A Signature Test Framework for Rapid Production Testing of RF Circuits

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Abstract

Production test costs for today's RF circuits are rapidly escalating. Two factors are responsible for this cost escalation: (a) the high cost of RF ATEs and (b) long test times required by elaborate performance tests. In this paper, we propose a framework for low-cost signature test of RF circuits using modulation of a baseband test signal and subsequent demodulation of the DUT response. The demodulated response of the DUT is used as a "signature" from which all the performance specifications are predicted. The applied test signal is optimized in such a way that the error between the measured DUT performances and the predicted DUT performances is minimized. The proposed low-cost solution can be easily built into a load board that can be interfaced to an inexpensive tester.

1 Introduction

Production testing cost is a major component of the total manufacturing cost of RF circuits because of elaborate tests and expensive testers. Today's RF measurement systems are extremely complex million-dollar ATEs. Innovative test solutions are needed to keep pace with the industry demand for higher performance products at a lower price.

Test cost reduction for RFICs can be categorized into three techniques: *test less*, *test earlier*, and *test faster* [1]. The *test less* techniques exploit redundancy among the tests, and between the wafer level tests and final tests. In the *test earlier* strategy, package scrap is reduced by performing as many tests at the wafer level as possible. Final test is still needed, but is often limited to continuity tests for high yield production lines. The *test faster* technique involves the use of test parallelism, or high-throughput testers. With continued price erosion and greater deployment of integrated RF devices into commodity products, most OEM end-customers are favoring the use of low-cost RF testers [2]. Low-cost testers are particularly attractive for low pin-count, high-volume RFICs. For these devices, there is great pressure to reduce test costs in the "mature" or "declining" stages of the product cycle through test time reduction. For these applications, the high performance and fully-loaded functionality of a high-end RF ATE is seldom fully exploited.

This paper presents a low-cost signature test alternative for high volume production testing of RFICs [3]. The proposed solution comprises of optimization algorithms for generating a "high quality" baseband test stimulus, load board circuitry for application of the test stimulus to the device-under-test (DUT), extraction of a baseband signature from the DUT response and a post processing system for mapping the DUT signatures into "data sheet" specifications. The proposed solution is targeted at low-cost testing of RF front-ends and front-end chips, such as LNAs, power amplifiers, attenuators and mixers. The key features of the proposed technique include low-cost test instrumentation (comprising of a RF signal generator, a baseband digitizer and an arbitrary waveform generator) and the ability to measure the DUT performance in a fraction of the test time required with conventional techniques. This results in a significant lowering of testing costs and improvement in test floor capacity.

The rest of the paper is organized as follows. Section 2 introduces RF signature testing concepts. Section 3 discusses the test optimization required for robust testing. Section 4 illustrates the proposed approach by means of a simulation example and measured data from real devices. Section 5 concludes the paper.

2 Signature Testing: A Low-Cost Alternative for RF Testing

In contrast to conventional testing where the DUT is subjected to a number of parametric tests, the signature test methodology involves applying a short duration test stimulus to the DUT and using the DUT response to estimate its performance. The difference between the two testing methodologies is illustrated in Figure 1. Compared to conventional specification

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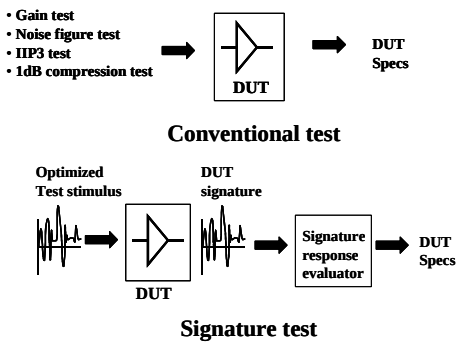

Figure 1: Signature testing vs. Conventional testing

testing, signature testing has the following advantages:

1. Multiple DUT specifications can be computed using a single response acquisition.

2. With conventional testing, each specification test involves an overhead for setting up the instruments and the test configuration. On the other hand, the signature test approach uses a single test configuration and a single test stimulus, thereby eliminating the overheads.

3. The instruments used to apply the signature test stimulus and measure the resulting response are much simpler and inexpensive, compared to the specialized instruments required for full specification testing.

In view of these benefits, signature testing has been proposed as a low cost alternative to specification testing of analog circuits [4], [5]. It has been shown that without explicitly testing for the circuit specifications, analog performance can be predicted by using the transient response of the DUT as a signature (hence the name *signature testing*).

While the scenario depicted in Figure 1 can be advantageously applied to low frequency analog circuits, generation and measurement of transient radio-frequency signals is impractical. Nevertheless, the concepts of modulation and demodulation can be applied to translate a baseband test stimulus to the RF spectrum for application to the DUT, and for converting the resulting DUT response back to a baseband signature. The use of modulated signals for the testing of RF circuits has been well investigated. Techniques such as the modulated vector network analysis (MVNA) [6] have been proposed for making classic RF measurements on wideband modulated signals. Similar concepts can be exploited to facilitate signature testing of RF circuits. The basic signature test configuration for testing RF circuits is illustrated in Figure 2. The proposed approach involves the following steps: (a) the ATE supplies a carefully designed baseband test stimulus to the loadboard (b) on the loadboard, the test stimulus is modulated onto a carrier and the modulated carrier acts as the test input signal to the DUT, (c) the DUT response is demodulated and the baseband stimulus is sent back to the ATE and (d) the design of the test stimulus (baseband+carrier) is done in such a way that the performance variations in DUT cause significant changes in the response seen by the ATE.

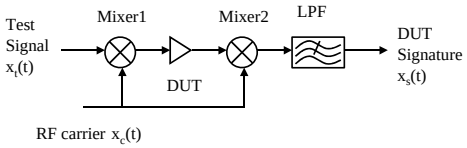

Figure 2: Basic Signature test configuration for RF circuits

2.1 Practical Considerations

The basic signature test configuration configuration in Figure 2 is sensitive to phase variations in the signal path. Let $x_t(t)$ be the baseband test signal and $x_c(t) = sin(\omega_0 t)$ be the carrier signal that is input to the two mixers. The output of the first mixer is given by

$$x_1(t) = x_t(t) sin(\omega_0 t) \tag{1}$$

For illustration, assume the DUT is a simple gain device with a gain A. The output of the second mixer is then given by

$$\begin{aligned} x_2(t) &= A\, x_t(t) sin(\omega_0 t) sin(\omega_0 t + \phi) && (2) \\ &= A\, x_t(t) cos\phi - A\, x_t(t) cos(2\omega_0 t + \phi) && (3) \end{aligned}$$

where the phase difference ϕ in Equation 3 is introduced due to a mismatch in the paths between the source and the mixers. Ignoring the second term in Equation 3 which is removed by the low pass filter, the signature output is given by

$$\begin{aligned} x_s(t) &= A x_t(t) cos\phi && (4) \\ &= 0 \quad for\ \phi = (2n+1)\frac{\pi}{2} \end{aligned}$$

Equation 4 suggests the possibility of complete cancellation of the signature output due to a slight difference in the signal paths between the RF source and the two mixers. This also results in random fluctuations in the signature output due to variations in the signal paths (such as the length of connecting cables), thereby affecting the test quality. Since at 10GHz, a quarter

wavelength is about 0.75cm, this is a very realistic possibility.

The problem can be solved by offsetting the carrier frequencies applied to the two mixers. If $sin\omega_1 t$ is the carrier signal to the first mixer and $sin(\omega_2 t + \phi)$ is the input to the second mixer, a simplified expression for the signature output is given by

$$x_s(t) = Ax_t(t)cos((\omega_1 - \omega_2)t + \phi) \quad (5)$$

Although the ϕ term in Equation 5 seems like a source of signature variation, it can be noticed that the magnitude of $x_s(t)$ remains unaffected by the phase difference. Therefore, the effect of phase variations can be removed by taking the FFT of the DUT signature, and considering the magnitude of the resulting FFT spectrum as the new signature. The resulting modified configuration is shown in Figure 3.

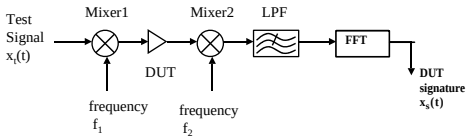

Figure 3: Modified Signature Test Configuration

3 Signature Test Theory

The basic idea behind signature test is that the fluctuations in the DUT performance result from process variations. Therefore, it is possible to predict the DUT performance using alternate tests that are sensitive to the manufacturing process. The relationship between process variations, DUT performances, and the DUT signatures is illustrated in Figure 4. Due to the fact that the signature tests require a short test time and simpler test resources, the test process is considerably less expensive compared to explicit performance testing of RF circuits.

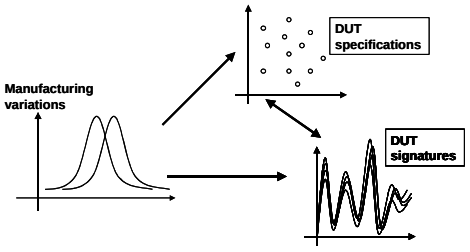

Figure 4: Relationship between the manufacturing process, DUT performances, and DUT signatures

3.1 Test Optimization

It is clear that the test costs can be significantly reduced by measuring DUT signatures and mapping the signatures into performance specifications. The quality of the mapping is determined by the robustness of the test stimulus. A *robust* test stimulus yields a consistent mapping between the DUT signature and the DUT performances even in the presence of measurement noise and tester variations. The goal of this section is to develop a framework for deriving robust signature tests, using the theory of linear systems.

Consider the vector of nominal statistical circuit parameters, denoted by x_0 and the vector of nominal DUT performances denoted by p_0, where $x_0 \in R^k$ and $p_0 \in R^n$. Using a linear model, the perturbation in the nominal performance vector $x \in R^k$ resulting from a process perturbation $p \in R^n$ is given by

$$p = A_p x \quad (6)$$

where A_p is the sensitivity matrix. The rows $a_{p,i}^T$ of the sensitivity matrix A_p denote the sensitivity of i^{th} performance with respect to the process parameters.

Let $s_0 \in R^m$ denote the nominal DUT signature obtained by sampling the output response of the DUT y(t) to an input stimulus v(t). The perturbation s in the DUT signature caused by process perturbation x can be similarly related, through the sensitivity matrix A_s

$$s = A_s x \quad (7)$$

We seek to determine a test stimulus and a signature such that there exists a transformation $A_p = AA_s$. If such a transformation exists, any perturbation p_i in the i^{th} performance , caused by a process perturbation x, can be predicted from the corresponding signature perturbation s. In practice, it is hard to guarantee the equality condition in the transformation $A_p = AA_s$ exactly, so the problem is solved in a least squares sense. In particular, denoting the i^{th} row of matrix A by a_i^T, a test stimulus v(t) is optimized in such a way that the least square error

$$\sigma_{p,i}^2 = \|a_{p,i}^T - a_i^T A_s\| \quad (8)$$

is minimized for i=1,2,3,..,n. The minimum norm solution of Equation 8 can be computed using singular value decomposition[7]. The solution is given by

$$a_i^T = A_s^\dagger \, a_{p,i}^T \quad (9)$$

The pseudoinverse of A_s is computed using the expression $A_s^\dagger = V\Sigma^\dagger U^T$, where $A_s = U\Sigma V^T$ is the SVD form of A_s.

In practice, measurements are corrupted by noise. This in turn affects the accuracy of the predicted DUT

performances. If ${\sigma_m}^2$ is the variance of the noise associated with measuring the signature, the total error in predicting the i^{th} performance is given by

$$\begin{aligned} {\sigma_i}^2 &= {\sigma_{p,i}}^2 + {\sigma_m}^2 \\ &= {\sigma_{p,i}}^2 + {\sigma_m}^2 \|a_i^T\|_2 \end{aligned} \quad (10)$$

The objective function to be minimized is now obtained as

$$F = \sum_n {\sigma_i}^2$$

The resulting objective function is minimized by optimizing a piecewise linear baseband test stimulus using a genetic algorithm [8]. Breakpoints of the PWL stimulus are encoded as a genetic string, and successive generations of the genetic optimization yield a waveform with decreasing values of the objective function.

3.2 Mapping DUT signatures into performance specifications

The proposed approach to extract the DUT specifications from the measured signature test responses is implemented in a software module called *FASTest Runtime System*. The process is illustrated in Figure 5. First, a training set of devices are measured for their specifications as well as signature test responses. Using nonlinear regression techniques on the measured data, normalized calibration relationships between the DUT specifications and signatures are extracted [4], [9]. The calibration effort involves the use of an RF ATE, but this is only a one-time effort preceding actual production test. During production test, the signature response of the DUT is measured on a low-cost tester and the performance specifications are computed from the obtained signature using a process of normalization.

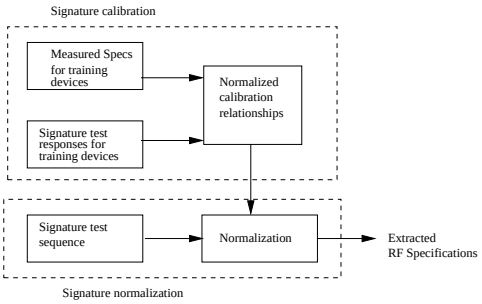

Figure 5: FASTest RF Runtime System

4 Experimental results

In this section, the results of the proposed signature test approach are presented using a simulation example. The approach is subsequently demonstrated using measured data from real devices.

4.1 Simulation results

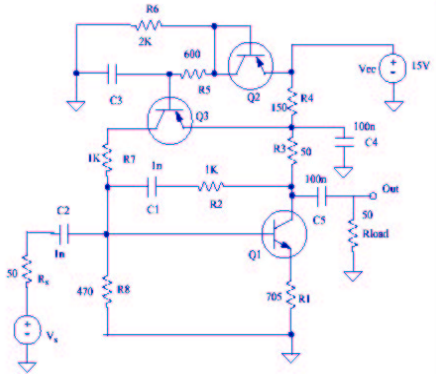

Figure 6: 900 MHz Low-noise Amplifier

The circuit used for simulation is a 900 MHz low-noise amplifier [10] shown in Figure 6. Three specifications of the amplifier are considered: gain, noise figure, and third-order intercept (IIP3). Gain and the noise figure performances were simulated at 900 MHz, while IIP3 was simulated by applying two input tones at 900 MHz and 920 MHz and measuring the resulting third-order harmonics. The circuit was simulated using the well known Cadence RF simulator *SpectreRF*.

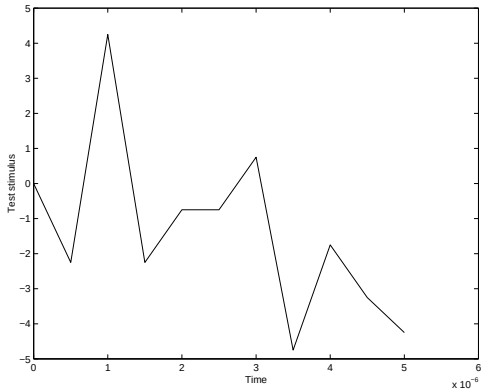

Figure 7: Optimized test stimulus

The proposed signature test framework needs to accurately estimate DUT performance over the range of process variations. The following parameters were considered variable: values of the resistors, capacitors, and the BJT model parameters saturation current (Is), forward current gain (β_f), forward early voltage (V_{af}), base resistance r_b, and current corner for beta (i_{kf}). Other parameters were found to have negligible impact on the DUT performance. The parameter variations are assumed to be uniformly distributed within a +/- 20% range around their nominal values. For upconversion of the baseband test stimulus and downconversion of DUT response, a 10dBm, 900 MHz

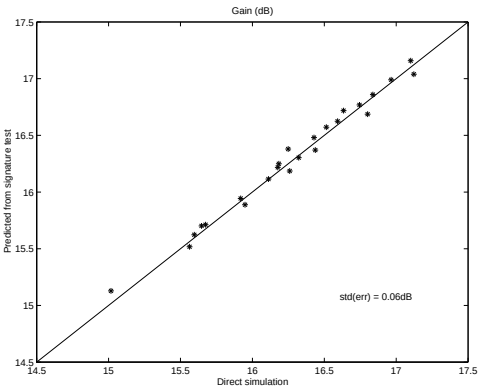

Figure 8: Gain results for the simulation example

carrier was selected. The mixer was modeled to generate cross products of the RF and LO signals and their second and third harmonics. Using the test optimization procedure described in Section 3, a piecewise linear test stimulus was optimized by running five iterations of a genetic algorithm. The circuit was simulated for 5us and the resulting test stimulus is shown in Figure 7. The signature response was obtained after passing the downconverted signal through a low pass filter with a cut off frequency of 10 MHz and sampling the the filtered response at 20MHz.

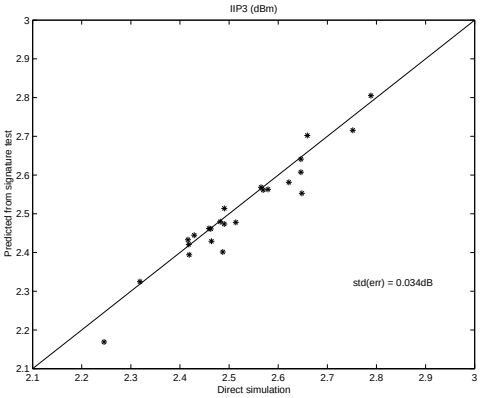

Figure 9: IIP3 results for the simulation example

A training set of 100 circuit instances were simulated to build the normalized calibration relationships. Thereafter, a separate set of 25 circuit instances were used to validate our methodology. To model the effects of noise, 1mV gaussian noise was added to the DUT signatures after simulation. Figure 8 shows the simulated and estimated performance for LNA gain. The x-axis displays the gain obtained by direct simulation and the y-axis displays the values estimated using signature test. Figure 9 and Figure 10 show the corresponding plots for IIP3 and noise figure specification. The plots for gain and IIP3 demonstrate close

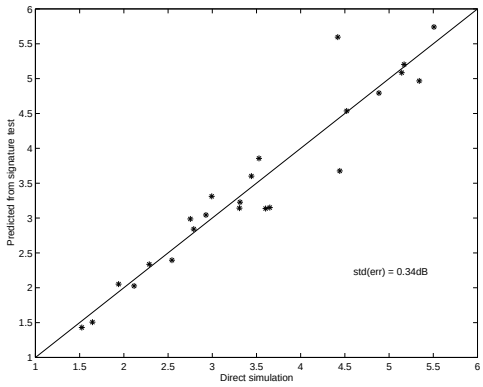

Figure 10: Noise figure results for the simulation example

matching between the simulated and estimated signature performance. The RMS error between the measured and predicted specs for both gain and IIP3 was within 0.05dB and that for the noise figure spec was 0.35dB.

4.2 Measurement Results

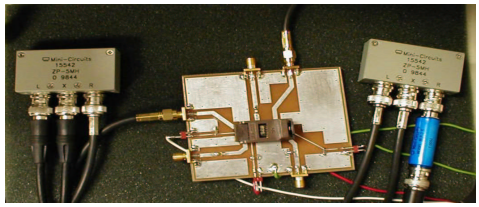

Figure 11: RF signature test hardware prototype

A 900 MHz RF frontend module using a RF2401 monolithic integrated receiver front-end IC from RF Microdevices was built to illustrate the application of the proposed approach on "real" hardware. Frequency conversion components needed for signature test were obtained from Mini-Circuits. Figure 11 shows a picture of the signature test prototype. As there was no access to the simulation netlist of the device from the manufacturer, the baseband test stimulus in this case was obtained by applying the optimization process on a behavioral model of the LNA. The intent of this experiment was to demonstrate the ability to measure DUT performance specifications on a low-cost ATE using a baseband test stimulus and a baseband signature response.

To illustrate our approach we used 55 LNA devices - 28 devices for building the calibration relationships, and 27 devices for test validation. The results are likely to be significantly better with a larger set of calibrating devices. We performed gain and IIP3 measurements at 900 MHz for all the 55 devices. Subsequently, signature responses of all the devices were

measured, with a 100 KHz offset between the mixer LO frequencies (900MHz and 900.1MHz), and a 1MHz digitizing rate. FFTs of the resulting DUT responses were computed and their magnitudes were used as test signatures in order to remove the phase dependencies due to the test lead interconnects.

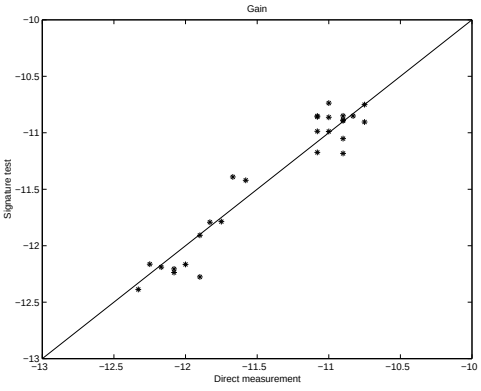

Figure 12: Gain results for RF2401 LNA

Figure 12 shows the comparison between the measured gain and the gain predicted from signature tests for the validating devices. The data shows good correlation between the two cases as evidenced by the number of data points adjoining the ideal 45^o straight line. The RMS error between the measured and predicted gain was 0.16dB. Figure 13 shows the corresponding results for IIP3. The RMS error in this case was 0.13dB. It is to be noted that the results for this experiment were based on a small number of devices and a prototype board. We expect correlation to improve significantly with better socketing and with the use of a larger number of devices for building the calibration model. Further improvements are also expected with the availability of a simulation netlist for the DUT. It to be noted that the signature test in this case required only 5 milliseconds of data capture, and a negligible time for data transfer and computation of the FFT. Therefore, significant improvement in test throughput is possible.

5 Conclusions

In this paper, we proposed a framework for low-cost signature testing of RF circuits. The proposed solution can be easily built into a load board or an add-on module that can be interfaced to an inexpensive tester. Due to the use of an extremely short duration baseband test stimulus for extracting the DUT performance specifications, the approach promises significant test time savings for RF circuits.

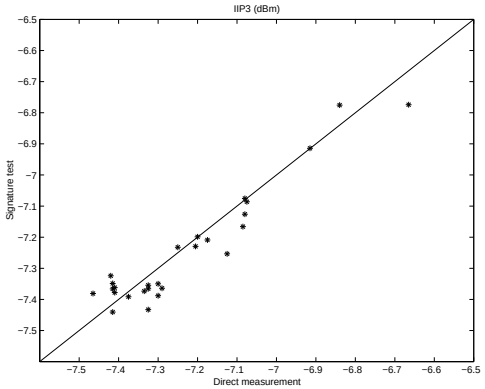

Figure 13: IIP3 results for RF2401 LNA

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