

# Improvement to Load-pull Technique for Design of Large-signal Amplifier in *K* band

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**Abstract.** An improvement to the load-pull technique for a large-signal design of a transistor amplifier is proposed. On the contrary to the current load-pull technique – a small-signal pre-matching on the output of the transistor is applied which results in reduced demands on a maximum VSWR of the tuner. This minimizes the launcher radiation in the *K* band and reduces measurement uncertainty. The proposed method has been verified on a design of 22 GHz large-signal amplifier using a Excelics EPA018A-70 transistor.

## Keywords

*K* frequency band, large-signal measurement, load-pull, microstrip launcher radiation, large-signal amplifier, small-signal pre-matching.

## 1. Introduction

A microwave amplifier design is generally a complex and difficult task. Manufacturer of the microwave transistor usually provides a large-signal model that a microwave engineer can work with and use it to design a device working under a large-signal conditions. Unfortunately in many cases accuracy of these models is still far from being acceptable in a practical design [1]. Application of a load-pull technique to determine the optimum load impedance is a practical solution in these cases.

The load-pull method was originally described in 1976 by Takayama [2] and many improvements have been published since then [3]. The load-pull method makes possible to vary the load impedance connected to a transistor while measuring its actual performance. In case of the large-signal amplifier the optimum large signal load impedance of the transistor can be experimentally determined by this way.

The load impedance is varied using microwave tuners with coaxial connectors. The reference plane of the load impedance is usually at the output of the transistor which is mounted inside a planar transmission line structure e.g. in microstrip line placed in a proper test fixture. There are various components between the reference plane and

the tuner: microstrip transmission line with some bias filters (if needed), microstrip to coaxial launcher, some coaxial adapters and possibly a coaxial transmission line connected between the output of the test fixture and the microwave tuner. Due to their losses all these additional components increase the demand on a maximum reflection coefficient of the tuner if the transistor with a large output reflection coefficient should be optimally matched. In practice these demands can exceed the specifications [4] of the tuner. Reflections of these components can interfere with a reflections from the microwave tuner which increases uncertainty of our measurement.

The situation may be more complicated due to the radiation of the launcher. It has been shown in [5] that microstrip to coaxial launcher is a potentially radiating structure in dependence to its position with respect to the Electric field's standing wave. The purpose of this paper is to present a new modification of the load-pull technique which can solve the problems with losses between the tuner and the reference plane where the optimum magnitude of a reflection coefficient should be realized.

## 2. Problems of the Load-Pull Technique

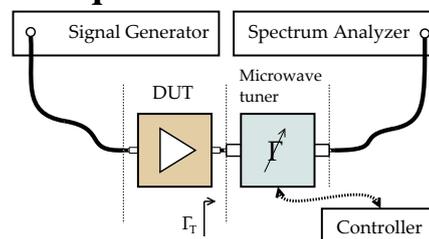


Fig. 1. Typical load-pull measurement setup.

The common set-up when performing a common load-pull measurement is shown in Fig. 1. Fig. 2 shows schematic arrangement of the device under test (DUT). The DUT consists of the microstrip structure with a transistor, bias circuits and a coaxial to microstrip launchers. In order to create the best match for the transistor in the large-signal operation it is usually necessary to achieve large magnitudes of reflection coefficient  $|\Gamma_L|$  at the specific reference plane.

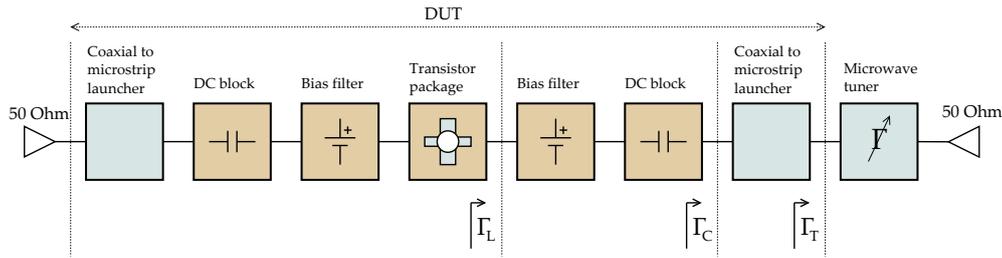


Fig. 2. Scheme of the common load-pull measurement.

Due to the losses of the bias filter, DC block and the launcher the magnitude  $|\Gamma_T|$  of the tuner should be appropriately larger. The situation is even more complicated with respect to the radiation losses of the launcher.

It has recently been published in [5] that the magnitude of radiated power is dependent on VSWR and on the position of the launcher with respect to the voltage standing wave. It may result in a situation that even for maximum values of  $|\Gamma_T|$  some amplitudes of the desired reflection coefficient  $|\Gamma_L|$  cannot be achieved in case that the maximum of the VSWR is placed near the launcher. On the contrary they can be achieved simply in the event that the minimum of the VSWR is not far from the launcher.

To evaluate the influence of radiation losses a 3D model of the launcher has been simulated using CST Microwave Studio. The evaluation was performed at the frequency 22 GHz. The simulation scheme is shown in Fig. 3 and the cross-section of 3D model is shown in Fig. 4.

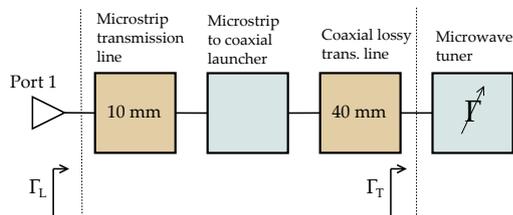


Fig. 3. The simulation scheme in CST Microwave Studio which contains model of the launcher connected to a 50 Ω microstrip line, 50 Ω lossy transmission line and a ideal microwave tuner.

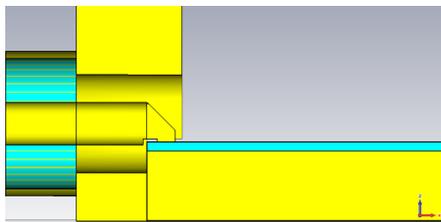


Fig. 4. The model of coaxial to microstrip transition in CST Microwave Studio.

The simulation scheme shows that the 3D model was connected between 10 mm of a microstrip line and a lossy coaxial line connected to the microwave tuner with the reflection coefficient  $|\Gamma_T|$ . Then values of  $|\Gamma_L|$  were obtained while varying the phase of  $\Gamma_T$  of reflected wave from the microwave tuner.

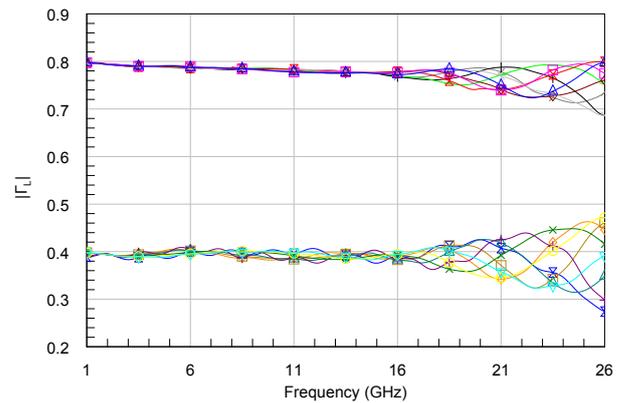


Fig. 5. Values of  $|\Gamma_L|$  as a function of frequency while varying the phase of reflected wave for  $|\Gamma_T| = 0.4$ , and 0.8 respectively.

Fig. 5 shows the values of  $|\Gamma_L|$  as a function of frequency and with the phase of the reflected wave as a parameter. If the amplitude of the reflection coefficient  $|\Gamma_T|$  was set to 0.4 it can be seen that depending on the phase of reflected wave the achieved value of  $|\Gamma_L|$  varies around the desired value of 0.4. In case of  $|\Gamma_T|$  set to 0.8 the reflection coefficient  $|\Gamma_L|$  varies in a similar way, but it is always smaller than 0.8.

The uncertainty of  $|\Gamma_L|$  is due to the non-zero reflection coefficient of the launcher itself which is increasing with frequency. Reflected wave from the launcher interferes with the reflected wave from the tuner and this creates the ripple visible in the resulting values of  $|\Gamma_L|$ .

It can be concluded that the launcher radiation increases losses of the structure. It results in the situation that some larger amplitudes of desired reflection coefficient of  $|\Gamma_L|$  cannot be achieved for certain phase shifts. It limits practical applications of load-pull technique. Therefore it would be very useful to limit VSWR at the reference plane  $\Gamma_C$  (see Fig. 2) as much as possible.

### 3. Proposed Modification

As a solution to the problems specified in the previous section, a modified load-pull method is proposed. To reduce the magnitude of  $|\Gamma_T|$  needed to find the optimal load impedances (with corresponding values of  $|\Gamma_L|$ ) a pre-matching subcircuit was added to the structure of the DUT,

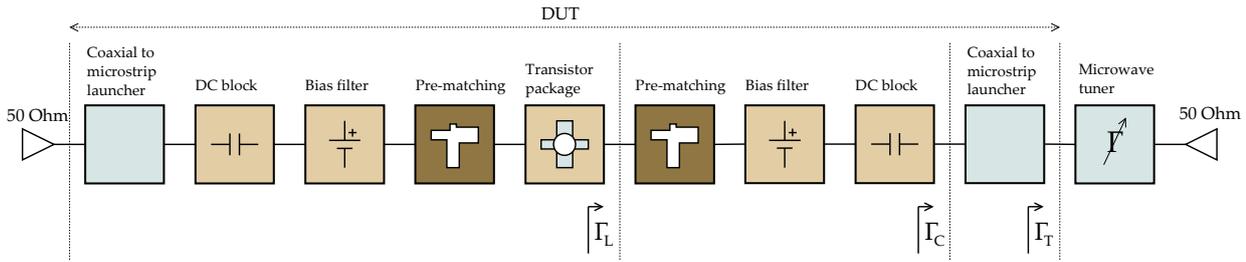


Fig. 6. Scheme of the modified load-pull measurement.

see Fig. 6. The pre-matching subcircuit is designed using small-signal S-parameters of the transistor. The modified load-pull measurement process can be described as following.

- An amplifier based on measured small-signal S-parameters at specific bias point of our transistor is designed and fabricated.
- Then it is placed into the test fixture for a load-pull measurement and the optimal large-signal parameters and corresponding optimum  $\Gamma_{Topt}$  are found.
- $\Gamma_{Topt}$  is transformed into the reference plane as  $\Gamma_{Lopt}$ . The output matching circuit is redesigned to obtain  $\Gamma_{Lopt}$  for  $\Gamma_T = 0$  corresponding to 50  $\Omega$  load.
- The amplifier with redesigned output matching circuit is fabricated and measured to compare its performance to the unmodified amplifier.

Pre-matched amplifier design is created in any suitable CAD software. It is good choice to verify desired performance of the redesigned matching circuit in a full-wave 3D EM field simulator.

### 4. Measurement and Verification

The modified load-pull measurement process was experimentally verified. Fig. 7 shows the amplifier used as the DUT. Pre-matching subcircuits were designed based on small-signal S-parameters. The amplifier was fabricated on a 0.254 mm thick Arlon CuClad 233 substrate with relative permittivity  $\epsilon_r = 2.33$ . The pHEMT packaged transistor Ex-celics EPA018A-70 with a typical output power 20 dBm at 1 dB compression was used. The small-signal pre-matching was achieved using a broadband matching technique described in [7].

Measured parameters of this amplifier are shown in Tab. 1.

$P_{in}$ (dBm)	$P_{out}$ (dBm)		
	21 GHz	22 GHz	23 GHz
8.67	14.67	13.17	12.83
10.17	15.17	14.50	13.83
11.33	15.50	14.83	14.17

Tab. 1. Measured DUT performance at various frequencies (small-signal design).

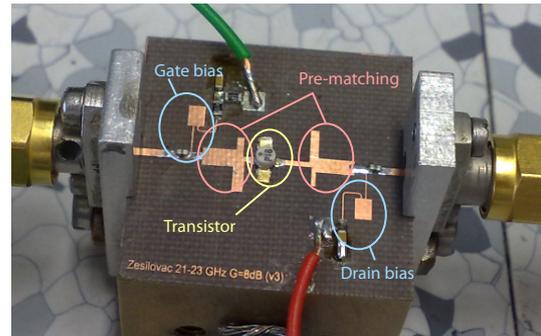


Fig. 7. Photo of designed amplifier using small-signal pre-matching.

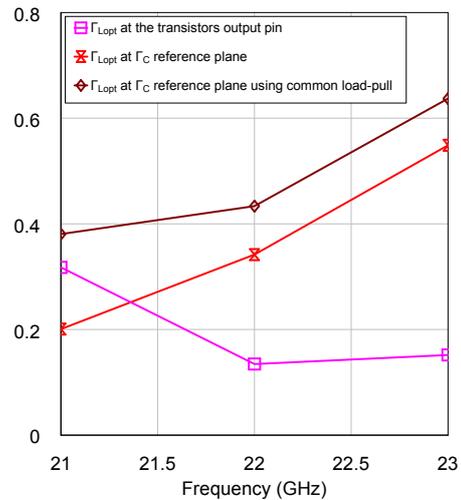
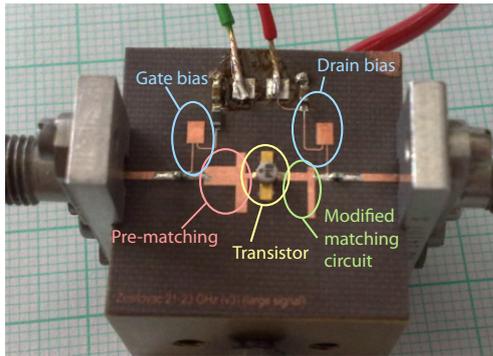


Fig. 8. Frequency dependence of  $|\Gamma_{Lopt}|$ ,  $|\Gamma_{Copt}|$  and  $|\Gamma_{Ccomm}|$ .

Then the modified load-pull method was applied and  $\Gamma_{Topt}$  was determined and transformed by embedding appropriate subcircuits to obtain  $\Gamma_{Copt}$ ,  $\Gamma_{Lopt}$  respectively, see Fig. 6.  $\Gamma_{Lopt}$  was also transformed back to  $\Gamma_{Ccomm}$  corresponding to common load-pull technique with no pre-matching or modified matching circuits used.

Fig. 8 illustrates the advantage of the modified load-pull method. Significant reduction of nearly 50 % of  $\Gamma_{Copt}$  was achieved. Using  $\Gamma_{Lopt}$  the modified matching circuit was designed as a double open-ended microstrip stub. AWR Microwave Office and the 3D Simulator AWR AXIEM were used so that the simulated performance of the designed matching circuit was fitted to the desired values of  $\Gamma_{Lopt}$ .



**Fig. 9.** Photo of the new amplifier. The modified load-pull technique applied in the design.

The new amplifier was fabricated using the modified output matching circuit (see Fig. 9). Measured data are shown in Tab. 2.

$P_{in}$ (dBm)	$P_{out}$ (dBm)		
	21 GHz	22 GHz	23 GHz
8.67	15.50 (+0.83)	14.70 (+1.53)	14.50 (+1.67)
10.17	15.87 (+0.70)	15.67 (+1.17)	15.00 (+1.17)
11.33	16.10 (+0.60)	16.08 (+1.25)	15.90 (+1.73)

**Tab. 2.** Measured DUT performance with modified output matching circuit and achieved improvements compared to Tab. 1.

It can be seen that the large-signal performance of the amplifier was improved. Its available output power is roughly 1 ÷ 1.5 dB better compared to the original small-signal design. Also, we have been able to verify (see Fig. 8) our proposed improvement of the load-pull method. It is possible to perform a solid load-pull measurement with pre-matched amplifier based on small-signal S-parameters to avoid large magnitudes of VSWR and thus reduce potential losses due to power leakage on the microstrip to coaxial launcher.

## 5. Conclusions

The new modification of the load-pull technique was designed. The method reduces demands on magnitude of reflection coefficient realized by a tuner and reduces radiation losses of the microstrip-coaxial launcher. It results in moderate demands on maximum VSWR of the tuner reducing its cost. Experimental verification in frequency band 21 to 23 GHz confirmed nearly 50 % reduction of magnitude of reflection coefficient at the launcher at 21 GHz. Up to 1.7 dB improvement of the output power of the amplifier designed by the new method was achieved at 23 GHz compared to small signal S-parameter design.

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