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MEASUREMENT UNCERTAINTY IN VECTOR NETWORK ANALYZER

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Abstract: Precision design work and tight manufacturing tolerances demand highly accurate measurements. A Vector Network Analyzer (VNA) is one of the most important aids for linear RF analog designs. It can give accurate information about the passive network performance in both the frequency domain and the time domain. Designers heavily rely on these measurement results to locate the design problems and to evaluate the network performance. But the measurement errors always exist. In any high frequency measurement, there are measurement errors associated with the system that contribute uncertainty to the results. Therefore, measurement accuracy of a VNA is an important concern to the instrument designers and suppliers. This paper gives the overview of the uncertainty and errors associated with VNA measurement. Based on the low cost Vector Network Analyzer developed by INTEC, University of Gent, Belgium, the estimations of the uncertainty and errors in the reflection and transmission measurements are discussed. The measurement results are present to illustrate the improvement of the measurement accuracy after taking into account these measurement issues in the design procedure.
Keywords: Vector Network Analyzer, Measurement.

1 INTRODUCTION

Precision design work and tight manufacturing tolerances demand highly accurate measurements. A Vector Network Analyzer (VNA) is one of the most important aids for linear RF analog designs. It can give accurate information about the passive network performance in both the frequency domain and the time domain, such as insertion loss, return loss, phase response, group delay, impulse response and so on. Designers heavily rely on these measurement results to locate the design problems and to evaluate the network performance. But the measurement errors always exist. In any high frequency measurement , there are measurement errors associated with the system that contribute uncertainty to the results. Therefore, measurement accuracy of a Vector Network Analyzer is an important concern to the instrument designers and suppliers. As well as the VNA measurements themselves, most errors in VNA measurements are complex quantities that vary as a function of frequency. By characterizing and virtually removing the systematic errors, measurement accuracy can be improved by several orders of magnitude. The estimation of the uncertainty and errors in the measurements is fundamental to optimize the design of the VNA . It can be of the help to locate the problem in the design procedure as the measurements are not acceptable. In order to get more accurate measurement in VNA , the study of uncertainty and errors in the measurement is extremely necessary.

2 THE UNCERTAINTY AND ERRORS ASSOCIATED WITH VNA MEASUREMENT

Commercial network analyzers are instruments that measure transfer and/or impedance functions of linear networks through sine-wave testing. Such system accomplishes these measurements by configuring its various components around the device-under-test (DUT). The first part of a VNA instrument is the VNA transmitter, a broadly tunable sine-wave signal source to stimulate the DUT. Since transfer and impedance functions are ratios of various voltages and currents, a means of separating the appropriate signals from the measurement ports of the DUT is required. Finally, the network analyzer receiver must detect the separated signals, form the desired signal ratios, and display the results in the format requested by the user.

Generally, there are two basic types of test sets that are used with network analyzers. They are illustrated in Figure 1.

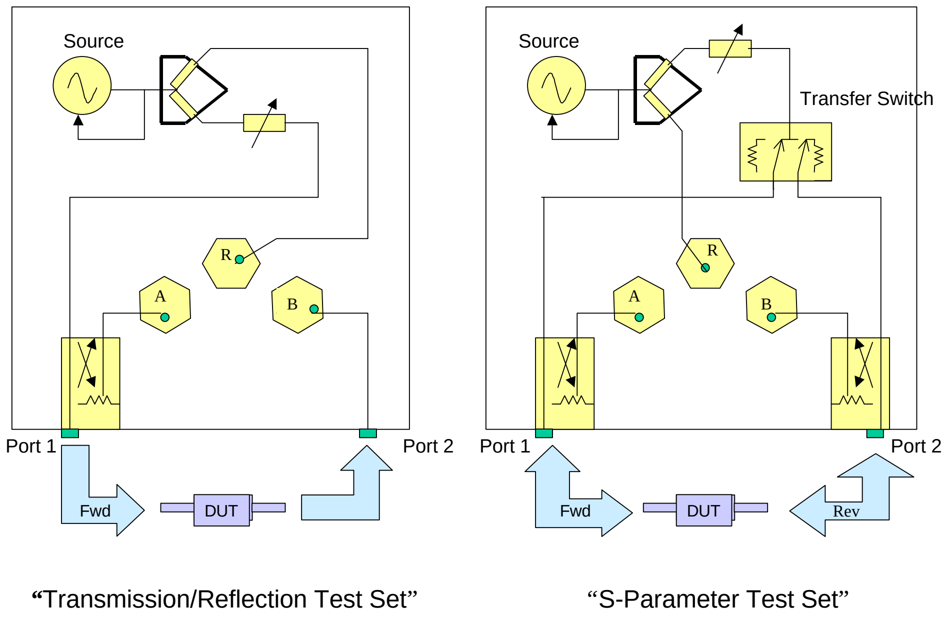

Figure 1. The two basic types of test sets that are used with network analyzer

A real life VNA measurement is the vector sum of the DUT response plus all error terms. The precise effect of each error term depends upon its magnitude and phase relationship to the actual test device response. Network analysis measurement errors can be separated into systematic, random, and drift errors. In a well conceived high frequency measurement, the systematic errors are the most significant source of measurement uncertainty. Since each of the systematic errors can be characterized, and the DUT is operated in its linear range, their effects can be effectively removed to obtain a corrected value for the DUT response. These errors are qualified as directivity, source match, load match, cross-talk, and frequency tracking errors. Directivity and cross-talk errors are related to signal leakage, while source and load match errors are related to signal reflections. The final class of errors is related to imperfect frequency response of the receivers. Meanwhile random and drift errors can not be precisely quantified, so they must be treated as producing a cumulative uncertainty in the measurement results.

In general, calibration can be applied to remove the system errors before measurement. For the Transmitter/Receiver-based analyzers (T/R test set), however, it offers only one-path, two-port calibration. Some errors still exist after this procedure. The following section will discuss the uncertainty and errors in the measurement based on a low cost VNA, and propose the approaches to locate such measurement errors and remove them.

3 DISCUSSION OF THE UNCERTAINTY AND ERROS IN A LOW LCOST VNA MEASUREMENT

A low cost VNA(VNA99) has been developed by INTEC-design team, University of Gent, Belgium. It comprises a T/R test set with one directional coupler, two measurement channels and one reference channel for measuring the magnitude and phase responses of the forward S-parameters S11 and S21 of a linear two port. The analyzer 's built-in synthesized source produces a swept RF signal in the range of 50kHz to 200MHz with a resolution of 100Hz. It can deliver the output power from –25dBm to +6dBm with a flatness of less than 1dB. The system block diagram is showed in Figure 2.

The uncertainty and errors in VNA99 measurements are mainly focus on the estimation of the uncertainty and errors in the reflection measurement and transmission measurement. They are discussed in the following sections

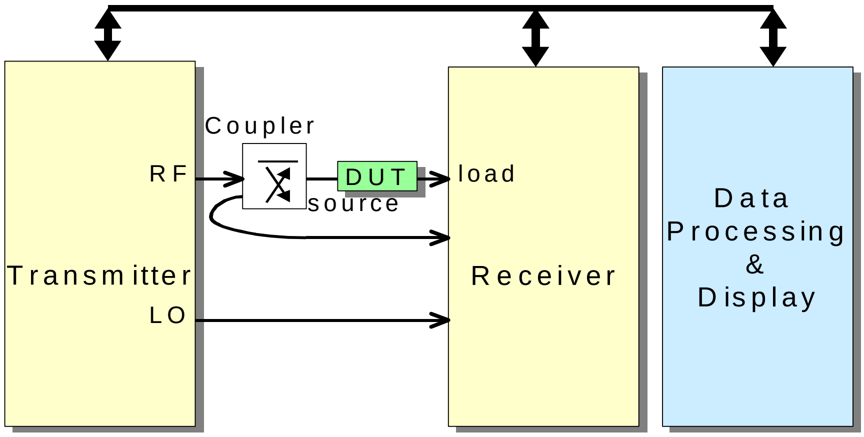

Figure 2. The system diagram of VNA99

3.1 Estimation of the uncertainty and errors in the reflection measurement

The reflected signal is directed by a directional coupler, which has a bridge-like configuration in VNA99. An ideal directional coupler has low loss and high reverse isolation. The bridge-like directional couplers can be made to work over a very wide range of frequency, but they do exhibit substantial loss to the transmitted signal. So the uncertainty and errors in the reflection measurement are mainly resulted from the low directivity of the directional coupler. The further estimation of the uncertainty and errors in the reflection measurement related to the directivity is done in the following. These kinds of uncertainty and errors in the reflection measurement are :

3.1.1 Caused by coupled arm power loss

Directional couplers separate signals based on the direction of signal propagation. If a directional coupler is used to sample power in the measurement configuration, the coupled arm power loss should be taken into account, and compensation may be required for the directional coupler response.

3.1.2 Caused by the inductive or capacitive behavior of the passive bridge component at high frequency

It should be noted that control of the behavior of the passive bridge components at higher frequencies is essential to make the directional bridge coupler truly balanced. Due to the fact that 50-ohm is used here as the bridge - arm components, parasitic components from the board material as well as the 50-ohm resistor HF behavior have impact on the coupler performance, as the frequency for the network analyzer is sweeping from 50KHz to 200MHz. The passive component behavior is practically more critical here in the bridge than in other places of the VNA99. At least 3dB ~ 5dB improvement of directivity could be obtained in VNA99 by using HF resistors.

3.1.3 Caused by the variation of the injected RF signal

RF injected signal variation will cause variation of the directivity, and consequently cause directivity error. Moreover, a small change of the reference signal, which is split by the injected RF signal, can result in a considerable change of the reflection signal, adding to the overall measurement uncertainty. It is a kind of frequency tracking errors.

3.1.4 Caused by the source mismatch

This error signal is caused by some of the reflected signal from the DUT. The error contributed by source match is dependent on the relationship between the actual input impedance of the DUT and the equivalent match of the source. It is a factor in the reflection measurements.

3.2 Estimation of the uncertainty and errors in the transmission measurement

The uncertainty and errors associated with the transmission measurement can be estimated as the errors:

3.2.1 Caused by low dynamic range

System dynamic range in the transmission channel is limited by the noise level relative to a " through ". It is calculated as the difference in dB between the maximum receiver input level and the receiver noise floor.

The dynamic range is affected by several factors, such as the test port input power, the test port noise floor and the receiver crosstalk. Random noise is the part of noise which contribute to the noise floor. An efficient way to remove the effect of random noise is to apply weighted successive measurement traces, called "averaging". But its consequence is that the speed of measurement will decrease when more averaging is applied, as more measurement samples are needed for each frequency point to be measured. Another way to reduce the noise floor is to reduce system bandwidth, i.e., the bandwidth of the heterodyne receiver intermediate frequency (IF). In the VNA99, the RX IF bandwidth is fixed to 3 kHz, as a compromise between measurement speed and RX dynamic range, and cannot be changed by the user.

Therefore, in order to get high dynamic range of RX, firstly be sure that no loss comes from the impedance mismatch with the input impedance of the mixer over the whole range of the frequency. Secondly 0.1dB compression point is used to define as the maximum power level available at the output of the mixer. Thirdly the following analog drive circuit of ADC could make the output signal of the mixer swing the full ADC input scale , in order to get the maximum dynamic performance of ADC.

3.2.2 Caused by the load mismatch

It is caused by impedance mismatch between the DUT output and the Port-Two of the measurement system. Due to the fact that the input impedance of the mixer is frequency dependent, broad-band matching network should be designed to reduce the loss from the load mismatch at high frequency.

3.2.3 Caused by the source mismatch

In a transmission measurement, the source match error signal is caused by reflection from the DUT that is re-reflected from the source. It is a factor in the transmission measurements.

3.2.4 Caused by the variation of the injected RF signal

This variation not only results in the directivity error, but also penalize the design of the broadband RX dynamic range, which is reduced by an amount roughly equal to the peak RF signal variation. This is also a kind of frequency tracking errors. Moreover, a small change of the reference signal can also result in a considerable change of the transmission signal like it does in the reflection channel, consequently also adding to the overall measurement uncertainty. This is a kind of frequency tracking errors.

3.2.5 Caused by RX crosstalk

The reference signals are obtained by the injected signal. If they are not attenuated to approach a proper level, the leakage of these strong signals will influence the other channels. In a commercial VNA with a full S parameter test-set, the final RX crosstalk could be reduced by isolation measurement calibration. This can remove a type of leakage term through the DUT from one channel to another. But the VNA99 has only a T/R test-set, so the isolation measurement calibration is not available. Therefore, it is important to reduce the crosstalk by optimizing the hardware. So in the design , the reference signal is firstly attenuated , and then distributed to the two channels, i.e., the transmission channel and the reflection channel. Adjusting this attenuator until the power levels of the IF signals in the 3 channels are in the same power level range, can reduce the inter-channel crosstalk significantly. This measurement should be done in the case that a standard "through" is used.

Actually the estimation of the uncertainty and errors in the transmission measurement of the VNA99 could be the combination of the estimations above. None of them are totally independent on the others. It will certainly increase the difficulty to estimate the exact error sources.

It is noted that most of the errors and uncertainty of the measurement could be removed by the calibration procedure. Due to the fact that the VNA99 performs one path , two-port calibration, the uncertainty and errors could not be removed completely by the calibration procedure. In order to reduce the uncertainty and errors in both of the reflection and transmission measurements as much as possible , the measurement issues discussed above should be taken into account in the design procedure. The discussion of the estimations of the uncertainty and errors in both of the transmission and reflection channels above are giving the basic ideas of how to do the estimation and how to practically reduce these uncertainty and errors in the measurement . In the design procedure, some of the other factors should be taken into account, such as the parasitic components associated with PCB board, the high frequency transmission path and so on. Since they do impact on the system performance, therefore adding the uncertainty and errors to the measurement.

4 MEASUREMENT RESULTS BASED ON TAKING INTO ACCOUNT THE MEASUREMENT ISSUES

Based on the estimation of the uncertainty and errors in the VNA99 measurement, careful designs to reduce the measurement uncertainty and errors have been done. Figure 3 and 4 show the transmission measurement result of MCL-PBP-21.4 band-pass filter from Mini-Circuits® and the reflection measurement result of a T-linear network respectively. The final measurement errors of S21(dB) and S11 (volt) are calculated as 0.58dB and 0.001volt respectively.

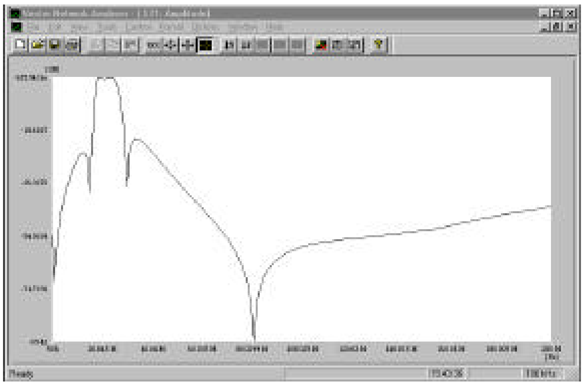

Figure 3. Transmission characteristics of MCL-PBP-21.4 band-pass filter measured by VNA99

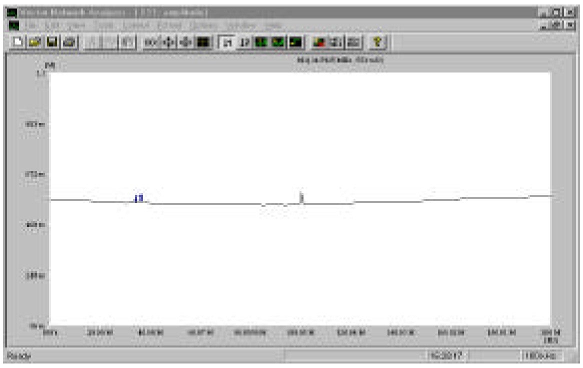

Figure 4. Reflection characteristics of the T-linear network measured by VNA99

5 CONCLUSION

The uncertainty and errors associated with VNA measurements are discussed. The estimations of the uncertainty and errors in both of the reflection and transmission measurements of VNA99 are present, along with the approaches of how to reduce the uncertainty and errors in the series of measurements. With the aid of these estimations, careful designs of the instrument have been done. The measurement errors of S21(dB) and S11 (volt) have been reduced to 0.58dB and 0.001volt respectively.

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