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Application Note 25

High Reflection Load Pull: Possibilities and Tradeoffs

This note summarizes state of the art possibilities to generate high reflection coefficients in test fixtures and on-wafer using mechanical tuners of Focus Microwaves. It presents tradeoffs between high reflection and measurement accuracy. It uses latest available data on low loss wafer probes and cables and high reflection tuners.

Introduction

Programmable microwave tuners are mostly used for Noise and Load Pull measurements. Key requirements are in both cases fundamentally different. In Noise the tuners have to be highly accurate and fast. In Load Pull the tuners have to: Be Highly reflective and low loss, have high resolution and support high power. There are important technical reasons for each of these requirements, which are summarized below:

Tuner Property	Application	Main Technical Reason for...
High Accuracy	Noise	Data must be accurate within less than 0.1dB to be able to compute the 4 noise parameters of the noise model from arbitrarily distributed impedances
High Speed	Noise	Swept frequency operation is useful to smooth out data. Points have to be measured again if the data do not converge to a meaningful noise parameter set
High Reflection	Load Pull	Devices must see actual optimum impedance. There exist no "load pull parameters" to be computed from arbitrary load impedance measurements. This is particularly true for prematching the source side of the DUT
Low Loss	Load Pull	Permits to use low power signal source to drive DUTs into saturation. Keeps dissipated RF power low
High Power	Load Pull	Permits to test high power devices (>50 Watt CW, >1kW peak)
High Resolution	Load Pull	Permits to fine tune in- and output of DUTs. Very important for high performance devices and input pre-matching [1]

Limitations in High Reflection Load Pull

The maximum reflection factor that can be presented to the DUT is limited. Typical values vary between 0.7 and 0.99 depending on the setup, the test fixture (coaxial, microstrip or wafer probe station) and the technique used to generate the reflection (direct tuning or use of transforming networks). There are basically two kinds of limitations:

- Limitations due to existing and used hardware
- Limitations due to measurement accuracy

Limitations due to Hardware

In a load pull setup the tuner is connected to the DUT via a cable, test fixture or wafer probes. All these components are lossy and reflective. This affects the reflection factor that can be generated at the DUT reference plane. In the case of a DUT in chip form on a wafer the required setup looks as follows:

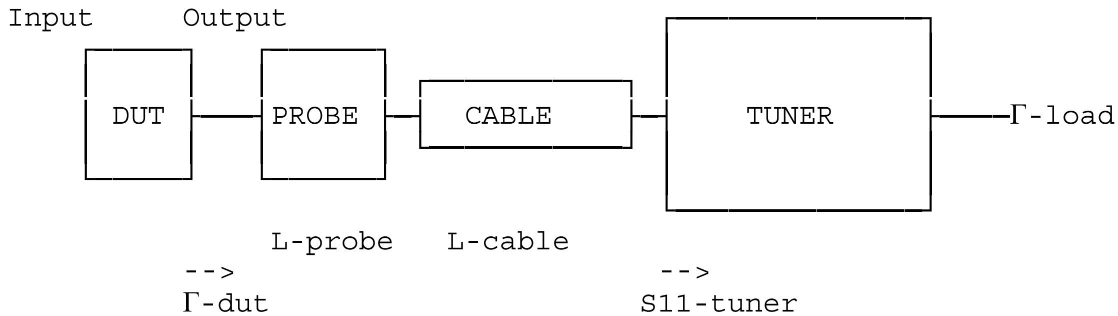

Figure 1: Schematics of a wafer load pull setup

As long as Γ-load and S11, S22 of the probe and the cable are less than -23dB (0.07) they do not have an important effect on the reflection factor Γ-dut generated using S11 of the tuner. If these residual reflections are higher then measurable multiple reflections occur between the components of the setup and may shift the centre of the Smith Chart to one side with the effect that the tuner calibration points appear offset. Assuming low residual reflections, a high reflection tuner and typical low loss wafer probes and flexible cables we can summarize the effect of the different components above as follows:

S11-tuner-Max = 0.905 (VSWR = 20:1)

Frequency	L-probe [dB]	L-cable [dB]	Γ-dut	VSWR-dut
1.0 GHz	0.02	0.02	0.901	19.1 : 1
10 GHz	0.17	0.1	0.877	15.2 : 1
26 GHz	0.30	0.35	0.840	11.5 : 1
40 GHz	0.40	0.45	0.820	10.1 : 1

Table 2: Typical state of the art reflection factors for on-wafer load pull. For test jig data see [6].

It is hardly possible, at this point of time, to obtain higher reflection factors at DUT reference plane. Focus' tuners may generate higher VSWR (as much as 40:1) but not over a very wide frequency band and mostly in the centre of the frequency range of operation.

Load pull measurements need to be done with a dense net of impedance points mostly in the area where the maximum performance of the DUT is expected to be. In power transistors this is around 0.1 to 5Ω output impedance and slightly inductive (the transistor is capacitive). In this case a good solution is to use transforming networks.
In the case of microstrip test fixtures it is relatively easy to design and manufacture even very wideband transformers with transforming ratio of more than 5:1. This makes load impedances of less than 1Ω possible at 40 GHz.
In wafer probe operations, however, transformer networks are difficult to realize [2].
Some probe manufacturers claim that they can manufacture transforming wafer probes [3]. This would be an elegant approach to solve the problem but at this point of time we do not possess any data proving the feasibility of this technology.
The only proven alternative to the issue of limited reflection factor for wafer testing is "active load pull" [4]. However, eventhough the feasibility of active load pull systems has been proven, there is no such system commercially available yet.

Limitations due to Measurement Accuracy

When generating a high reflection factor using a tuner (figure 1) all sections between DUT output and tuner operate with high reflective loss, since they are facing a very low (or high) load impedance. Not only the corrections for the reflected power are higher than the measured quantity itself, but also the error in the characterization of the tuner is important [5]. As a rule of thumb we can retain that the reflection loss becomes about 15 times higher (in dB) than S12 (S12 is defined at 50Ω source and load impedance), when the transmitting section (probe or cable) face a VSWR of 20:1 (or S11-tuner = 0.905).
The table below summarizes the expected measurement errors due to measurement uncertainties in S-parameter characterization of the components in figure 1.

S11-tuner-Max = 0.905 (VSWR = 20:1)

Frequency	L-probe+cable [dB] (S12 ±δS12)	Total Reflective Loss [dB]	Total Error [dB] (not incl. tuner)
1 GHz	0.02±0.01	0.30	±0.15
10 GHz	0.27±0.02	4.05	±0.3
26 GHz	0.65±0.05	9.75	±0.75
40 GHz	0.85±0.07	12.75	±1.05

This potentially high error occurs only because we generate very high reflection after a relatively lossy transmission section, as is the case above 10 GHz.
Would we use some kind of transforming section in the measurement chain and be able to keep the maximum VSWR at any point to less than 10:1 the measurement error would shrink to about 1/3 of the value shown.
There are procedure precautions that can help avoid measurement errors. Except of systematic errors, as shown in table 3, additional errors can occur if the setup needs to be calibrated piece by piece and the pieces connected together lateron. Some versions of the Focus Load Pull software still use this technique, which has the practical advantage of not needing an automatic

network analyzer to be part of the load pull system. Recent versions of the Focus load pull software, however, can calibrate the tuners and the (wafer) setup without disconnecting the components (in situ).

Figure 2 shows a tuner calibration made "in situ" using low loss air-coplanar probes of Cascade Microtech with 3.5mm connectors and an ordinary (not specially tuned) CCMT tuner model 1808 (0.8 to 18 GHz).
The calibration points are slightly offset towards low impedances due to residual reflections of the setup but reach maximum Γ-dut of 0.885 (VSWR = 16.4:1). These numbers are close to the expected best values shown in table 2.

Figure 2: On wafer tuner calibration.

Conclusion

This note summarizes the limiting mechanisms and presents state of the art reflection factors for load pulling low impedance high power transistors on wafer. Further details on low impedance load pull testing including active and passive techniques can be found in the literature listed below.

Literature

[1] "High resolution tuners eliminate load pull performance errors", Application Note 15, Focus Microwaves, 1995.

[2] A.K.Sharma et al. "Ka-band Power PHEMT on-wafer characterization using prematched structures", proceedings IEEE MTT-S, 1993, Atlanta Ga.

[3] E.Strid, Cascade Microtech, G.Boll, GGB Industries, personal communication.

[4] B.Hughes et al. "Accurate on-wafer power and harmonic measurements of mm-wave amplifiers and devices", Proceedings IEEE MTT-S 1992.

[5] "Accuracy and Verification of Load Pull measurements", Appl. Note 18, Focus Microwaves, 1994.

[6] "Setup Configurations for Very Low Impedance Tuning", Product Note 24, Focus Microwaves, 1995.