and the reference planes involved in the calibration process. A technique to calibrate this system for absolute power levels was first developed in [15-16], but it is only applicable to coaxial systems, since it requires an absolute power measurement directly to the device port during calibration. To extend this technique to on-wafer measurements, either an on-wafer power sensor need to be used or a de-embedding procedure has to be carried out to remove the wafer probes effect. In the latter case the input probe needs to be disconnected at section 1 to

allow for a conventional power sensor insertion; moreover three coaxial loads plus 6 on-wafer loads are required by the de-embedding procedure.

When testing devices with on-wafer microprobe stations at millimetre waves, the use of semi-rigid cables with stiff connections is mandatory at least between sections 0-2 and between sections 3-5 of the figure 4. Thus recurrently disconnecting the couplers from the microprobes after the calibration affects the overall system accuracy.

A technique which performs both the vector and the power calibrations at the on-wafer probe tips, without breaking the coaxial-to-wafer signal path and without requiring either power sensors or probe de-embedding procedures, is suggested in [17].

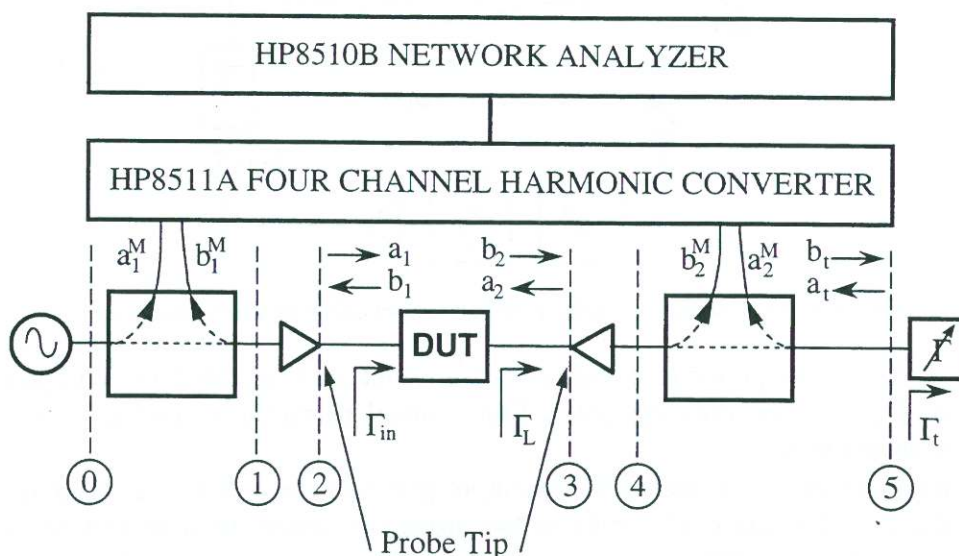


Figure 4. Test set block scheme and definition of the reference planes

This technique is accomplished with the introduction of an error model for the output dual directional coupler which extends the reference plane from the on-wafer probe tips to the coaxial section 5 for the absolute power level calibration. According to the suggested error model, a coaxial power meter connected, during the calibration, at the section 5, provides a power reference value that can be extended up to the on-wafer probe tips, without breaking the coaxial-to-wafer signal path. The procedure consists in a four steps. First the input reflectometer is calibrated by connecting at section 2 three on-wafer standard loads, like an open, a short and a matched load, following a classic one-port error box model. Then an ideal zero length "thru line" is inserted between the two probes so that the sections 2 and 3 of figure 4 become coincident.

Three standard coaxial loads are connected at section 5 and their reflectances can be correctly measured at the probe tip 2 by means of the calibrated input reflectometer. At the same time these standard loads are roughly measured by the output dual directional couplers and linear system of three equations can be written using these raw measurements and the corrected ones. The system solution gives the error parameters of the error box which shifts the reference plane from the section 5 to the section 3. Finally a power meter is inserted at section 5 to calibrate the absolute power levels at the d.u.t. reference planes.

Recently a more complete solution, based on a TRL like approach, has been develop which integrates load pull and s-parameter calibration. This new algorithm is based on the insertion of a Thru, a Line and a fully know Reflection (generally a Short) at the on wafer reference planes plus

three coaxial standards and a power meter at section 5. This technique avoids the use of both the load and the open on-wafer standards and allows for the integration of custom standards (simply a Thru a Line and a Short) on the same substrate of the measured devices [19].

## PERFORMANCES OF RECENT MILLIMETRE SYSTEMS

A brief review of recently developed Load Pull system performances at millimetre wave is here presented. The first example was presented in [8] where an in-fixture millimetre system based on a NWA and a two ways active loop was introduced. In [10] Hughes and one of the authors presented the first on-wafer millimetre test set which makes S-parameter, fundamental and harmonic load pull up to 50 GHz. This system has been upgraded to accomplish for intermodulation and ACPR measurement and it is today widely use to characterise both devices and MMICs [12]. A 26-40GHz system based on the two signal technique is presented in [6] while in [18] a 60GHz harmonic system was introduced and used to characterise harmonic multipliers.

In figure 5 and 6 some typical load pull results on an HEMT device at 19GHz are given. Figure 7 shows the fundamental gain and the harmonic output powers corresponding to an input power sweep for a 12 GHz power amplifier, and figure 8 shows the millimetre test set realised at the Politecnico di Torino for Alcatel-Telettra.

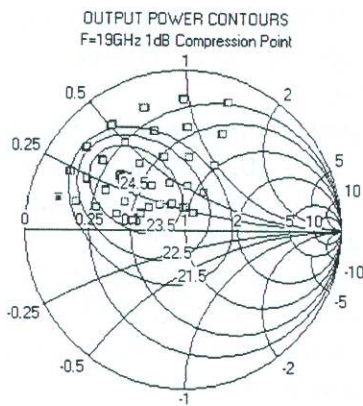


Figure 5. Output power contours @ 1 dB compression

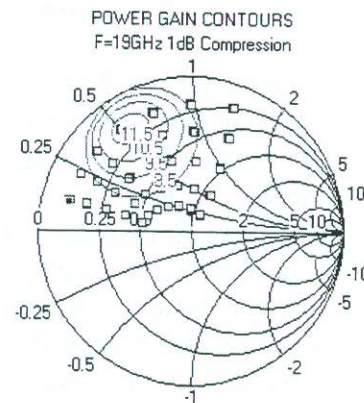


Figure 6. Power gain contours @ 1 dB compression

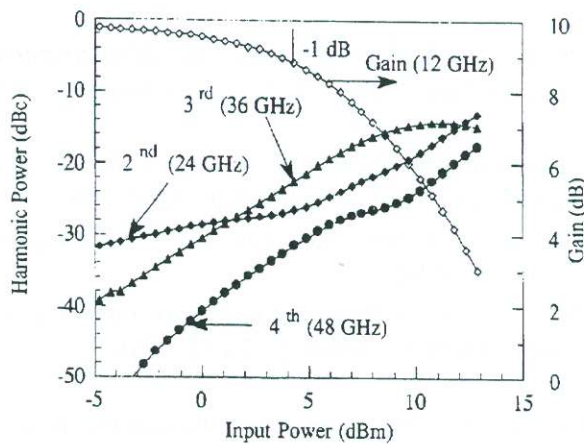


Figure 7. Fundamental gain and harmonic output power of a 12 GHz power amplifier

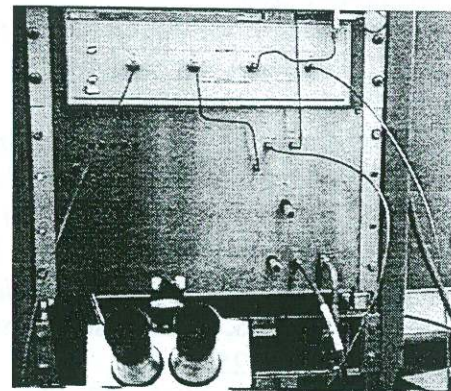


Figure 8. Millimetre load pull test set realised at the Politecnico di Torino

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