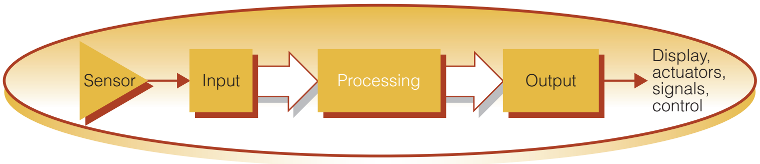

Introduction to Load-Pull Systems and their Applications

Part 43 in a series of tutorials on instrumentation and measurement

Mohammad S. Hashmi and Fadhel M. Ghannouchi

Large-signal or non-linear characterization of transistor devices is essential for determining their performance in such non-linear applications as power amplifiers (PAs), considering the limitations of linear S-parameter characterization techniques in such applications. Load-pull is one of the most frequently used techniques for estimating and optimizing device performance in the non-linear domain.

The load-pull technique was first reported almost four decades ago. It was pioneering work, as it brought a paradigm shift in the characterization, measurement, design, and optimization of transistor devices and Radio Frequency PAs (RFPAs). Although the load-pull setups as reported initially now can be considered very rudimentary, they definitely advanced the way the design and optimization of RPFAs are carried out [1]-[2]. Load-Pull provides the measurement in terms of a reflection coefficient at the load-port of transistor devices and hence, derives its name from them.

Why Load-Pull?

Load-pull is the colloquial term applied to the process of systematically varying the impedance presented to a device under test (DUT), most often a transistor, to assess its performance and the associated conditions to deliver that performance in a network. While the term load-pull implies impedance variation at the load port, impedance can also be varied at any of the ports of the DUT, such as the source (input) port, for noise characterization.

Load-pull is required when linearity breaks down, a situation which occurs, for example, under large-signal operating conditions associated with substantial harmonic generation or other manifestations of nonlinearity. Load-pull is the most common method globally used for RF and microwave power amplifier (PA) design, transistor characterization, semiconductor process development, and ruggedness analysis. A central theme of load-pull is management of nonlinearity versus

1094-6969/13/$25.00©2013IEEE

analysis of nonlinearity, the latter being the domain of advanced mathematics that often yields little physical insight into nonlinear phenomena and suffers from an inability to accurately render actual behavior embedded in a network with significant parasitic and distributed effects. With an automated load-pull, it is also possible to reduce the design cycle-time for optimal design of power amplifiers [3].

What Is Load-Pull?

In generic terms, load-pull refers specifically to presenting known impedance to a DUT in a precisely controlled fashion to extract the optimal performance from the DUT. In load-pull measurements, optimal performance is assessed qualitatively by varying terminal impedances, along with frequency and bias, to rapidly and accurately establish conditions under which optimal performance from the specified DUT can be obtained.

For PAs, the optimal loading conditions primarily depend on the nonlinearities exhibited by transistors. These are significantly different from linear cases, where the optimal loading conditions are directly identified from S-parameters. In the nonlinear case, load-pull systems determine the appropriate impedance values experimentally through impedance tuners while physically changing the load reflection coefficient Γ_L, as Fig. 1 shows, for the extraction of desired design parameters from transistor devices. The desired matching impedance Z_L, the incident and reflected traveling waves a_2 and b_2 at the output port, and reflection coefficient Γ_L are related by the expressions in (1.1) and (1.2):

$$\Gamma_L = \frac{a_2}{b_2} \tag{1.1}$$

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{1.2}$$

A load-pull system includes: an active or passive impedance-tuner; the controlling mechanism to precisely set the tuner impedance to achieve desired impedance; and equipment and test set to measure the traveling waves at the input port, a_1 and b_1, and at the output port, a_2 and b_2, of the DUT.

For example, Fig. 1 provides a conceptual presentation of a passive tuner at the output port (load port) of a DUT. In such a hypothetically ideal tuner, vertical movement of the stub/slug/probe of the tuner varies the magnitude of the reflection coefficient (Γ_L), whereas horizontal movement varies the phase of Γ_L. The desired matching impedance (Z_L) at the DUT port is thus obtained by physically moving the stub/slug/probe of the impedance tuner in the vertical and horizontal directions.

The load-pull is an effective tool in rapidly, precisely, and reliably determining the optimized matching parameters for a transistor device. For example, Fig. 2 shows experimental results while optimizing a 1-W GaAs device by fixing the fundamental impedance (using a tuner) and varying the third harmonic impedance (using a harmonic tuner). Such data definitely help in high performance PA design.

Common Load-Pull Techniques

As mentioned in the last section, the type of impedance tuner employed in the load-pull test setup defines the features and types of load-pull. The choices of these tuners are primarily regulated by the type of measurements required [4]. For example, passive tuner based load-pull (i.e., passive load-pull) is employed in applications requiring high speed measurements while active tuner based load-pull (i.e., active load-pull) is more commonly utilized in applications requiring high reflection coefficient values.

In theory, there are no physical limits on the frequency at which load-pull can be performed. Most load-pull systems are based on passive distributed networks using either a slab transmission line in its TEM mode or a rectangular waveguide in its TE01 mode. Lumped tuners can be made for HF and VHF frequencies, whereas active load-pull is ideal for on-wafer mm-wave environments, where substantial loss between the tuner and DUT reference-plane limits maximum achievable reflection coefficients using a passive load-pull setup.

Illustrating the passive technique mentioned earlier, Fig. 3 shows the reflection coefficient is synthesized by tuning the phase and/or the amplitude of the passive tuner. The main advantages of the passive technique are:

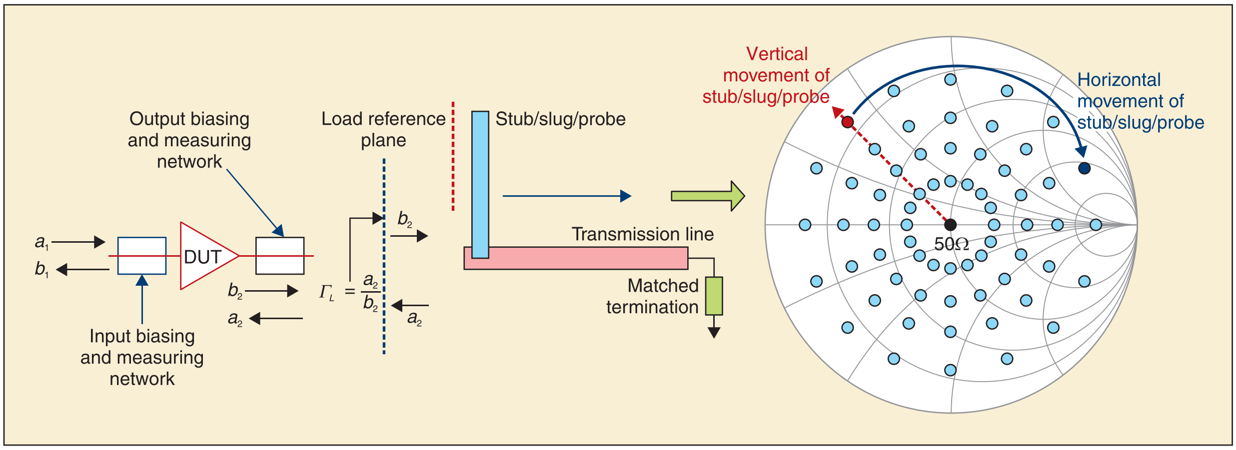

Fig. 1. Pictorial presentation of a typical load-pull test setup and the depiction of reflection coefficient synthesis concept over a Smith chart (© IEEE 2010, *IEEE Microwave Mag.*, used with permission, [5]).

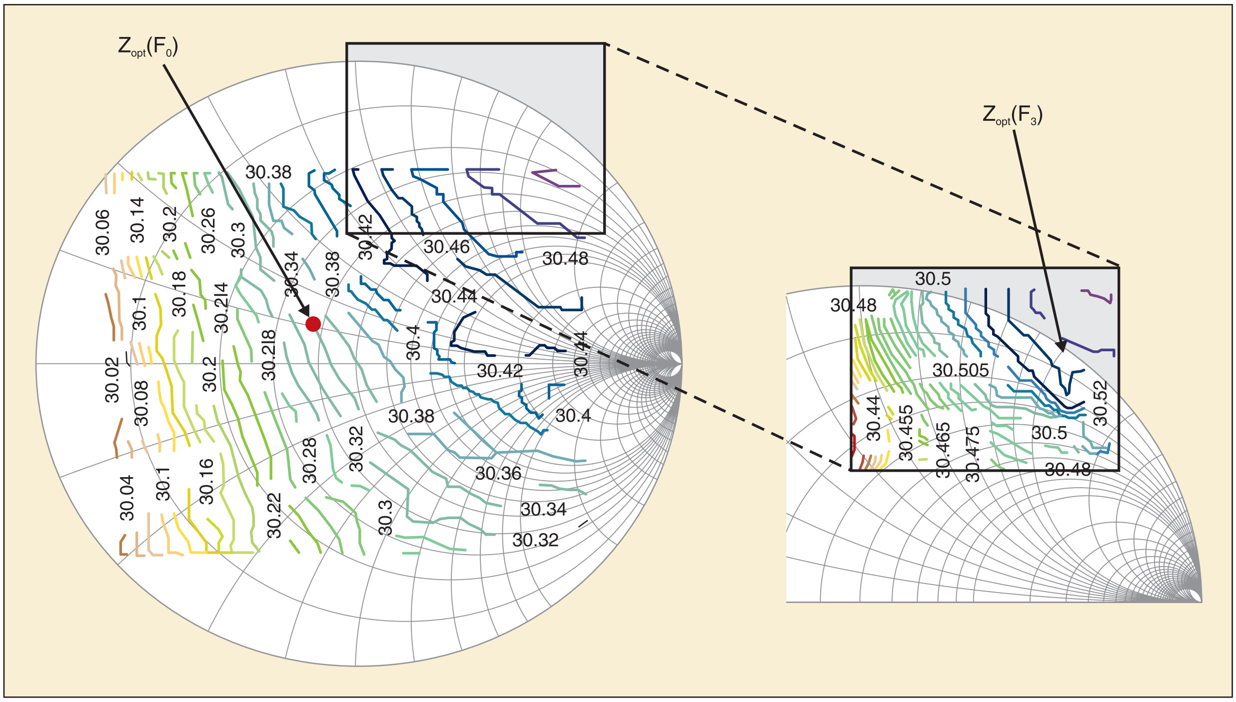

Fig. 2. Output fundamental power contours from sweeping third-harmonic reflection coefficients while holding fundamental impedance at its optimal value (© 2009 IEEE).

- rapid impedance synthesis,
- relatively higher power handling capability and measurements of high power devices without any non-linear effect,
- ease of usage,
- low maintenance cost,
- relatively low implementation cost, and
- the absence of any oscillation.

The main disadvantage of this technique is the limitation of synthesized impedances due to limitation of the maximum achievable magnitude of reflection coefficients. It is safe to say that any standard passive load-pull is usually unable to synthesize reflection coefficients near the boundary of the Smith chart. As a result, it is not possible to synthesize the appropriate matching impedance for DUTs possessing low output impedances (2 Ω or below).

Active load-pull techniques, shown in Fig. 4, are based on signal injection at the load-port of the DUT. These techniques, categorized as open-loop systems and closed-loop systems, can synthesize reflection coefficients near and on the boundary of the Smith chart and, therefore, can synthesize extremely small impedances for matching DUTs. In both the active load-pull techniques, the reflection coefficient is synthesized at a DUT access plane by controlling the complex gain around the active structure.

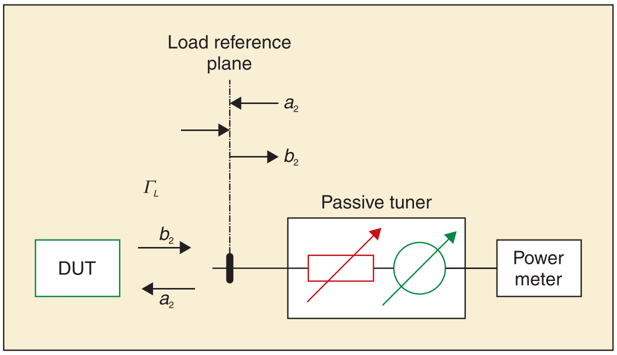

Fig. 3. A basic representation of the passive load-pull technique.

In the case of the open-loop active load-pull technique, as shown in Fig. 4, Γ_L, presented to the load reference plane, is synthesized by controlling the variable attenuator *ATT* and phase-shifter *DEPH* to fix the magnitude and phase of the externally injected travelling wave a_2. The synthesized reflection coefficient depends on *ATT, DEPH* and the delivered power of the RF generator. The open-loop active load-pull setup requires custom algorithms for iterative convergence to synthesize desired reflection coefficients because the output of DUT (transmitted traveling wave, b_2) is dependent on device operating conditions. This makes the technique effectively too slow for high measurement throughput applications.

Closed loop active load-pull, depicted in Fig. 4, overcomes the slow impedance synthesis characteristic exhibited by the active open-loop technique. In this approach, the reflected traveling wave a_2, is a modified form of the DUT output (b_2). Therefore, any change in b_2 is immediately sensed in a_2, which discards the need of any convergence algorithm. In the closed-loop load-pull technique, the synthesized Γ_L depends on the loop parameters, such as amplifier gain, attenuator and phase-shifter values. The main drawback of this setup is the risk of oscillations that can happen since a closed loop structure is used. This setup requires an amplifier with high gain and high linearity in the feedback loop, and this is definitely an added constraint. Incorporating a highly selective filter in the loop can mitigate

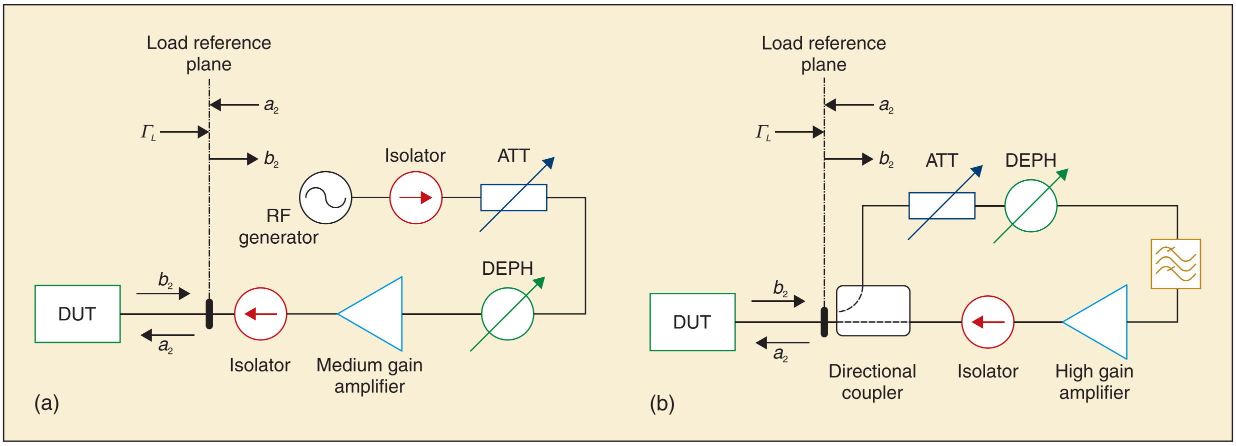

Fig. 4. Generic setup architectures. (a) The active open-loop technique. (b) The active closed-loop load-pull technique.

the oscillation problem to some extent, although it increases the complexity and cost of the setup.

Advanced Load-Pull Architectures

Any load-pull setup based on the conceptual descriptions of the previous section only marginally caters to the need of measurement applications. To make the load-pull setup more practical, there have been continuous advancements in the original load-pull setup architectures. In the passive load-pull setup, major changes in configurations have been made to enhance the maximum achievable load reflection coefficient, whereas in the active load-pull technique, the emphasis has been to improve the setup so that the requirements on loop amplifier gain are reduced.

Pre-matched load-pull is one of the most popular passive load-pull techniques. In this approach, two probes called pre-matching and tuning are placed side-by-side on the central conductor as Fig. 5 shows. These two probes are capable of individually generating smaller reflection coefficients, $\Gamma_{Pre\text{-}match}$ and Γ_{Probe}, which combine to achieve a higher reflection coefficient, Γ_{Total}, given by equation (1.3):

$$\Gamma_{Total} = \Gamma_{Pre\text{-}match} + \frac{S_{12}S_{21}\Gamma_{Probe}}{1 - S_{22}\Gamma_{Probe}} \tag{1.3}$$

where S_{12}, S_{21}, and S_{22} are the S-parameters of the pre-matching tuner.

A practical, pre-matched load-pull setup, however, utilizes a low-loss central conductor; therefore, it is reasonable to assume that $S_{21}S_{12}$ approaches unity. Furthermore, the term S_{22} can be assumed to approach zero, considering that there is no discontinuity in the central conductor. In such a situation, the Γ_{Total} generated by the pre-matched load-pull setup can be approximated by [3]:

$$\Gamma_{Total} = \Gamma_{Pre\text{-}match} + \Gamma_{Probe}. \tag{1.4}$$

The concept of reflection coefficient synthesis by a pre-matched load-pull setup using (1.4) is illustrated in Fig. 5.

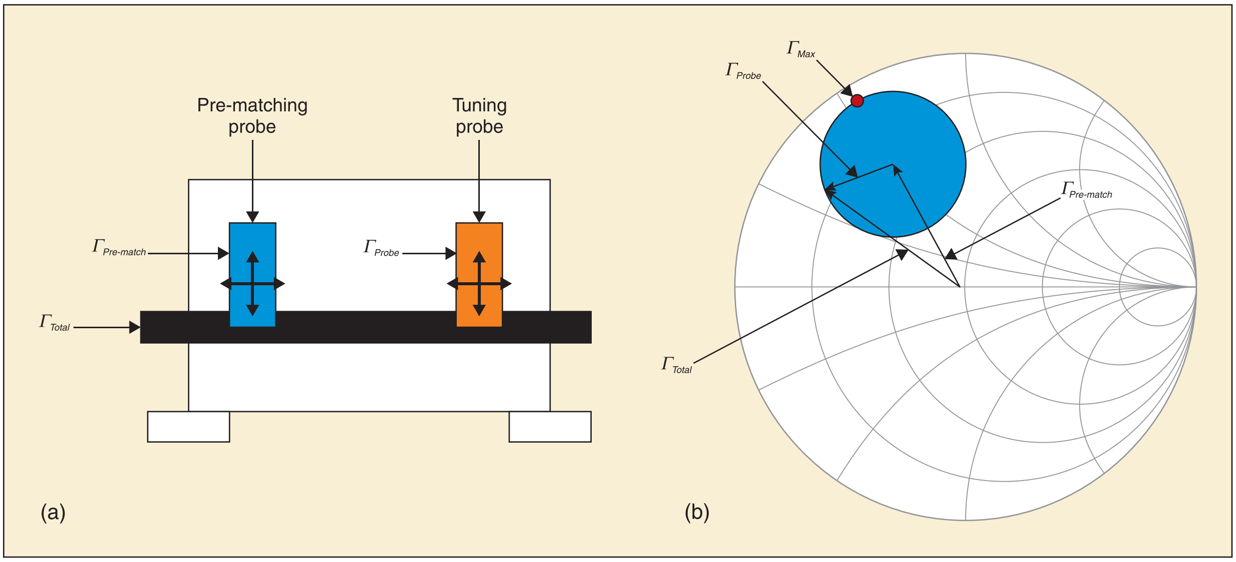

Fig. 5. Mechanical drawings of a pre-matched load-pull system. (a) The setup orientation. (b) Demonstration of higher reflection coefficient generation using a pre-matched load-pull setup [Courtesy of Focus Microwaves].

Initially, the pre-matching probe moves the matched condition from 50 Ω (in the centre of the Smith chart) to some other desired region of the Smith chart. This position of the pre-matching probe defines the reflection coefficient of the pre-matching probe $\Gamma_{Pre\text{-}match}$ as the figure shows. Movement of the tuning probe in horizontal and vertical positions then generates the reflection coefficient of the tuning probe, Γ_{Probe}, whose vector addition with $\Gamma_{Pre\text{-}match}$ results in the overall synthesized Γ_{Total}. For certain horizontal and vertical positions of the tuning probe, the overall synthesized reflection coefficient achieves the highest value, denoted by Γ_{max}.

The pre-matching technique is still limited in some applications requiring impedances less than one Ohm because the maximum achievable tuning range in this approach is reduced by the adapters and the insertion loss of the associated fixture hosting the DUT. It is important to note that, in many fundamental characterizations of high-power DUTs requiring a load-pull setup with high reflection coefficients, the approximate optimal impedance is known. In such applications, with impedance transforming networks between the DUTs, the tuner brings a significant advantage relative to pre-matched load-pull setups. The quarter wave (λ/4) transformer technique is one such approach in which a λ/4 impedance transformer is incorporated between the DUT and the tuner as Fig. 6 shows. In principle, this is a special type of pre-matched load-pull system in which the pre-matching is fixed and is provided by the λ/4 impedance transformer.

In the quarter wave transformer technique, the λ/4 impedance transformer moves the matched impedance environment from 50 Ω (point ‘a’) to some other smaller value (point ‘c’) as Fig. 6 shows. The matched condition at point ‘c’ results in an enhanced tuning range, albeit with reduced Smith chart coverage. It should be kept in mind that usually none of the measurement applications require full Smith chart coverage, and therefore, reduced Smith chart coverage is not a serious issue. Another important point to be noted is that the 50 Ω line in Fig. 6 is needed to provide the match between the quarter wave transformer and the load-pull tuner.

The pre-match and quarter wave impedance transformer load-pull setups substantially fulfill the needs of fundamental load-pull measurements. However, recent trends in PA design require multi-harmonic characterization of DUTs, and this obviously necessitates harmonic load-pull test setups. The quarter wave impedance transforming network with bandwidth of only about 5 to 10 percent of the carrier frequency prevents harmonic load-pull applications. This limitation can be overcome by replacing the quarter wave transformer with a broadband impedance transformer, such as the “Klopfenstein” taper with bandwidth covering from a few 100 MHz to 12 GHz [5], between the DUT and the tuner as shown in Fig. 7. The broadband impedance transformer does reduce Smith chart coverage with increasing impedance transformation ratios, as can be seen in Fig. 7. In this setup, the 50 Ω line matches the load-pull to the impedance transformer, whereas the line stretcher provides the necessary matching between the DUT (with impedance Z_d) and the impedance transformer.

It is important to note that the incorporation of an impedance transformer is beneficial for both the passive as well as active load-pull setups. Incorporation of an impedance transformer in a passive load-pull enhances the reflection coefficient tuning range, whereas the incorporation of such a transformer in an active load-pull reduces the stringent requirement on the loop amplifier for achieving a high reflection coefficient. In many applications, a passive impedance tuner and active load-pull, called a hybrid load-pull setup, is used to achieve the desired load-pull functionality. A hybrid load-pull setup can essentially satisfy all the measurement needs.

Recent Advances

There have been several recent advancements in both the passive and active load-pull techniques [6]–[12]. One such advancement is called the enhanced loop passive load-pull technique. It consists of an impedance tuner and a passive loop cascaded together, as Fig. 8 shows. The impedance tuner, *LP Tuner*, is a standard low-loss passive tuner, whereas the passive loop is built using a high directivity circulator and a coupler.

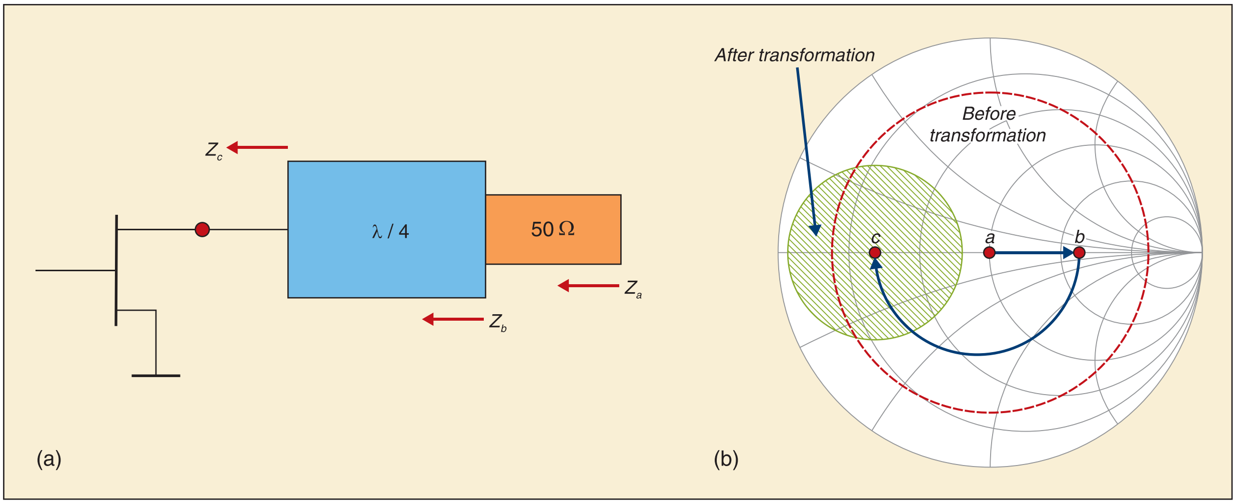

Fig. 6. Pictorial representation of the quarter wave transformation technique (© IEEE 2011, *IEEE Microwave Mag.*, used with permission, [5]).

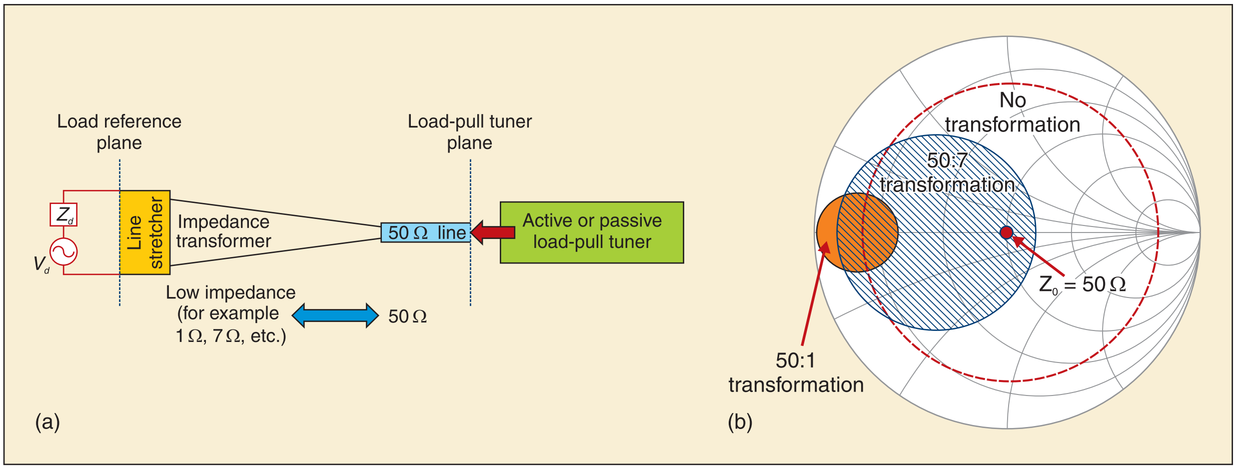

Fig. 7. Conceptual representation of broadband impedance transformer based load-pull setup (© IEEE 2010, *IEEE Microwave Mag.*, used with permission, [5]).

In this technique, the passive loop first moves the matched point farther from 50 Ω by Γ_{LOOP}, which is regulated by the length of the cable L_2, and the position of probes in the impedance tuner. The impedance tuner then adds its contribution to the reflection coefficient generated by the passive loop, to synthesize the high reflection coefficient at the load reference plane. The expression in (1.5) clearly identifies the dependence of the reflection coefficient synthesized at the load reference plane Γ_{Total} on the contributions from the impedance tuner and the passive loop:

$$\Gamma_{Total} = \frac{a_2}{b_2} = S_{11TUNER} + \frac{S_{12TUNER}.S_{21TUNER}.\Gamma_{LOOP}}{1 - S_{22TUNER2}.\Gamma_{LOOP}} \qquad (1.5)$$

$$\text{where, } \Gamma_{LOOP} = \frac{b_3}{a_3} = \left|\Gamma_{LOOP}\right|.e^{-2j\beta L_2} \;. \qquad (1.6)$$

The term Γ_{LOOP} is the reflection coefficient generated by a passive loop and is a complex term dependent on the loop component characteristics, i.e. the transmission factors of the coupler and the circulator, the phase velocity β of the travelling waves, and the length of the loop L_2. The length of the loop and, hence, the reflection coefficient can be changed by employing cable of appropriate lengths. It has been experimentally determined that cables of only three different lengths L_2 can cover the entire Smith chart. The need for only three distinct cables results in reduced calibration and measurement time of the enhanced loop load-pull system compared to the pre-matched load-pull techniques where separate pre-characterization of the tuner is required to cover the desired Smith chart region for any specified DUT. Additionally, the maximum synthesizable reflection coefficients using the enhanced loop load-pull setup is higher than the corresponding maximum values using the latest state-of-the art pre-matched load-pull system, as Fig. 8 shows.

A second interesting and useful advancement is envelope load-pull, which is one of the closed-loop active load-pull applications and is depicted in Fig. 9. Envelope load-pull overcomes oscillation associated with the closed-loop active

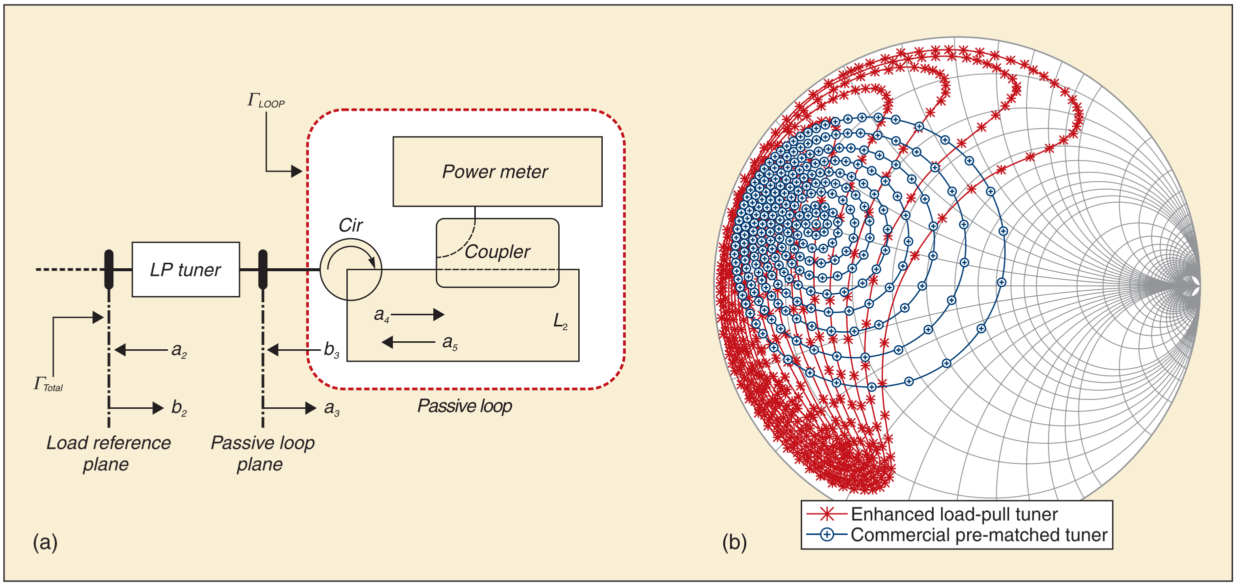

Fig. 8. Block diagrams. (a) An enhanced loop load-pull tuner. (b) A comparison of the maximum achievable reflection coefficient using enhanced loop load-pull and the latest commercial pre-matched load-pull setups (© IEEE 2010, IEEE Microwave Mag., used with permission, [5]).

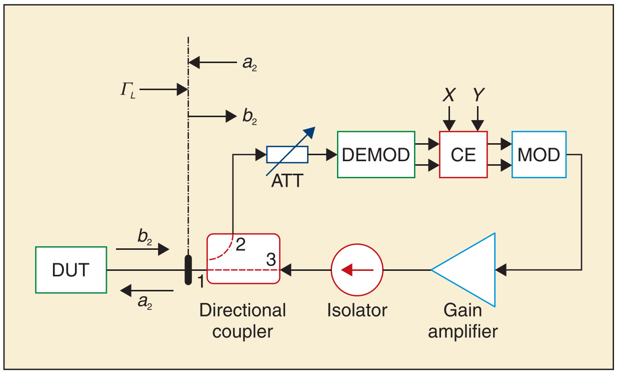

Fig. 9. A generic setup architecture of the active envelope load-pull technique.

load-pull technique. The magnitude and phase of the Γ_L at the load reference plane in this technique is directly related to the external control variables X and Y according to the expression given in (1.7):

$$\Gamma_L = \frac{a_2}{b_2} = X + jY \quad . \tag{1.7}$$

In this technique, the DUT output (b_2) is down-converted to its baseband components by a quadrature demodulator. The baseband components of b_2 are then modified by the control variables X and Y and up-converted to the carrier frequency by a quadrature modulator. The modified and up-converted signal is then appropriately boosted by the loop amplifier to form the reflected traveling wave a_2. Since the phase and magnitude modification of the reflected wave, a_2, in this technique takes place at baseband, there is absolutely no risk of RF oscillation. Furthermore, the control electronics (CE) in the loop works as a highly selective filter and thus, avoids the need for an additional filter in the loop. In addition to these useful features, envelope load-pull possesses all of the advantages of the closed-loop active load-pull technique.

Summary

This article presented the load-pull concept and its usefulness in modern wireless power amplifier design. It subsequently reviewed the most common load-pull techniques along with their advantages and limitations. A section on the latest advancements in load-pull setup configurations presented some of the most popular approaches adopted by the users of load-pull systems. The article discussed two of the latest developments in load-pull configurations which have either brought or have the potential to bring a paradigm shift in PA design techniques.

References

[1] J. M. Cusack, S. M. Perlow, and B. S. Perlman, "Automatic load contour mapping for microwave power transistors," *IEEE Tran. Microwave Theory and Techniques*, vol. 22, pp. 1146–1152, Dec. 1974.

[2] F. Secchi, R. Paglione, B. Perlman, and J. Brown, "A computer controlled microwave tuner for automated load pull," *RCA Review*, vol. 44, no. 4, pp. 566–583, Dec. 1983.

[3] F. M. Ghannouchi and M. S. Hashmi, *Load-Pull Techniques with Applications to Power Amplifier Design*, *Springer Series in Advanced Microelectronics*, New York, NY: Springer, 2012.

[4] J. E. Mueller and B. Gyselinckx, "Comparison of active versus passive on-wafer load-pull characterization of microwave MMwave power devices," in *Proc. IEEE Microwave Theory and Techniques Society's International Microwave Symposium Digest*, San Diego, CA, pp. 1077–1080, June 1994.

[5] M. S. Hashmi, F. M. Ghannouchi, P. J. Tasker, and K. Rawat, "Highly reflective load pull," *IEEE Microwave Mag.*, vol. 12, no. 4, pp. 96–107, June 2011.

[6] V. Teppati, A. Ferrero, and U. Pisani, "Recent advances in real-time load-pull systems," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 11, Nov. 2008.

[7] M. Thorsell and K. Andersson, "Fast multi-harmonic active load-pull system with waveform capabilities," *IEEE Trans. Microwave Theory and Techniques*, vol. 60, no. 1, pp. 149–157, Jan. 2012.

[8] V. Camarchia, V. Teppati, S. Corbellini, and M. Pirola, "Microwave measurements part II – non-linear measurements," *IEEE Instrum. Meas. Mag.*, vol. 10, no. 3, pp. 34–39, June 2007.

[9] F. M. Ghannouchi, M. S. Hashmi, S. Bensmida, and M. Helaoui, "Loop enhanced passive source- and load-pull technique for high reflection factor synthesis," *IEEE Trans. Microwave Theory and Techniques*, vol. 58, no. 11, pp. 2952–2959, Nov. 2010.

[10] M. S. Hashmi, A. L. Clarke, S. P. Woodington, J. Lees, J. Benedikt, and P. J. Tasker, "An accurate calibrate-able multi-harmonic active load-pull system based on the envelope load-pull concept," *IEEE Trans. Microwave Theory and Techniques*, vol. 58, no. 3, pp. 656–664, Mar. 2010.

[11] J.-M. Nebus, P. Bouysse, J. M. Coupat, and J.-P. Villotte, "An active load-pull setup for the large signal characterization of highly mismatched microwave power transistors," in *Proc. IEEE Instrumentation and Measurement Technology Conference 1993*, Irvine, CA, pp. 2–5, May 1993.

[12] F. Deshours, E. Bergeault, F. Blache, J.-P. Villotte, and B. Villeforceix, "Experimental comparison of load–pull measurement systems for nonlinear power transistor characterization," *IEEE Trans. Instrum. Meas.*, vol. 57, no. 11, pp. 1251–1255, Dec. 1997.

Mohammad S. Hashmi (mshashmi@ucalgary.ca) is an assistant professor at IIIT Delhi, India and an adjunct researcher at University of Calgary, Canada. His current research interests are nonlinear measurement techniques and advanced RF front-end design. He holds two patents (one pending) and has co-authored one book and over 45 research papers. He was recipient of 2008 ARFTG Microwave Measurement Fellowship.

Fadhel M. Ghannouchi is an AITF and Tier-I CRC professor at University of Calgary, Canada and director of iRadio Laboratory at the university. He and his research group are engaged in advancing the RF technology for enabling multi-band and multi-standard radios. He holds sixteen patents (five pending) and has co-authored three books and more than 500 scholarly papers. He is fellow member of IEEE, IET, IEC and Royal Society of Canada.