Recent technological advances for modular active harmonic load-pull measurement systems

RECENT TECHNOLOGICAL ADVANCES FOR MODULAR ACTIVE HARMONIC LOAD-PULL MEASUREMENT SYSTEMS

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***Abstract* – Load-pull systems are today widely accepted as fundamental tools for non-linear performance evaluation, from device design and modeling in R&D labs to MMIC production testing. This paper presents an overview of the recent innovations in load-pull measurements. After a brief introduction on novelties regarding passive set-ups, the survey deals with technological advances for active systems. Finally, a realization of a modular broadband system for on-wafer measurements in the 0.5-18 GHz frequency range is described. S-parameter capability up to 26.5 GHz is also integrated, and the system is easily configurable for harmonic source-pull measurements.**

I. INTRODUCTION

Harmonic load-pull measurements consist in monitoring the device under test (DUT) characteristics while changing the loading conditions at fundamental and harmonic frequencies [1, 2]. Microwave power amplifier design is a typical application, where the proper output matching network is synthesized after that optimum loads for maximum output power or maximum power added efficiency (PAE) are determined experimentally.

For some applications, load-pull technique is extended to characterize the DUT while driving it with different source impedance values. Harmonic source-pull systems allow controlling the reflection coefficient that the DUT sees from its input port at one or more frequencies. It was proved that this technique is effective for high efficiency power amplifier and mixer design [3, 4].

Original load-pull systems were based on manual tuners and power meters, owing to which device characterization was a time consuming and rather inaccurate process. The advent of vector network analyzers and personal computers gave a great impulse to the development of fully automated and accurate measurement systems.

At lower microwave frequencies (i.e. up to few GHz), the simple use of passive tuners is still the most effective and economic way to control the DUT loading conditions. The introduction of harmonic tuners [5] recently provided a compact and economic solution for harmonic source and load-pull setup. On the other hand, the need for better measurement accuracy while characterizing highly mismatched transistor pushed towards the use of pre-matching networks [6]. Latest versions of mechanic passive tuner integrate programmable pre-matching capabilities [7]. Finally, a passive system was recently used to demonstrate the first on-wafer cryogenic load-pull characterization of microwave transistors [8].

At higher frequencies, test-set based on passive tuners cannot offer highly reflective load conditions due to losses. The problem is evident especially for harmonic tuning, since the optimum harmonic termination is typically on the edge of the Smith chart. Active load systems were introduced as a solution to this problem and, to the authors' opinion, they still represent the most reliable scheme for microwave and millimeter wave load-pull test-sets. Moreover, passive systems require pre-characterizing the tuners at each possible position. This operation can be really time-consuming, especially if harmonic tuning is required. On the other hand, typical active load-pull setups are based on real-time vector-corrected measurements preformed by commercial automatic network analyzers or six-port systems. A complete test-set for source- and harmonic load-pull based on six-port techniques has been recently presented in [9].

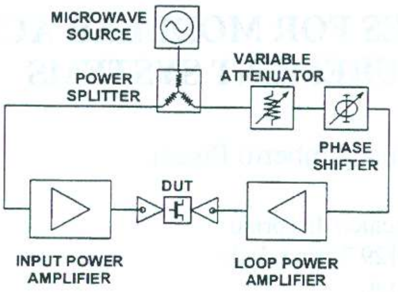
This paper presents an overview of the recent innovations for active load-pull systems in literature, along with some original advances and a novel modular system developed by the authors.

II. ACTIVE LOAD-PULL SYSTEMS: AN OVERVIEW

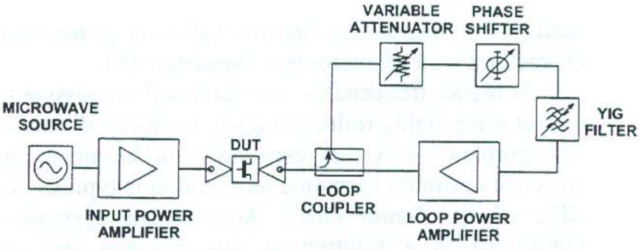
An interesting comparison of different load-pull techniques is presented in [10]. Figure 1 shows the test-set configurations for active load-pull described in literature. The first one is often referred as the *two signal paths technique* and it is originally due to Takayama [11]. A power divider splits the source signal into two parts. The first one drives the input port of the device. The second one is properly amplified, phase-shifted and injected into the DUT output port as b_2. The load reflection coefficient $\Gamma_L = b_2/a_2$ is controlled by changing the attenuator and phase-shifter settings.

The second configuration is known as the *active loop technique* [12] and the basic scheme is sketched in figure 1b. A portion of the DUT output signal is drawn by a directional coupler, properly controlled in amplitude and phase and sent back to the DUT. The magnitude of Γ_L is ideally proportional to the loop gain, while the load phase depends on the loop phase shift. As shown in figure 1b, a high selectivity filter has to be introduced in the loop to avoid oscillations due to the relative broad band of the loop components.

Because of the high isolation of the power amplifiers, the two signal paths technique shows no risk for



(a)



(b)

Fig.1. Active load-pull system configurations:
(a) two signal paths, (b) active loop.

oscillations. For this reason, the technique is still considered for developing systems at millimeter waves [12]. In addition, a source-pull set-up based on this technique has been recently proposed in [5] for operation at fundamental frequency. However, the two signal paths technique suffers from a severe drawback, since it is difficult to keep the load condition constant when the input power or the DUT characteristics change.

Once the oscillation problem is solved, with the active loop solution it is much simpler to control the load magnitude and phase. Moreover, since the loop is frequency selective, the same scheme can be easily extended for harmonic load pull measurements [13], with a separate active loop for each harmonic load.

III. Broadband Harmonic Systems: An Example

Figure 2 shows the simplified block scheme of a novel 0.5-18 GHz system. The measurement setup is based on a traditional vector network analyzer, used as a four-channel microwave receiver. Signal a_{REF} provides a stable reference for phase locking. Waves a_1 and a_2 are selected by a PIN-diode switch drive directly by the network analyzer. This is a well-established technique already experimented in many load-pull systems [13, 14] and it allows fast acquisitions of all four DUT waves.

Two independent 0.5-4 GHz and 2-18 GHz active loops are enclosed with the configuration circuitry in a single unit, shown in figure 3. While commercial active load-pull systems are currently available up to 3 GHz [15], the new active load allows 0.5-18 GHz operation by using as loop components a coaxial phase shifter and a broadband PIN diode attenuator.

To perform S-parameter measurements without disconnecting the DUT, configuration switches bypass the input power amplifier and the active load. Reflectometers are mounted directly on the prober to improve the accuracy, while few other components are left outside the load unit for easy reconfiguration according to the user needs.

Novel key feature of the system is the new loop YIG

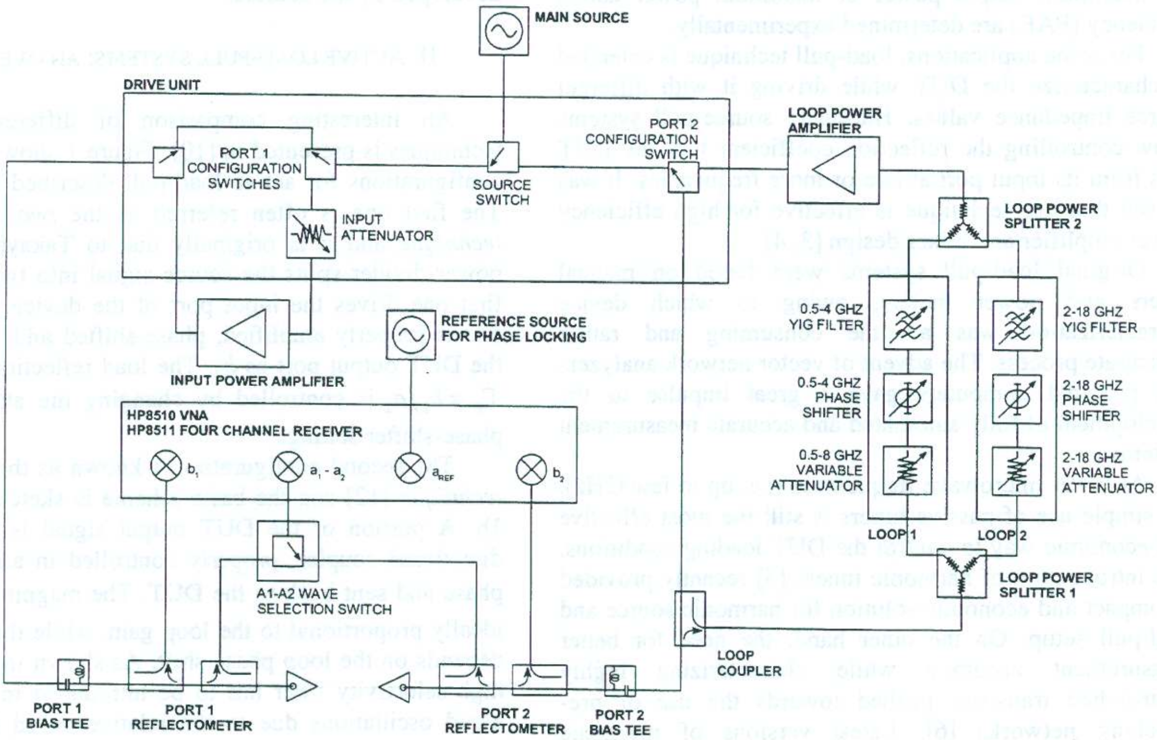


Fig.2. Measurement system configured for harmonic load-pull.
Drive unit, active loops and selection switch are included inside the active load unit, shown also in figure 3.

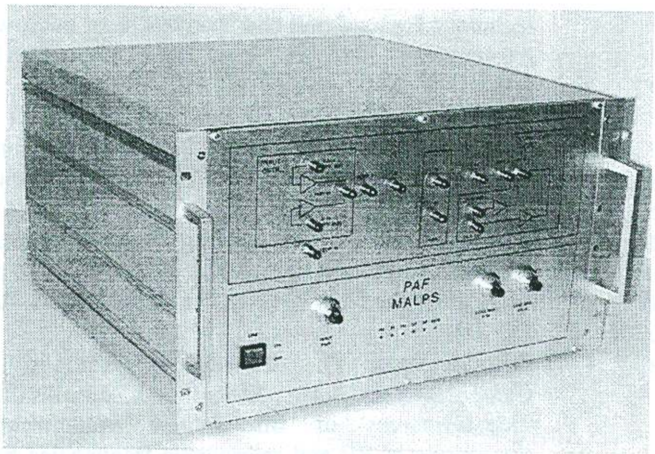


Figure 3. Two-loop active load unit.

filter technology. To avoid loop oscillations, traditional technique involves using a tracking YIG filter, which is locked to the loop signal to obtain a stable gamma-load value. This is troublesome for loops at harmonic frequencies, since the signal level is generally low. The new technology is based on an accurate open-loop control of the YIG filter coil current and it does not require locking the filter to any microwave signal. As a typical performance, the active load reflection coefficient is stabilized within 0.02 dB in magnitude and 1.5 degrees in phase.

The same system can be easily configured for harmonic source-pull measurements, as shown in figure 4. This is obtained simply by moving the loops at the input side of the test-set and by adding just a power-combiner before the input power amplifier.

The measurement of the source reflection coefficient can be performed without disconnecting the device. Two techniques are available, either by switching the RF main source to the output port or by switching the DUT bias (as recently described in [16]).

For S-parameter measurements and load-pull at the only fundamental frequency, the main source is used for both driving the DUT and providing a stable reference to the receiver. For harmonic measurements, two sources are used as demonstrated in [13] and shown in figure 1. Due to the reference source and the new loop YIG filter technology, the user is able to choose three independent frequency sets:

- the frequency at which the DUT is driven (source frequency);
- the frequencies (one or more) at which the DUT is measured (measurement frequencies);
- the frequencies (one or two) at which YIG filters are tuned, i.e. the load reflection coefficients are controlled (loop frequencies).

In other words, it is possible to drive the DUT at one frequency, while controlling the loading conditions at other twos and measuring the DUT at a third set of frequencies, even not harmonically-related with the previous ones.

Figure 5 shows some experimental results obtained with the described system. First optimum load at fundamental frequency is found for maximum PAE. Then, a set of loading conditions at the second harmonic (represented by circles) is applied. Finally, contour lines are computed.

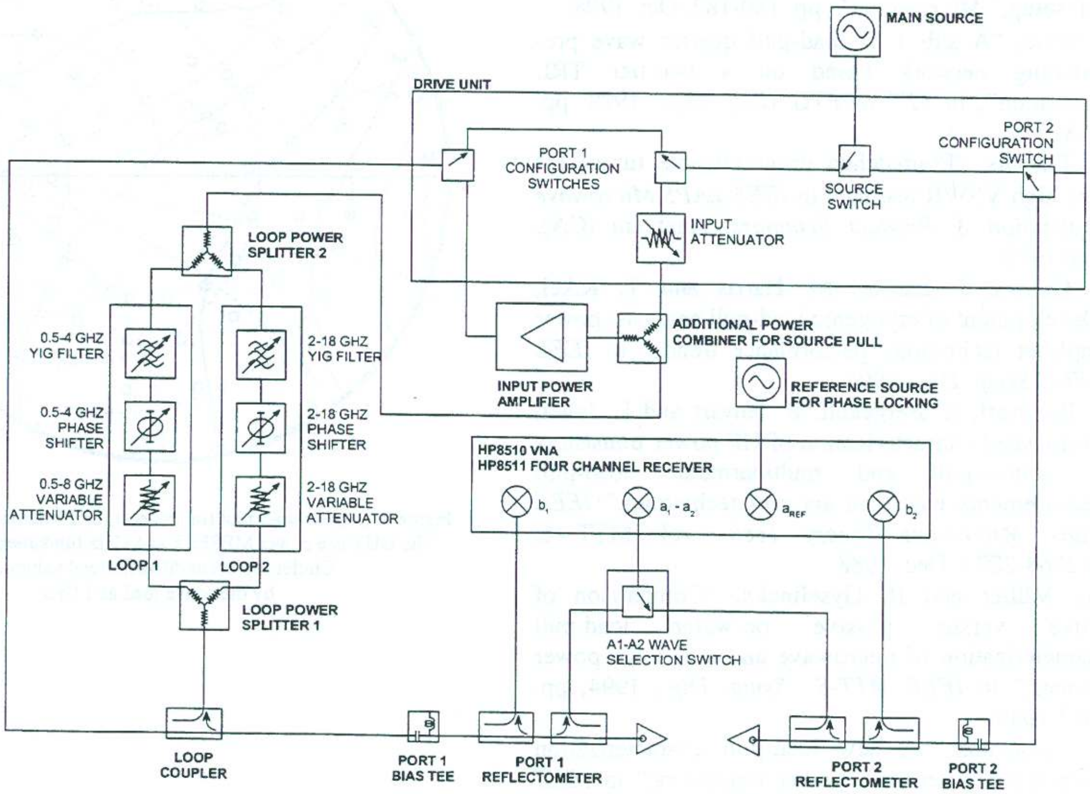


Fig.4. Measurement system configured for harmonic source-pull.

V. CONCLUSIONS

An overview of recent innovations in source/load-pull systems for characterizing microwave and millimeter wave devices has been presented, along with an original realization from the author. It has been demonstrated that recent technological advances greatly enhanced the reliability of active setups in terms of load stability and flexibility for both harmonic load and source-pull use. This makes these systems suitable for a large range of characterization needs, especially in the frequency range where the performances of traditional passive systems are seriously affected by losses.

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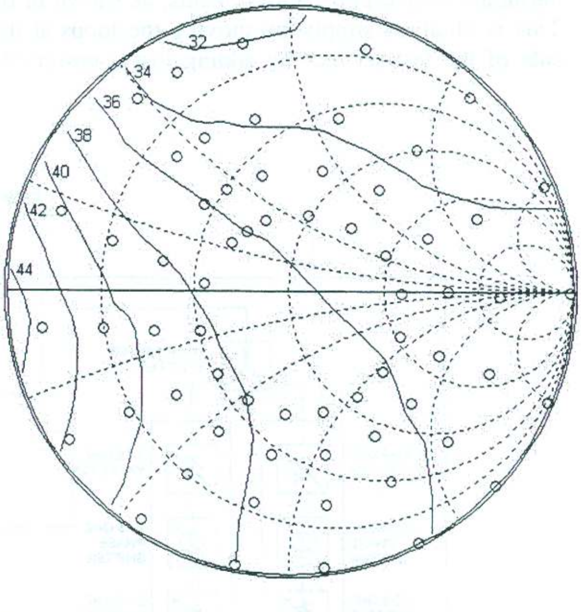

Figure 5. PAE contour plot (in percent) for 2nd harmonic load tuning. The DUT is a power MESFET at 4 GHz fundamental frequency. Circles represent different load values set by the active load at 8 GHz.