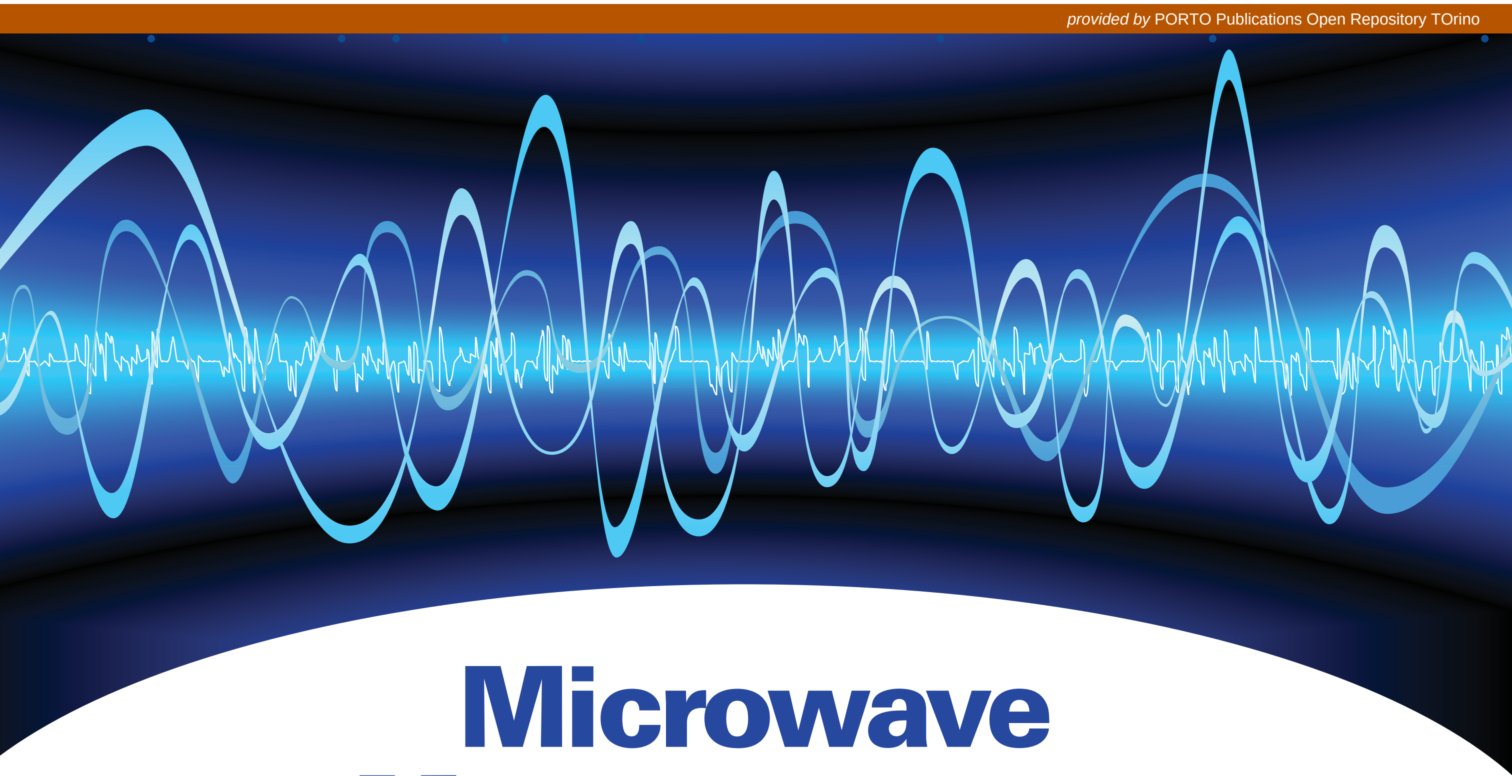

Microwave Measurements Part II

Non-linear measurements

Vittorio Camarchia, Valeria Teppati, Simone Corbellini, and Marco Pirola

RF system design requires accurate measurements. This is true both for passive and active elements; however, while the passive ones can be assumed linear, and therefore completely identified through *S*-parameter measurements as a function of frequency [1], active element are usually driven in mild or deep non-linear regime. In these cases the amplitudes at the fundamental frequency of the port voltages and currents depend in a non-linear way from the inputs, and the non-linearities generate spectral components, harmonics or intermodulation products, not present in the excitations. Within the framework of power amplifier characterization, to which this article is devoted, the input and output terminations play a determinant role on the amplifier behavior and performances, and therefore their effect must be properly exploited; for instance, their correct choice can optimize performance such as the output power or the power added efficiency. While this is true for the load and source termination at the fundamental frequency, the harmonics often have some significant impact; for example, their effect is crucial in applications based on harmonic tuning, e.g. class E and F amplifiers [2].

For these reasons, an experimental setup for characterizing power amplifiers must be able to measure the complex spectrum of the waves at the amplifier ports as a function of frequency, input power, and source and load termination at the fundamental and harmonic frequencies. Once the terminations are fixed to 50 Ω and only the wave amplitudes are accounted for, the classical simple scalar setup is used to determine the amplifier transfer curve output power (P_{OUT}) versus input power (P_{IN}). The power units are normally expressed in logarithmic scale as decibel for watt (dBW) or, for longer power ranges, in decibel for mW (dBm).

The vector network analyzer (VNA) is the core instrument used in the non-linear characterization scenario. The basic idea is to keep the operations of VNA/mixers linear, diverting to them only a small portion of the signal present at the device under test (DUT) ports, therefore keeping unaltered the VNA capabilities already exhibited for small signal measurements.

This solution enables sharing between *S*-parameters and non-linear parameters, which avoids unnecessary duplication of the measurement systems. But there are many challenging problems that must be faced and overcome.

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- New calibrations are necessary because the measure of the wave ratios at the amplifier ports is not sufficient. An absolute calibration reference must be adopted to fix the absolute value of the signal at the ports
- The actual power levels to be measured must be taken into account, and bias tees, power splitters and combiners, power terminations, and attenuators must be designed accordingly. For example, measurements on GaN or SiC-based devices, the latest-generation FET power devices, require handling tens of watts. These adverse conditions cause self-heating of the test-bench, which must be cooled during the characterization.

The vector network analyzer (VNA) is the core instrument to use in the non-linear characterization scenario.

- A large amount of power is needed to push large periphery devices into their non-linear zones. The non-linearities become significant for complete characterization with conditions closest to the actual operating conditions. The driver amplifiers affect the power stage; they must be linear to avoid spurious contribution to the harmonic levels. The applied stimulus is important from a quantitative and qualitative standpoint. The stimulus must be carefully chosen to excite the measured elements in a realistic condition. For example, in new communication link applications, the characterization should be accomplished in the presence of an input signal with complex broad-band modulation (e.g., Wideband Code Division Multiple Access - WCDMA) to measure the amplifier effects on the figure of merit as spectral re-growth or adjacent channel power ratio.
- To provide comprehensive information, non-linear characterization requires a large amount of data; at the moment there is no explicit or implicit standardization that is individualized for its management, and care must be taken in the handling and processing.
- Fully automated linear benches are the present state-of-the-art, and no special knowledge or skill is required by the operator. Conversely, non-linear measurements must be carried out, step by step, by trained operators who manually control the measurement setup.

This article discusses techniques to synthesize loads, the most used non-linear measurement techniques, and harmonic load-pulling.

Termination Synthesis Techniques

Under non-linear conditions, Device-Under-Test (DUT) characterization cannot be achieved by either the scattering matrix or by any equivalent representation. The characterization can be carried out through the direct measure of key parameters such as input and output port powers (at fundamental and harmonic frequencies), operating gain, power-added efficiency, AM-AM/AM-PM conversion characteristic, intermodulation distortion, adjacent power channel ratio, and many other figures of merit. Unfortunately this generates many new measurement issues with respect to linear cases: most of these parameters depend on the operative conditions, and therefore, other quantities must be controlled to set the desired working ones.

Direct Current (DC) biases, input and output impedances, frequencies, and input power levels are the most important quantities to control during the characterization. DC biases require devices for either voltage or current polarizations that are able to handle the power and are able to control the signal even when strong rectifying behavior of the device is present. Tuning networks are required to set the impedence values. Passive tuners and active load synthesization are two different solutions [3].

Passive tuners are typically based on a slotted line with an inserted slug that can be moved along the longitudinal and vertical axes by either micrometer positioners or precision stepper motors [4]. Typically, the commercially available tuners have one or two slugs that are used in different frequency bands. Repeatability is assured by the accuracy of the stepper motors.

Figure 1 shows the basic structure of a slug tuner. The analysis is performed far from the slug resonant frequency. The change of the slug position along the vertical axis causes a change in the load magnitude, whereas the movement along the longitudinal axis changes the load phase.

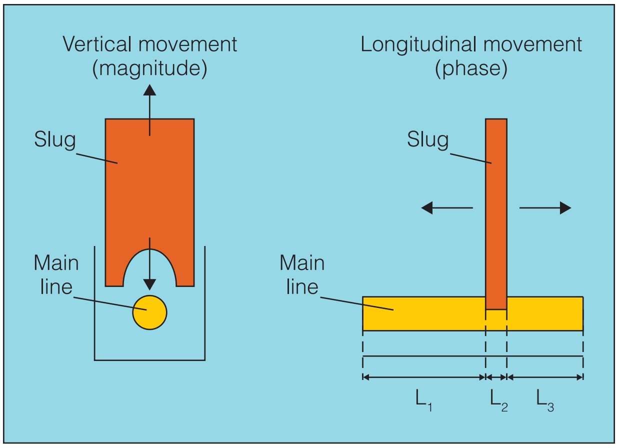

Fig. 1. A slug tuner transversal section (left) and longitudinal section (right). Vertical and longitudinal movements change reflection magnitude coefficient and phase, respectively.

Passive tuners are usually the most effective and economical way to control the DUT load conditions at lower microwave frequencies up to a few gigahertz and when high power is involved. However, at higher frequencies, the synthesized reflection coefficient is limited in magnitude by losses. In

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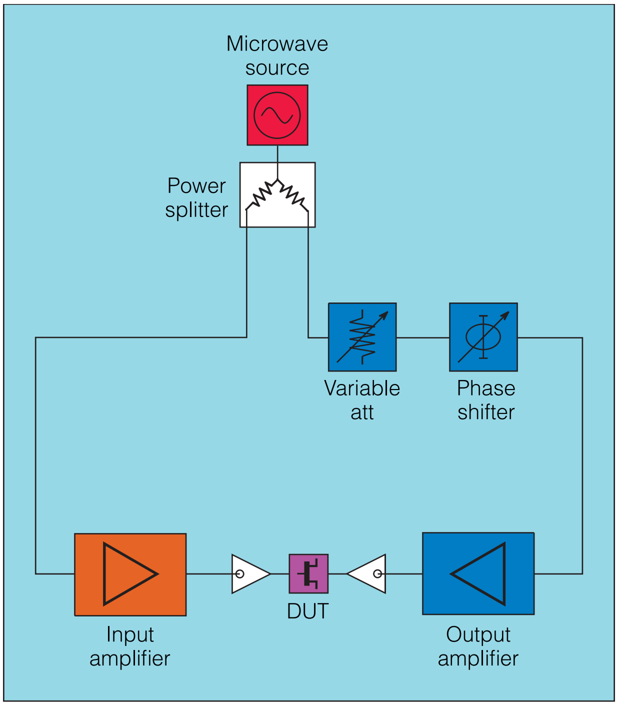

Fig. 2. An active load-pull system based on the two-signal technique.

high-power devices, the optimum termination of novel, high-breakdown materials usually is close to the Smith chart border. This is particularly true for small periphery devices but is also true for large devices because the magnitude of the reactive terminations increases as the frequency rises. To mitigate such a problem, pre-matching networks can be inserted very close to the DUT, although the use of active loads is preferable.

Active loads electronically synthesize the required reflection coefficient by amplifying, phase-shifting, and combining microwave signals to generate the reflected wave. Among the available solutions, two main techniques can be identified: the two-signal technique and the active-loop technique.

The first technique, attributed to Takayama [5], consists of a power divider that splits the source signal into two parts, as shown in Figure 2. The first part drives the input port of the device, while the second part is properly amplified and phase-shifted then injected into the DUT output port. The required reflection coefficient can be controlled by adjusting the attenuator and the phase-shifter settings.

This technique enables high reflective loads to be obtained but also has a severe drawback, because it is difficult to keep the load condition constant when the input power or the DUT characteristics change. This happens when the device heats up or it is close or within its compression range.

This problem can be solved by employing an active-loop technique (Figure 3) [6]. A portion of the DUT output signal is controlled in amplitude and phase by means of a directional coupler and sent back to the DUT. Therefore, the magnitude of the load reflection coefficient (Γ_L) is proportional only to the loop gain, whereas the load phase depends on the loop phase shift. A very selective filter is usually inserted into the loop to avoid oscillations caused by the relative broad band of the loop components.

This technique offers great flexibility in load control and selection as compared to the passive approaches. Setup losses are easily compensated by the loop amplifier. Highly mismatched or even active terminations are therefore easily synthesized. However, passive tuners exhibit higher power handling capabilities only by adopting expensive amplifiers.

Non-Linear Characterization at RF and Microwave

This section describes the acquired quantities and the common measurement approaches. The first technique measures all quantities related to power (scalar quantities) with large band power meters and all of the other vector quantities (reflection coefficients) with a previously calibrated VNA. As in all open-loop control systems, this setup is limited because the preliminary calibration determines the quality of the results. This approach relies on two assumptions: First, all of the networks measured with the VNA under small signal conditions are intrinsically linear (they do not change properties as the signal

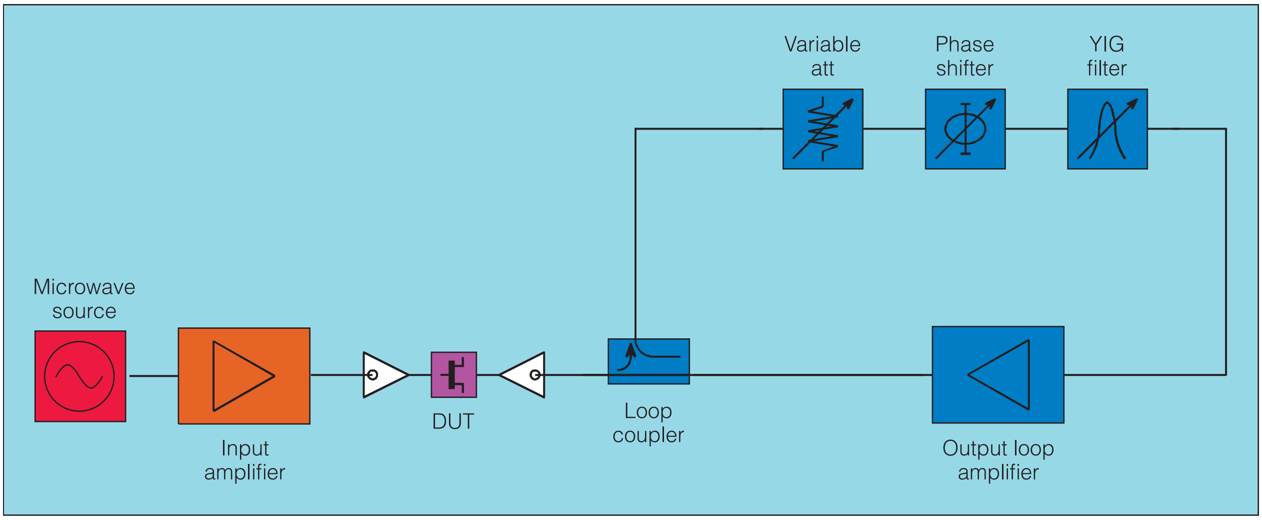

Fig. 3. An active load-pull system based on the active-loop technique.

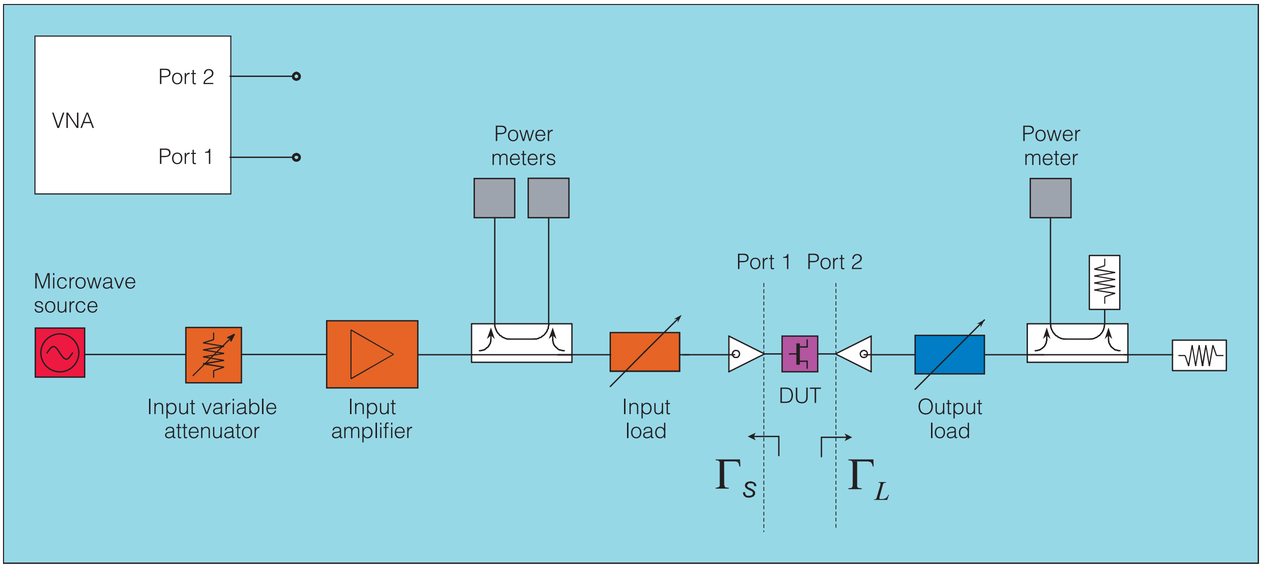

Fig. 4. A simplified scheme of a non-real-time, two-port, load-pull measurement system.

intensity rises), and second is the repeatability of the tuning device [7] and the connector insertions.

Figure 4 shows a simplified scheme of a two-port load-pull system with power meters. These systems are generally called non-real-time. They need a long, time-consuming pre-characterization phase for each system component, including load tuning devices, for each loading condition that is imposed during the measurement phase.

The second approach uses the VNA to measure all of the quantities of interest in real-time while exciting the system in non-linear conditions. High level signals are separated and reduced by proper coupling/attenuating devices. Calibration is performed as a classical VNA error correction in linear conditions. In this case, the assumption is that every device included in the calibration model is linear and does not change from the calibration to the measurement phase.

Classical VNA calibrations are able to correct only the wave ratios that in non-linear conditions lose their meanings. This is why a further calibration step that exploits an additional power meter measurement is needed to achieve information on the magnitude of each wave [8].

Figure 5 shows a real-time two-port load-pull system. Incident and reflected waves at the DUT reference planes are separated with directional couplers and measured with a VNA. The two systems in Figures 4 and 5 are based on the same main elements but used in different ways. The load tuning devices and the directional couplers are swapped, so that a unique VNA calibration can be used for each loading condition. This is why the real-time approach is definitely faster, more accurate, and straightforward [9].

Notice that when highly reflective loads must be synthesized at the DUT reference planes, the real-time configuration

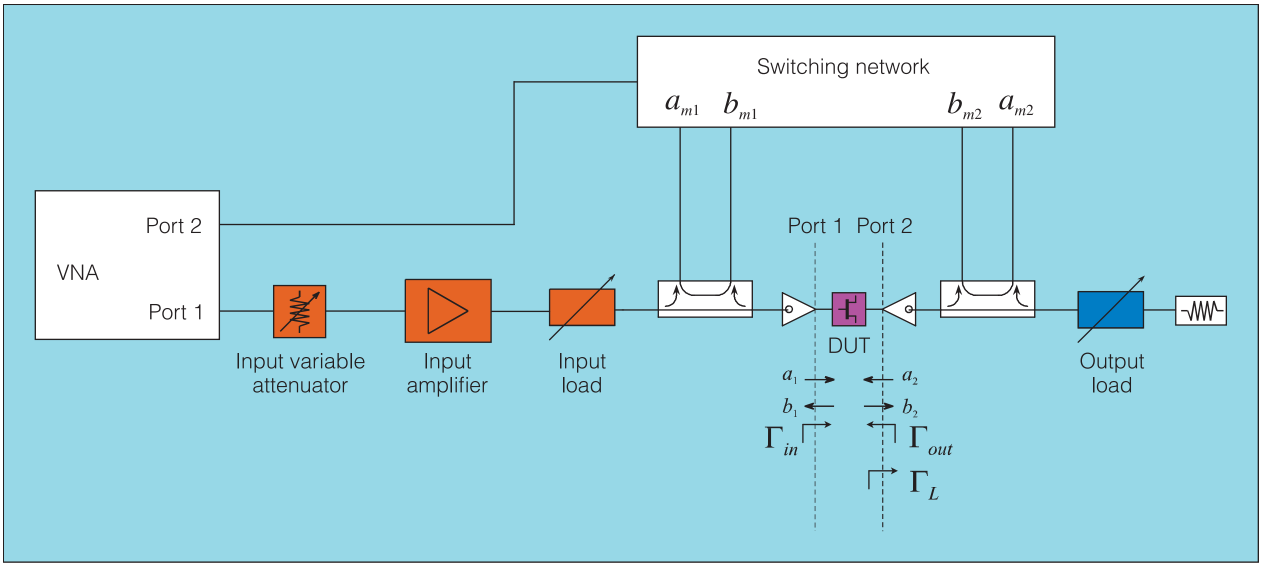

Fig. 5. A simplified scheme of a real-time, two-port, load-pull measurement system.

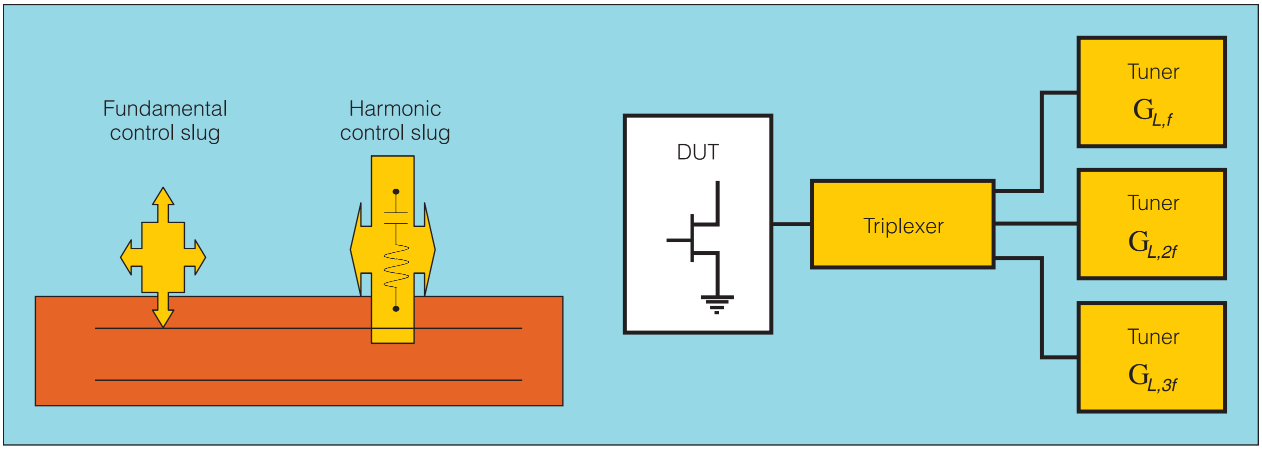

Fig. 6. (left) Harmonic control in passive load-pull systems by means of stub resonator tuner or (right) multiplexer, triplexer in the shown case.

illustrated in Figure 5 is less effective because of the losses introduced by the directional couplers. This problem was recently overcome by the introduction of low loss, wide-band directional couplers [10], so that the couplers are nearly "transparent," extending the passive tuner applicability to real-time configurations.

Harmonic Characterization

Almost all non-linear characterization systems are based on harmonic load-pull systems. Analysis must be carried out at the fundamental and at the harmonic frequencies. There are two new crucial issues. First, quantities must be measured at each harmonic. Second, the matching networks must be able to tune different loads for each harmonic.

The real-time approach solves the first problem, because the VNA can provide high-frequency selective measurements to separate the harmonic contributions. On the other hand, the non-real-time technique requires highly selective filters to resolve the harmonic components because of the broad band nature of power meter instrumentation.

There are passive and active solutions for harmonic load control. For passive tuners there are three methods: cascaded tuners, stub resonators, and a multiplexer with normal tuners [11].

- Cascaded tuners use a few basic slug tuners. They have great flexibility for frequency control and variation but increase the bench complexity. No independent harmonic control is possible because the movement of one of the tuners affects the impedance at both the fundamental and harmonics.

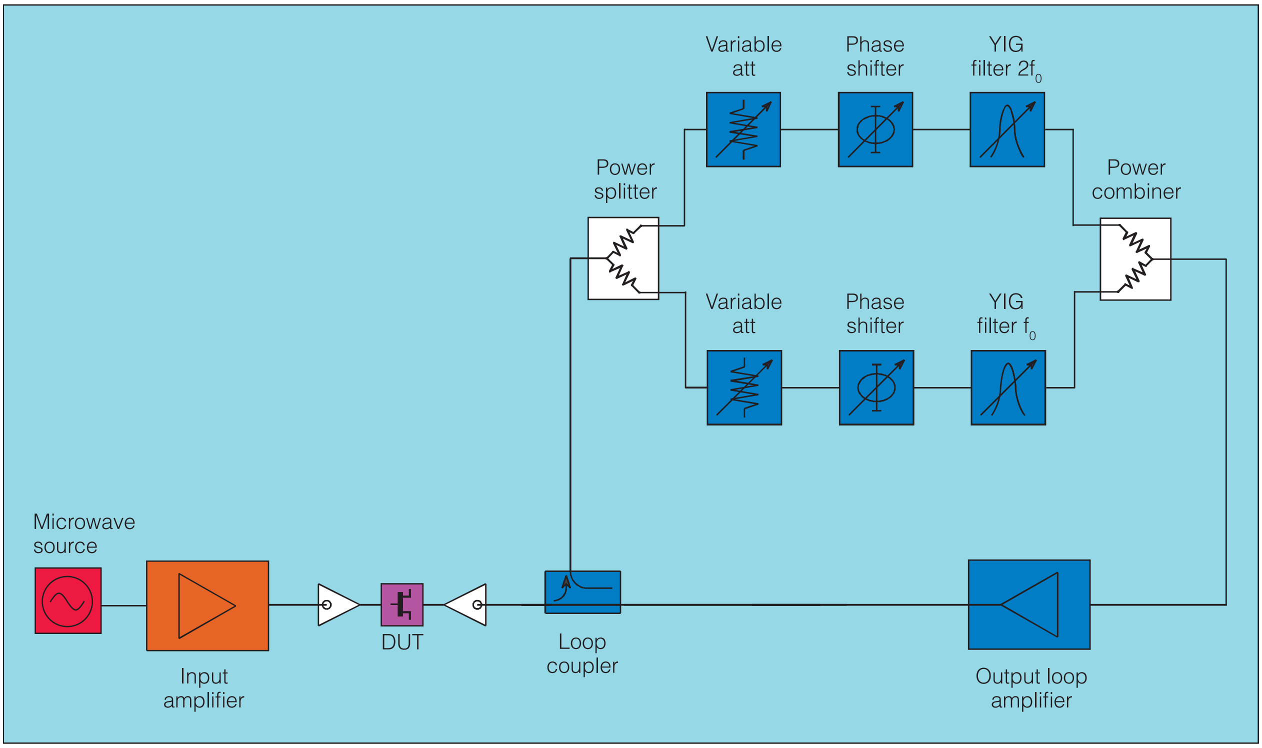

Fig. 7. An extension for harmonic load-pull of the active-loop technique.

- A stub resonator is a harmonic tuner with resonant slugs [Figure 6(left)]. It produces a very narrow band and has independent harmonic control but troublesome procedures are required to switch bands. It results in poor measurement repeatability.
- A multiplexer with different tuners [Figure 6(right)] for each harmonic and a filter separates fundamental and harmonic signals so that they can be tuned independently.

In an active tuner case, the preferable solution is based on the active-loop in which new loops are inserted for each harmonic (Figure 7). The presence of an yttrium-iron-garnet narrow band tuneable filter makes this scheme particularly suitable for harmonic analysis.

Conclusions

We have addressed the problems in microwave non-linear measurements. We have described the main characterization issues and the most adopted solutions. Particular emphasis was given to the load/source-pull technique. We addressed the passive as well as active loop approaches at both the fundamental and harmonic frequencies.

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