ADVANCED CALIBRATION AND NORMALIZATION TECHNIQUES FOR TIME DOMAIN REFLECTION AND TRANSMISSION MEASUREMENTS

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Abstract

In this paper, we present a new advanced data-processing technique for the error correction of the time domain network analyzer. Our calibration and normalization software package TTRECS (Time domain Transmission and REflection Calibration Software) is not restricted to the calculation of the normalized time domain signals (TDR/T-pictures), but the corrected frequency domain S-parameters can also be found.

1. Introduction

Time domain reflection and transmission pictures give important insight in the properties of impedance controlled interconnection systems. The behavior of discontinuities are easily detected by simple waveform examination. Until now, time domain data are often obtained without precision calibration techniques, which limits their utility. Recently, some new calibration algorithms for TDR/T-analyzers were presented [1]-[3]. However, the calibration is nearly always restricted to oneport structures, and many simplifying assumptions are used (such as ideal calibration standards, no secondary reflections (airlines), no directivity or leakage terms in the error model, no adequate deconvolution algorithms, ...). The procedure for normalization of the time domain signals is seldomly discussed in literature.

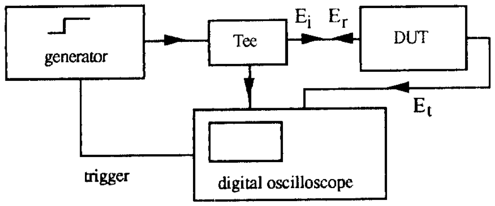

Figure 1 : Time domain network analyzer

In this paper, we present a new advanced calibration and normalization procedure for the time domain network analyzer. We use a simple measurement set-up which consists of one step or pulse generator and two samplers (figure 1). Our approach reduces the systematic errors of the time domain network analyzer significantly. The error correction is based on a frequency domain twoport error model. All measurements proceed in the time domain, while the error correction itself proceeds completely in the frequency domain. Our new calibration and normalization software package TTRECS calculates the normalized (time domain) TDR/T-pictures as well as the calibrated (frequency domain) S-parameters.

2. Calibration and normalization

2.1. Error correction

Calibration and normalization of the time domain network analyzer reduce the errors of the TDR/T-measurements significantly, and guarantee an enhanced measurement accuracy. We use a frequency domain error model to correct and to compensate the linear systematic errors caused by the generator, the oscilloscope, the cables and connectors. The accuracy of the measurements is limited by the noise level of the measurement equipment and by the accuracy to which the calibration standards are known. The calibration and the normalization procedure of the time domain network analyzer proceeds in three steps. First, the discretized measured time domain signals are transformed to the frequency domain. Secondly, the frequency domain data are corrected mathematically and the S-parameters of the DUT are calculated. Finally, the calibrated data are transformed back to the time domain, which results in normalized TDR/T-pictures.

2.2. Error model for TDR/T-measurements

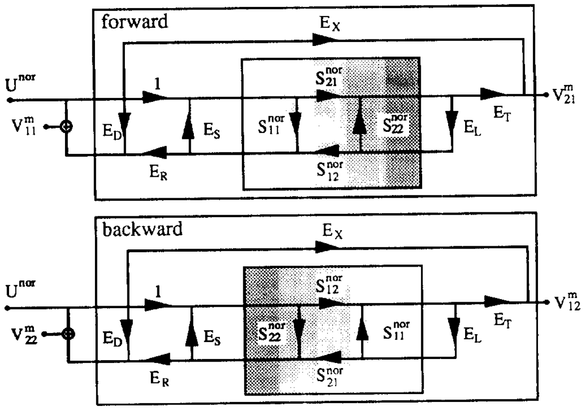

Figure 2 : Flow graph of forward and backward error model

The (voltage) flow chart used for TDR/T measurements is depicted in figure 2. The real TDR/T-system is modeled as an ideal TDR/T-system, which consists of a normalized voltage source and an ideal

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sampler, and an error network, which groups the linear systematic errors of the real measurement set-up (losses, mismatches, delays, ...). The normalized voltage source and sampler have an internal impedance of R Ω (quite often 50 Ω), and the voltage source generates a normalized step with amplitude $2U^{nor}$ and rise time t_r^{nor}. The twoport frequency domain error model consists of 6 error terms:

1. E_D the directivity,
2. E_R the reflection frequency response,
3. E_T the transmission frequency response,
4. E_S the source impedance match,
5. E_L the load impedance match and
6. E_X the isolation (leakage).

These parameters can be seen as the S-parameters of the error network (reference impedance = internal impedance of normalized step generator or pulser = R Ω). A similar error model is used for network analyzer measurements.

The *directivity factor* E_D describes systematic errors such as the crosstalk between the different channels, the trigger coupling, the reflections of cables and connectors. The *isolation factor* E_X describes the coupling between the source pulser and the transmission sampling head. The *transmission frequency response factor* E_T describes the transmission characteristics of the TDR/T-system if $E_D = 0$, $E_S = 0$, $E_L = 0$, and $E_X = 0$, while the *reflection frequency response factor* E_R describes the reflection characteristics of such an idealized TDR/T-meter. The *source impedance match factor* E_S represents the impedance mismatch of the reflection return port of the TDR/T measurement system. The *load impedance match factor* E_L describes the impedance mismatch of the transmission return port. The error factors E_L and E_S cause secondary reflections and disturb the TDR-pictures. In literature, long airlines and time domain windowing are often used to remove these secondary reflections.

Four time domain measurements are necessary to fully characterize an unknown twoport DUT, i.e. two reflection measurements and two transmission measurements. First, we perform the forward reflection and transmission measurements (figure 2.a), which results in V_{11}^m and V_{21}^m. Then, we rotate the physical DUT over 180°, and we perform the backward measurements (figure 2.b), resulting in V_{22}^m and V_{12}^m.

The six error factors E_D, E_R, E_T, E_S, E_L and E_X are completely defined in an unambiguous way by measuring a set of well-defined broadband SOLT- (Short-Open-Load-Thru) calibration standards, i.e. by four reflection measurements (SOLT) and two transmission measurements (LT). The quality of the definition of the reference standards determines the quality of the calibration. We will not go into the mathematical details at this point.

Once the (forward) twoport error model is fully characterized we can calculate the normalized TDR/T-pictures V_{ij}^{nor} (i, j = 1, 2). The relations between the measured and the normalized voltages are given by:

$$V_{11}^{nor} = \left[\left[1 + \left(\frac{V_{22}^m - E_D'}{E_R'}\right)E_S\right]\left(\frac{V_{11}^m - E_D'}{E_R'}\right)\right]\frac{U^{nor}}{\Delta'} - \left[\left(\frac{V_{21}^m - E_X'}{E_T'}\right)\left(\frac{V_{12}^m - E_X'}{E_T'}\right)E_L\right]\frac{U^{nor}}{\Delta'} + U^{nor} \qquad (1)$$

$$V_{21}^{nor} = \left[1 + \left(\frac{V_{22}^m - E_D'}{E_R'}\right)(E_S - E_L)\right]\left(\frac{V_{21}^m - E_X'}{E_T'}\right)\frac{U^{nor}}{\Delta'} \qquad (2)$$

where:

$$\Delta' = \left[1 + \left(\frac{V_{11}^m - E_D'}{E_R'}\right)E_S\right]\left[1 + \left(\frac{V_{22}^m - E_D'}{E_R'}\right)E_S\right] - \left[\left(\frac{V_{21}^m - E_X'}{E_T'}\right)\left(\frac{V_{12}^m - E_X'}{E_T'}\right)E_L^2\right] \qquad (3)$$

$$E_D' = (1 + E_D)\,U^{nor} \qquad (4)$$

$$E_R' = E_R\ U^{nor} \qquad (5)$$

$$E_X' = E_X\ U^{nor} \qquad (6)$$

$$E_T' = E_T\ U^{nor} \qquad (7)$$

The corrected reflection coefficients S_{ij}^{nor} (reference impedance = internal impedance of normalized voltage source) can be written as:

$$S_{11}^{nor} = \left[\left[1 + \left(\frac{V_{22}^m - E_D'}{E_R'}\right)E_S\right]\left(\frac{V_{11}^m - E_D'}{E_R'\ \Delta'}\right)\right] - \left[\left(\frac{V_{21}^m - E_X'}{E_T'}\right)\left(\frac{V_{12}^m - E_X'}{E_T'}\right)\frac{E_L}{\Delta'}\right] \qquad (8)$$

$$S_{21}^{nor} = \left[1 + \left(\frac{V_{22}^m - E_D'}{E_R'}\right)(E_S - E_L)\right]\left(\frac{V_{21}^m - E_X'}{E_T'\ \Delta'}\right) \qquad (9)$$

3. Example: Nonuniform microstrip line

We examine the time domain reflection and transmission behavior of a multiple step-in-width microstrip structure. The cross section and the top view of the nonuniform microstrip are depicted in figure 3.

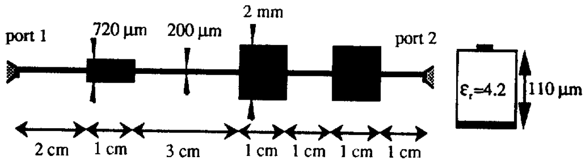

Figure 3 : Top view and cross-section of nonuniform microstrip

Both sides of the DUT are connected with the time domain network analyzer via a PCB probing system with coplanar high-frequency probes (Cascade Microtech PPH-100-150 package probe) [4]. These probes ensure a good broadband transition from the coaxial cable to the planar structure up to 12 GHz. Furthermore, we use a HP 54121T time domain reflectometer (bandwidth = 18.5 GHz, rise time ≈ 38 ps), and high-quality coaxial cables. The 50 Ω impedance, a short circuit, an open circuit and a thru on the Cascade Microtech "Impedance Standard Substrate" (ISS) are used to calibrate the measurement set-up. The calibration standards on this alumina substrate are well known and clearly described [5]. Based on these reference measurement, a digital filter is created. The "raw" and the normalized (rise time of 80 ps) TDR/T-pictures of the DUT are shown in figures 4 and 5 respectively.

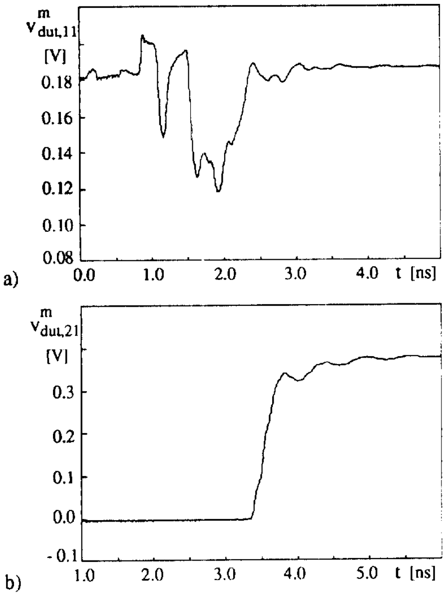

Figure 4 : Measured TDR/T-pictures of the DUT ($t_r \approx 38$ ps): a) $v_{11}^{m}(t)$, b) $v_{21}^{m}(t)$

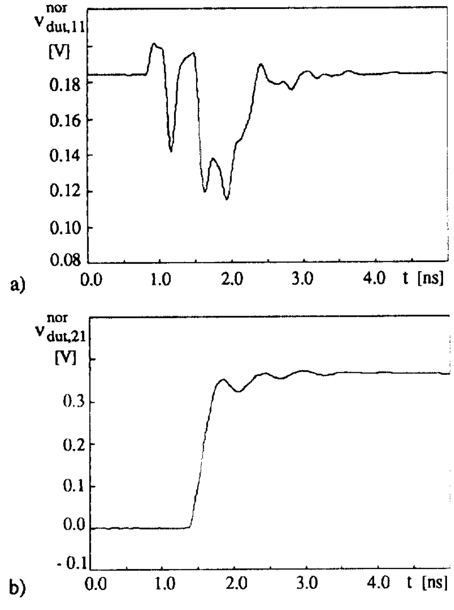

Figure 5 : Normalized TDR/T-pictures of the DUT ($t_r = 80$ ps): a) $v_{11}^{nor}(t)$, b) $v_{21}^{nor}(t)$

The software package TTRECS also calculates the scattering parameters of the DUT. The reflection coefficients $S_{11}(f)$ and $S_{21}(f)$ (reference impedance = 50 Ω) are depicted in figures 6. They correspond very well with the network analyzer measurements (HP 8510) which are shown in figure 7. The dynamic range of the time domain network analyzer is about 40 dB.

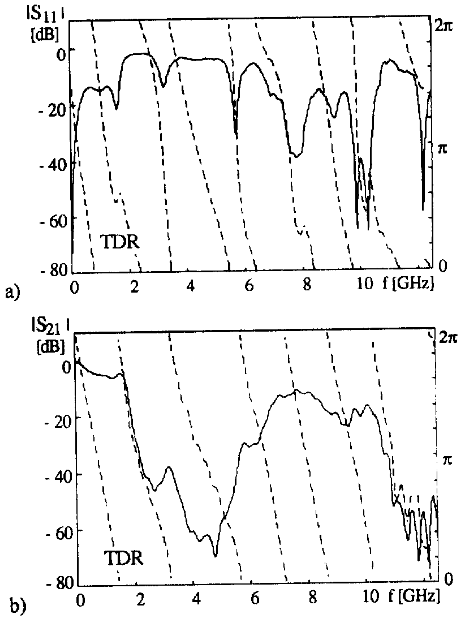

Figure 6 : $S_{11}(f)$ and $S_{21}(f)$ measured with a TDR-meter (HP 54121T) and calculated by TTRECS

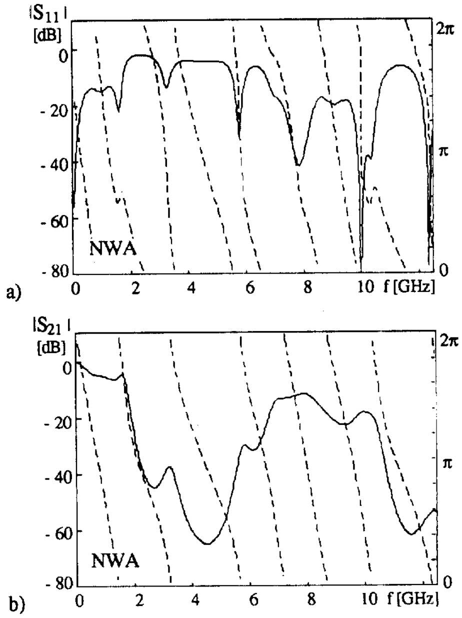

Figure 7 : $S_{11}(f)$ and $S_{21}(f)$ measured with a network analyzer (HP 8510)

4. Conclusions

We conclude that the new developed calibration and normalization software package TTRECS (Time domain Transmission and REflection Calibration Software) calculates the normalized TDR/T-pictures, and the corresponding frequency domain S-parameters in a precise way.

Acknowledgments

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