A Method to Compare Vector Nonlinear Network Analyzers

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Abstract – We address the difficult problem of determining measurement consistency between two vector nonlinear network analyzers, a new class of stimulus-response instruments that acquire multiharmonic waveform data instead of normalized network parameters. We develop a set of nonlinear verification devices and a method to compare the systems, and then demonstrate that measurements from three different nonlinear network analyzers are consistent to within 1.3 % of the amplitude of the applied stimulus signal.

I. INTRODUCTION

In this paper we present a new method for comparing measurement results from two or more vector nonlinear network analyzers. Such methods are now required since these instruments do not report parametric descriptions of devices under test; instead they measure input and output signals that cannot be normalized in a straight-forward way and whose characteristics depend on the specific instrument set-up.

The class of instruments known in general terms as vector nonlinear network analyzers [1-4] characterize nonlinear devices by supplying large-amplitude RF stimuli and measuring the resulting signals at the boundaries of the device under test (DUT). Unlike devices operating in a linear region, nonlinear devices cannot be adequately characterized by scattering parameters (ratios of outputs over inputs) since the nonlinearity transfers energy from the stimulus frequency (or frequencies) to products at new frequencies. As a result, measurements made on different nonlinear network analyzers cannot be directly compared. We address this problem in our paper by developing a set of stable nonlinear verification devices and by testing a comparative method that is based on the differences between measured and simulated results.

Our technique is similar to a comparison of linear vector network analyzer (VNA) measurements presented in [5]. In that study, each VNA system performed measurements on a set of verification devices. Differences were formed between the measurements and those from a reference system. For differences with magnitude less than the repeatability bound, the measurement was said to be "consistent" with that of the reference system.

For measurements made with vector nonlinear network analyzers, this consistency check is complicated by the fact that we cannot directly compare a measured parameter. No two measurement systems will have identical stimuli, connections, and port impedances. To solve this problem, we find the difference between the measured output and the output from a model of a given verification device for the same excitation conditions. The model is the same for all systems under consideration. For models capable of accurately representing device behavior over the range of input signals presented to a given verification device, the difference shows the level of measurement consistency between the systems.

Figure 1 gives an overview of our intercomparison technique. In the following sections we describe how we obtain the measured and modeled outputs and how we form the differences ε, Δ, and ζ These differences provide a check of the consistency of measurement results between systems without specifying a reference system.

Our method tells us how a set of measured outputs compares to a set of modeled outputs for a given excitation from system to system. For the group of verification devices we studied and for measurement systems placed in a variety of impedance states, we are able to compare measurements to within almost 1 % of the excitation signal's amplitude.

II. MEASUREMENTS

To test our comparative method, we measured three different nonlinear test circuits on two different nonlinear network analyzers, Systems 1 and 2 (see Table I). On one of the systems we also made measurements with a
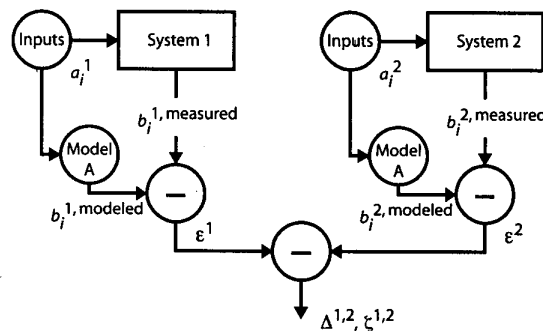

Fig. 1: Block diagram of the measurement comparison technique with a_i^x referring to System x input signals and b_i^x referring to System x output signals. The superscripts refer to the system under consideration and the subscripts refer to the ports.

Table I: Test cases considered in this study. Γ_2 refers to the Port 2 reflection coefficient at the fundamental frequency of 1 GHz.

	System 1 Γ_2=-42 dBm	System 2 Γ_2=-40 dBm	System 3 (Mismatch) Γ_2=-11 dBm	System 4 (Bad Meas.)
Model 1	Parallel	Parallel	Parallel	Parallel
	Antiparallel	Antiparallel	Antiparallel	-
	Series	Series	Series	-
Model 2	Parallel	Parallel	Parallel	Parallel
	Antiparallel	Antiparallel	Antiparallel	-
	Series	Series	Series	-

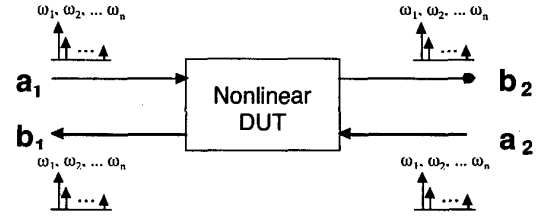**Fig. 2:** Flow diagram of measurements made with a vector nonlinear network analyzer showing vectors of input and output wave variables.

reconfigured port match condition, which we refer to as System 3. System 4 is an intentionally bad measurement we made by changing the system after calibrating it. We simulated the circuits using two sets of model parameters, as described in the next section.

We developed and fabricated wafer-level verification circuits using Schottky diodes in three different configurations: parallel, antiparallel, and series. We chose diode circuits as our verification devices because they provide us with both a wide range of nonlinear output signals, depending on DC bias and input signal level, and because they have well known equivalent-circuit models.

Two-port diode circuits were fabricated on alumina substrates by bonding beam-lead diode packages to the gold metallization layer with silver epoxy. The diodes were located in the middle of coplanar waveguide (CPW) transmission lines, with short lines connecting the diodes to probe pads at both ports (CPW lengths were 0.5 mm for the parallel and the antiparallel circuits, and 2 mm for the series circuit).

The instruments in this study provide accurate wave vectors by acquiring and correcting the phase and amplitude relationships of the fundamental and harmonic components in the periodic stimulus and response signals [4]. Figure 2 is a representation of our two-port measurements showing the input (a_i, i=1,2) and output (b_i, i=1,2) wave vectors at a given reference plane. In our study, the magnitudes of a_i and b_i in the frequency domain represent the peak voltage in $a_i(t)$ or $b_i(t)$, respectively.

We used an on-wafer Line-Reflect-Reflect-Match (LRRM) vector network analyzer calibration along with signal amplitude and phase calibrations, as described in detail elsewhere [4, 6, 7]. This process places the reference plane at the tips of wafer probes used to connect with the CPW interconnections. For all calibrations and measurements, we used a 1 GHz, 7.5 dBm sine-wave excitation at Port 1. Consequently, the calibrated components of the frequency-domain signal vectors fell between DC and 20 GHz on a grid with 1 GHz spacing.

Although the two nonlinear network analyzers used in our study have nominal port impedances of 50 Ω, it is important to note that an a_2 wave will exist because of the mismatch between the DUT and the measurement system.

This wave will modify the device response. We measured the Port 2 reflection coefficients at 1 GHz for the two systems as reported in Table I. We effectively implemented System 3 by detuning the Port 2 match of System 1.

III. SIMULATIONS

The next step in our measurement intercomparison was to find the modeled responses of our verification devices. We simulated the diode circuits using commercial harmonic-balance software and SPICE models described below. We used the measured a_i's as the inputs to our
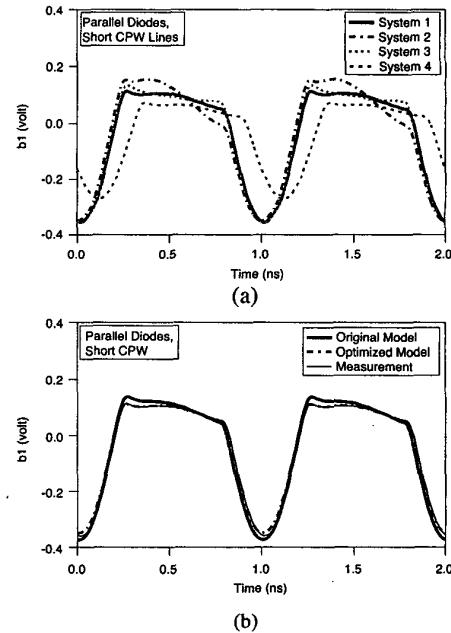

(a)

(b)

Fig. 3: Representative output time-domain data for the parallel diode verification circuit. The diodes have forward bias of 0.2 V and 1 GHz, 7.5 dBm sine-wave excitation. (a) $b_1(t)$ from the four measurement systems. (b) $b_1(t)$ for System 1 for the two models used in the intercomparison.

simulations. Because a_2 is nonzero with Port 1 excitation, we used both a_1 and a_2 as inputs [8, 9].

The same diode model was used in each set of system comparisons (as summarized in Table I). To explore the effects of model accuracy, we used both a set of model parameters specified by the manufacturer (Model 1), and a set optimized to our measured data (Model 2).

Figure 3(a) shows measured time-domain waveforms for the parallel-configured diode circuit. This is a typical set of output waveforms from Systems 1-4 and shows that these data cannot be compared directly. Figure 3(b) shows the simulated output waveform from System 1, $b_1^1(t)$, for the two models we compared. Also included is the measured $b_1^1(t)$ waveform, showing good agreement with the optimized model.

IV. THE INTERCOMPARISON

To perform an intercomparison (as outlined in Fig. 1), we first define and calculate a frequency-domain "predictive comparison." The predictive comparison, ε, is the complex difference between the measured and simulated responses of the nonlinear circuit. For example, the Port 1 System x predictive comparison is given by:

$$\varepsilon_1^x = b_1^{x,\ measured} - b_1^{x,\ modeled}, \qquad (1)$$

where ε_1^x, and the two b_1^x terms are vectors of complex numbers. What ε gives us is not a measure of accuracy, since at this point we are not choosing either the measurement system or the model to be the correct answer; ε forms the first difference we will use below to compare systems.

Figure 4 shows the magnitude of ε_1^x, $x=1,...,4$, for the parallel diode configuration using Model 1. For this diode configuration, b_1^x has higher harmonic content than b_2^x. We look at b_1^x results here to demonstrate a worse-case scenario. The highest measured noise floor of -75dBV is also shown. The unit dBV gives the voltage level in dB referenced to 1 V ($20*\log V_{peak}$).

For ε_1^1 and ε_1^2, we see that the magnitude of the difference between the measured and modeled responses is less than -30 dBV at all frequencies. This corresponds to less than 2.4 % of the peak input signal of 0.75 V at 1 GHz, and is larger than our noise floor for frequencies below 10 GHz. For ε_1^3 (where System 3 has $\Gamma_2 = -11.4$ dB at 1 GHz), a_2^3 increases significantly because of the Port 2 mismatch. Even for this mismatched case, we see close agreement between the measured and modeled results. This agreement indicates that our diode model is robust enough for comparison over the range of input signals considered here. The large values of ε_1^4 start to identify the bad measurement of System 4.

To compare two measurement systems, we next form the differences between the predictive comparisons:
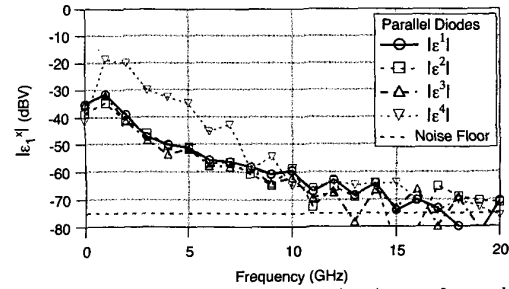

Fig. 4: Magnitude of ε_1, where the subscript 1 refers to b_1 of the parallel diode test circuit. The four different test configurations specified in Table I are shown. System 4 is an intentionally bad measurement. Subscripts in the figure legend are omitted for clarity.

$$\Delta_i^{x,y} = \left| \varepsilon_i^x \right| - \left| \varepsilon_i^y \right|$$
$$\zeta_i^{x,y} = \eta_i^x - \eta_i^y, \qquad (2)$$

where

$$\eta_i = \left(\arg\{\varepsilon_i\} - \arg\{b_i^{measured}\} \right). \qquad (3)$$

Here $\Delta_i^{x,y}$ is the difference in magnitudes of ε_i from measurement systems x and y, and η_i is the angle of ε_i relative to $b_i^{measured}$. The parameters Δ and ζ give a measure of consistency between the data acquired on two different vector nonlinear network analyzers.

Figure 5 shows representative Δ results for the three diode verification circuits. We show $\Delta^{1,3}$ since it is bigger than $\Delta^{1,2}$. In every case we computed, including cases not reported here, the measurement systems report data consistently to within approximately -40 dBV (except for the intentionally bad measurement of System 4). This corresponds to 1.3 % of our 0.75 V, 1 GHz input. We use ζ (not shown) to check whether ε's are pointing in opposite directions, which could cause ambiguity in our comparison. For the cases we studied, a comparison of magnitudes is sufficient.

In Fig. 6 we compare the original and optimized diode models for Systems 1-3 for the parallel diode case (the corresponding values of ε are shown in Fig. 4). The close agreement in Δ values indicates that, at least for the cases we studied, the quality of the model will not necessarily limit this approach to system intercomparison. This feature is what allows us to perform consistency checks between measurement systems without a statement of the model accuracy. The large $\Delta_1^{1,4}$ in Fig. 6(a) demonstrates that our comparative technique can clearly indicate a bad measurement system.
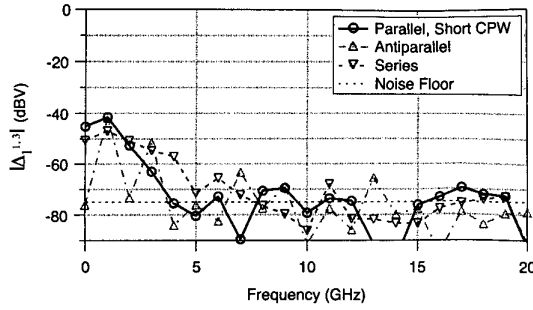
Fig. 5: Magnitude of $\Delta_i^{1,3} = |\varepsilon_i^1| - |\varepsilon_i^3|$ for the three diode configurations described in Table 1.
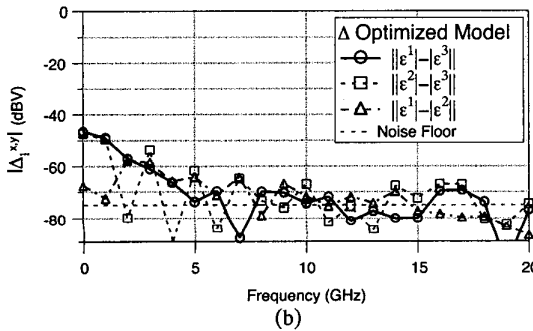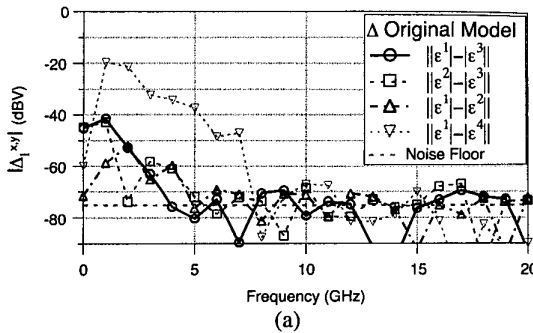

(a)

(b)

Fig. 6: Magnitude of $\Delta_i^{x,y}$ for the parallel diode case for (a) the original SPICE model and (b) a model optimized to measurements. Subscripts in the figure legend are omitted for clarity.

V. CONCLUSION

We developed a method for comparing measurements of nonlinear circuits made on different vector nonlinear network analyzers. We first measured verification devices and found a predictive comparison, the difference between a set of simulated and measured data. Next we compared the predictive comparisons between systems, holding the verification device model invariant. The difference between predictive comparisons given by Δ (magnitude) and ζ (phase) give us parameters for checking measurement consistency between vector nonlinear network analyzers. In this study, we show remarkably

small Δ values, less than 1.3 % of the stimulus amplitude for a variety of diode circuits measured with different measurements systems and various port impedance and connection configurations.

Interestingly, the difference between predictive comparisons is small even when different models are used in forming the comparison. For the cases we studied, it appears that the quality of the model is not an overriding feature of the technique, as long as the model is stable across the input states presented to the device. This result allows us to measure consistency even when we are not able to certify the accuracy of the model.

Our comparative method indicates how closely we can compare measurements. When we are able to specify the accuracy of one vector nonlinear network analyzer, we can apply this method to check accuracy of the measurements themselves. This is a topic of current research at NIST.

REFERENCES

[1] M. Sipilä, K. Lethinen, and V. Porra, "High-frequency periodic time-domain waveform measurement system," *IEEE Trans. Microwave Theory Tech.*, vol. 36, no. 10, pp. 1397-1405, Oct. 1988.

[2] G. Kompa and F. van Raay, "Error-corrected large-signal waveform measurement system combining network analyzer and sampling oscilloscope capabilities," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 4, pp. 358-365, Apr. 1990.

[3] M. Demmler, P. J. Tasker, and M. Schlechtweg, "On-wafer large signal power, S-parameter and waveform measurement system," in *Proc. 3rd Int. Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits* 1994, pp. 153-158.

[4] J. Verspecht, P. Debie, A. Barel, and L. Martens, "Accurate on wafer measurement of phase and amplitude of the spectral components of incident and scattered voltage waves at the signal ports of a nonlinear microwave device," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Orlando, FL 1995, pp. 1029-1032.

[5] D. C. DeGroot, R. B. Marks, and J. A. Jargon, "A method for comparing vector network analyzers," in *50th ARFTG Conference Digest*, Portland, OR, Nov. 1997, pp. 107-114.

[6] K. Rush, S. Draving, and J. Kerley, "Characterizing high-speed oscilloscopes," *IEEE Spectrum*, no. 9, pp. 38-39, Sept. 1990.

[7] J. Verspecht and K. Rush, "Individual characterization of broadband sampling oscilloscopes with a nose-to-nose calibration procedure," *IEEE Trans. Instrum. Meas.*, vol. 43, no. 2, pp. 347-354, Apr. 1994.

[8] J. Verspecht and P. Van Esch, "Accurately Characterizing Hard Nonlinear Behavior of Microwave Components with the Nonlinear Network Measurement System: Introducing `Nonlinear Scattering Functions'," in *Proc. 5th Int. Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits*, Duisburg, Germany, Oct. 1998, pp. 17-26.

[9] D. Schreurs, J. Verspecht, S. Vandenberghe, G. Carchon, K. van der Zanden, and B. Nauwelaers, "Easy and accurate empirical transistor model parameter estimation from vectorial large-signal measurements," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Anaheim, CA 1999, pp. 753-756.