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Further Improvements in Real-Time Load-Pull Measurement Accuracy

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***Abstract*—This letter proposes a new solution to improve the accuracy of real-time load-pull measurement systems. Since it is well known that load-pull measurement accuracy depends on the calibration residual uncertainty, the presented solution uses a new algorithm to reduce it. Measurement results that corroborate the proposed solution, with respect to the previous one, show the improvements that have been achieved.**

***Index Terms*—Directional coupler, microwave measurements, microwave phase shifter, tuners, uncertainty.**

I. INTRODUCTION

IN recent years, the characterization of linear and nonlinear devices has become more and more important. A successful technique for this kind of measurement is the well known load-pull characterization, based on the measurement of the Device Under Test (DUT) driven in nonlinear conditions. Load-pull systems can be divided into two categories: tuner precharacterization based [3] and real-time [4], [5]. In both cases, a vector network analyzer (VNA) is used, although in very different ways, to measure the reflection coefficients, thus affecting the overall accuracy.

Real-time systems accuracy is the topic of this letter. Every real-time system can be sketched as in Fig. 1: the waves to be measured are provided to the VNA by two reflectometers positioned at port 1 and 2, and the load reflection coefficient (Γ_L) can be tuned in phase and magnitude using an active loop (that allows to reach values of $|\Gamma_L|$ very close to the unity) or a passive tuner. The system is initially calibrated with the technique explained in [4]. Two sets of error coefficients are obtained, one for the scattering parameters/reflection coefficients and the other one related to the power information.

Typical uncertainty contributions are: the power level uncertainty, the VNA measurement repeatability, the connection repeatability and the residual uncertainty due to the calibration, which includes measurement repeatability and uncertainty in the standard definition. In [8] an optimization technique was proposed to address the latter problem; here we further reduce the residual calibration uncertainty by means of a new functional and different constraint definitions. Measurement results prove the effectiveness of this new approach explicitly for high $|\Gamma_L|$ levels which are typical of modern devices.

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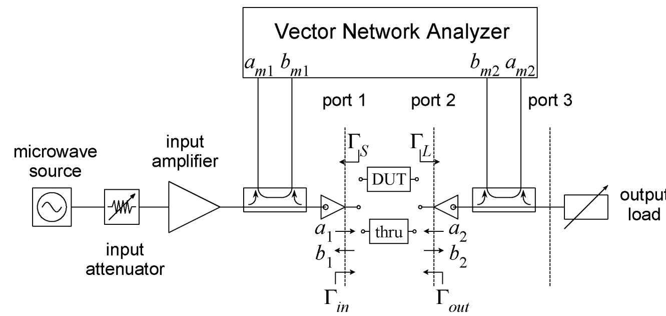

Fig. 1. Simplified scheme of a VNA-based real-time load-pull system.

II. PROBLEM DEFINITION AND PROPOSED SOLUTION

A typical parameter measured by the system in Fig. 1 is the operative gain (G_{op}), defined as

$$G_{op} = \frac{P_{out}}{P_{in}} = \frac{|b_2|^2 - |a_2|^2}{|a_1|^2 - |b_1|^2} = \frac{|b_2|^2 \left(1 - |\Gamma_L|^2\right)}{|a_1|^2 \left(1 - |\Gamma_{in}|^2\right)}$$

where $\Gamma_L = a_2/b_2$ and $\Gamma_{in} = b_1/a_1$.

This parameter, in case of a thru standard, is 0 dB since $a_1 = b_2, b_1 = a_2$ and $P_{in} = P_{out}$. Thus, the repeatable discrepancies from this value are a symptom of residual calibration uncertainty effects. As demonstrated in [6], the value of ΔG_{op} exponentially increases as $|\Gamma_L|$ reaches the edge of the Smith Chart.

The basic idea of this work is to find an optimization technique to reduce the value of ΔG_{op} over the entire Smith Chart by varying the set of error coefficients. An iterative process is used:

1) find a set of initial error coefficients by performing any chosen calibration technique;
2) measure a set of raw waves corresponding to a complete load-pull map of a thru, i.e. a set of measurements of a thru for different values of Γ_L;
3) correct the raw data with the set of error coefficients and compute the value of the minimization function;
4) if the minimization funtion reaches below a given tollerance, use the new error coefficients;
5) otherwise modify the set of error coefficients and return to point 3).

The speed of the procedure and the final uncertainty level depend on the kind of minimization function used. In [8] the considered function was

$$F = \sum_{i=1}^{N} a \left| G_{op}^{i}(u, w) \right| \tag{1}$$

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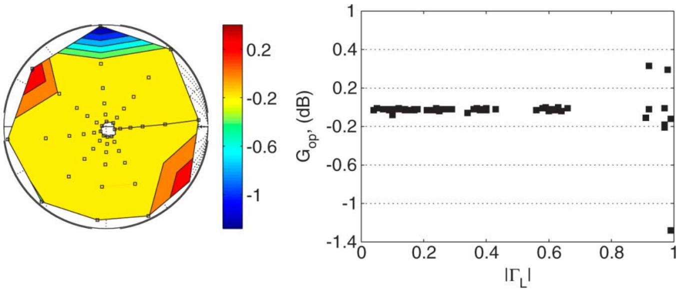

Fig. 2. Thru operative gain versus $|\Gamma_L|$ before the optimization process.

where u is the current set of error coefficients, w represents the raw waves, N is the number of different loads (i index) of the thru standard load-pull map and a is a vector of weights that depend on the value of $|\Gamma_L|$. This functional, although in [8] proved to be successful, can be less effective when the reflection coefficients involved in the optimization are very large. For example, in Fig. 2 and Fig. 3(a), the functional of [8] is not applicable for the largest gamma load. Since, as shown in Fig. 3(a), the role of the vector of weights a used in the optimization process is so important that the process itself can fail, we formulate a new functional that depends only on the measurement data. In this way the minimization function is more general, robust and applicable in any situation

$$F = \sum_{i=1}^{N} 1 - e^{-\frac{\left|G_{op}^{i}(u,w)\right|}{nG_{max}}} \tag{2}$$

where $G_{max} = max|G_{op}|$ and n sets the shape of the exponential function, as shown in Fig. 4. We found out that, in order to weight in an acceptable way the extreme values of $|G_{op}|/G_{max}$, a good choice for n is between $0.4 < n < 0.5$. This choice of n has been done because for $n < 0.4$ all $|G_{op}|/G_{max}$ between 0.7 and 1 would be weighted too much, giving convergence problems, while for values of $n > 0.5$ those points wouldn't be weighted enough, giving worst optimization results for high gamma values.

The minimization operation is done using the simple Nelder-Mead multidimensional non-linear algorithm and the convergence is reached after about 100–200 iterations depending on the initial load-pull map and on the setted tollerance.

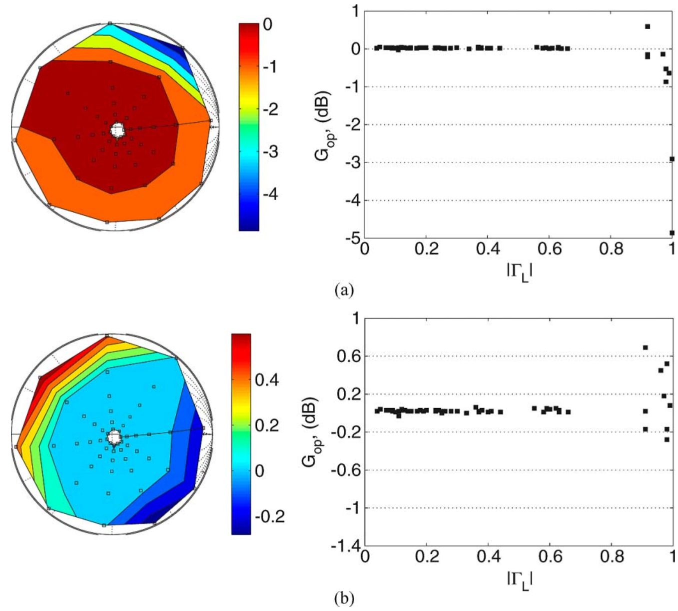

Fig. 3. Thru operative gain versus $|\Gamma_L|$ with the optimized calset of [8] (a) and with the new one (b).

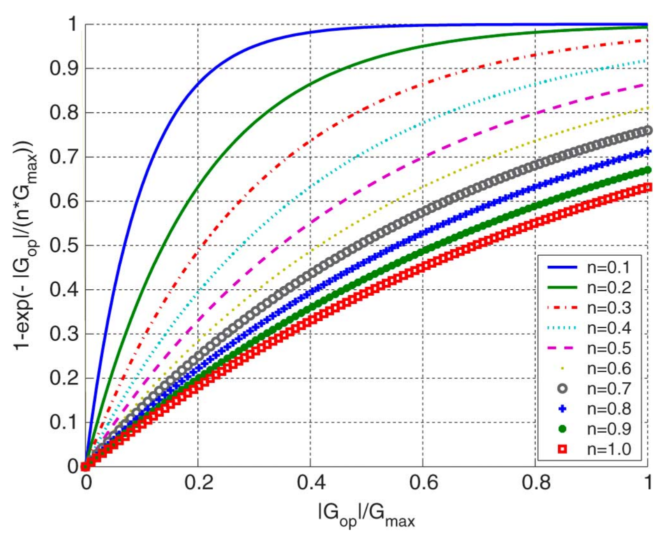

Fig. 4. Minimization function proposed in this letter.

III. Measurement Results

The measurement system used in the experiments is the one of Fig. 1.

First of all, we show an example where the functional presented in [8] does not give satisfying results.

The starting measurement map is shown in Fig. 2. After the optimization process, the results obtained are shown in Fig. 3(a). Note the fact that for the highest gamma load value, the maximum value of the gain after the optimization process is -4.9 dB while before it was -1.3 dB. To obtain better results with this functional, it would be necessary to change the weights a of (1). This fact points out the necessity to find a new, more general, minimization function. With the new functional of (2) the obtained gain spreading is from -0.3 dB to 0.7 dB, see Fig. 3(b).

Subsequently, some sets of on wafer measurements have been done in order to validate the effectiveness of the new minimization function. The starting point is a load-pull map of a thru device containing raw data calibrated with different techniques (LRM, SOLT, QSOLT, LSM, SOLR), similar to what was performed in [8]. In all cases, good results were achieved.

To further improve the optimization speed and performance, we run the optimization on different subsets of the initial raw data. Since the SOLT calibration technique provides more interesting results, it is considered further. In fact other calibration techniques, like for example the LRM one, are very accurate by themselves, and so the results of the presented optimization process are less evident.

In our study we consider the following different cases:

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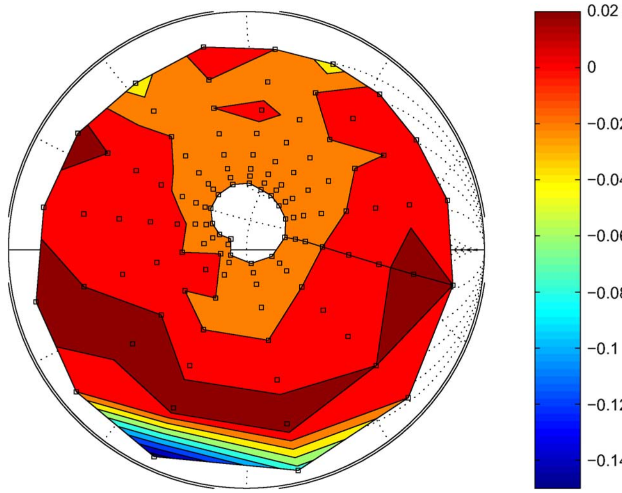

Fig. 5. Contour of the load-pull map de-embedded with the set of error coefficients obtained from the optimization process considering all the points of the map (case 1).

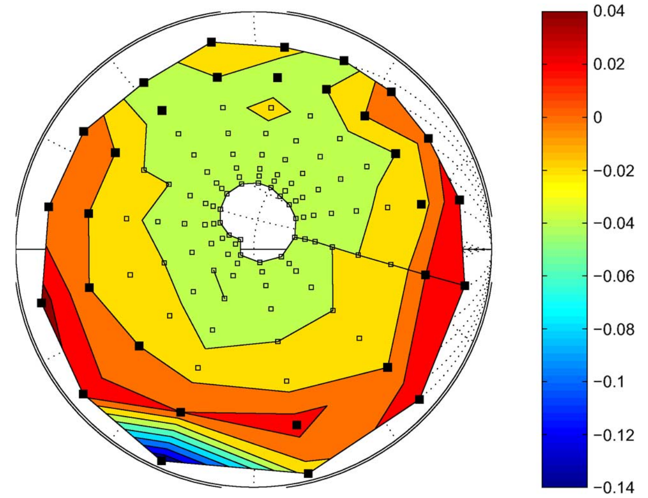

Fig. 6. Contour of the load-pull map de-embedded with the set of error coefficients obtained from the optimization process considering the two highest gamma rings (case 3 a).

- case 1: whole thru map de-embedded with the set of error coefficients obtained from the optimization of all the data contained in the map (see Fig. 5)
- case 2: whole thru map de-embedded with the set of error coefficients obtained from the optimization of a subset of the magnitudes contained in the map

In case 2 we use, for the optimization process, only the highest gamma points (black squares in Fig. 6), since these are the critical data for our problem. In this way we obtain faster results (the optimization algorithm converges with a less amount of iterations), but the uncertainty of the central points of the Smith Chart slightly increases (see Fig. 6). Thus, we inspect another approach, considering for the optimization process also some points that lie in the center of the Smith Chart (black squares in Fig. 7). In this way we achieve good results all over the Smith Chart, and improve the speed of the optimization. In particular, using an Intel Core 2 Quad CPU Q9400 @ 2.66 GHz with 3 GB of RAM, the optimization process over all the Smith Chart takes 2 min and 27 s, whereas the one done on the points of Fig. 6 takes 31 s and the one done on the points of Fig. 7 takes 1 min and 23 s.

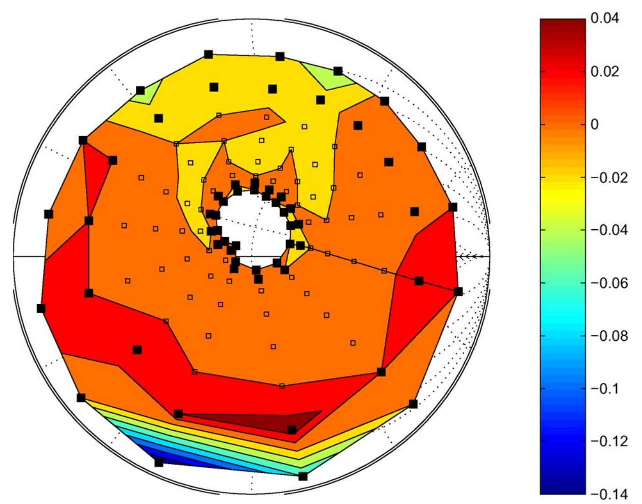

Fig. 7. Contour of the load-pull map de-embedded with the set of error coefficients obtained from the optimization process considering the two highest gamma and two internal rings (case 3 b).

IV. Conclusion

A new solution for calibration improvement of a load-pull real-time system is proposed in this letter. Although based on a technique similar to [8], we introduce a new optimization function, which proves to reduce the residual calibration uncertainty as the reflection coefficient values increase. This procedure allows to obtain good and reliable optimization results in a smaller amount of time and in a wider range of cases.

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