Transparent Full-Two Port Network Analyser for Microwave Lab Courses

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***Abstract*—In this paper a measurement device is presented which has been developed only for lab courses in RF technology. In a student's thesis work a transparent network analyzer was developed, which has been assembled with different Rohde & Schwarz vector voltmeters devices of older age. The objective is to measure the scattering parameters of a device under test vividly for students. The RF circuitry controlling the port excitation is placed in a box which is accessible by students for educational purposes. The whole measurement is controlled and analyzed by MATLAB.**

***Index Terms*—RF measurement, VNA, scattering parameters**

I. Introduction

The initial point of the thesis work is to find a way to teach students the operating principles of network analyzers and the relevance of scattering parameters in RF technology. One typical lab unit is the measurement of a black box with different passive components (e.g. a T-filter or an attenuator in π-structure) which yield a set of frequency dependent scattering parameters. These scattering parameters show the ratio between the reflected or transmitted voltage wave and the incident voltage wave on each measurement port. Scattering parameters describe the adaption of a component to the wider circuit. These scattering (S-) parameters must be transformed into impedance (Z-) or admittance (Y-) parameters in order to find out what is inside the box or to model a component like a resistor or a capacitance with its parasitics [1]. Nowadays network analyser are doing this job automatically, thus the learning effect for students is zero. Furthermore network analyser from Keysight, Rohde & Schwarz, or Anritsu offer many functionalities accessible over many buttons [2], [3], [4] and the handling is too complicated to learn during only 5-6 lab sessions. Therefore a network analyzer was developed out of several different devices to show up the required parts of a custom network analyzer and the way it measures a device under test (DUT). Each network analyzer needs to be calibrated before measurement and here it is possible to take calibration standards from the shelf [5]. These calibration standards are often enclosed in a housing for protection reasons and implementations of ”open”, ”short” and ”match” are not visible. Thus unique calibration standards were fabricated on printed circuit boards (PCBs) for explanation and a calibration routine was programmed in MATLAB in order to calibrate the measurement unit and the vector voltmeters.

II. Standard network analyzers

Network analyzers are one of the most important measuring units in the field of radio frequency technology. Their ability to reckon scattering parameters makes them essential since those parameters are relevant for all components used over a high frequency range. Of course these measurement devices are cost-intensive also when they are purchased as an used or refurbished device. In addition some student have the talent to destroy anything only with one single button push and thus the owner of a network analyzer which is used for research and development is not really willing to offer his equipment for students.

Network analyzers of actual state-of-the-art are fully automatic measurement units, surely it requires some appreciation to operate these correctly. A comprehension about the internal measurement setup and procedure is not necessary. This makes it tough to understand what is actually done during a measurement, hence network analyzers are often considered by students as a black box.

III. Custom-made network analyzer with open architecture

The objective of our assembled network analyzer is to show the internal measuring setup. Because of its open architecture it is more easy to comprehend the internal measurement procedure as it is for a standard network analyzer. Each part of the overall unit has a separate simple function and is known by the students from former practical exercises. Thus the individual device tasks are quickly understood by students. For example a student is able to discover that the signal generator is producing the harmonic voltage wave and that the vector voltmeters are measuring the voltages of the incident and the reflected waves. In order to measure typical two-port scattering parameters like reflection and transmission additional ”external” hardware is needed. The following fig. 1 shows the complete measurement setup with the closed white wiring box with RF-terminators, RF waveguides and a transfer relais inside. In the background the complete stack with 19-inch devices is visible. It concludes two R&S ZPV vector voltmeters, a R&S signal source and a HP Switch Control unit 3488A. The measuring ports are on the backside of the box and are realized with standard SMA connectors.

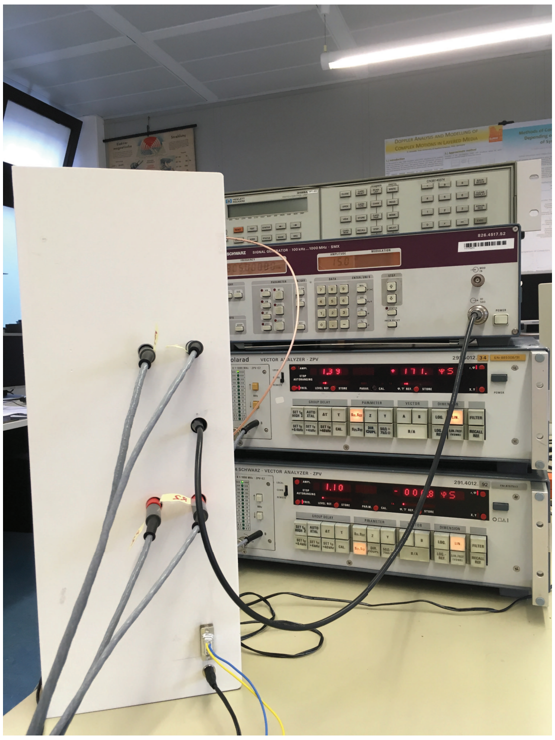

Fig. 1. Overview measuring unit

The core of the setup consists of two R&S ZPV vector voltmeters. These voltmeters can be equipped with different measurement slots measuring up to 50 MHz, 1000 MHz and 2000 MHz. Because in the Bachelor RF lecture only technologies up to 1 GHz are teached, two slots measuring up to 1000 MHz are used. The vector voltmeters are ”only” able to measure two voltages and the phase relation between these voltages. Fig. 2 shows the schematic of the measurement setup including the vector voltmeters.

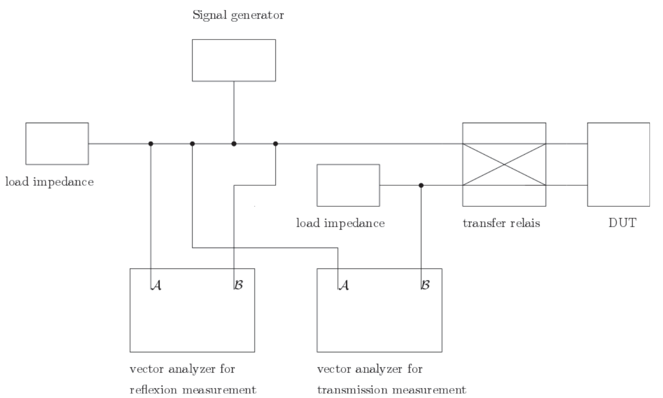

Fig. 2. measuring schematic

This is not the classical way as vector network analyzers are measuring scattering parameters. The voltages are measured with high impedance, not with 50 Ω termination. A wave travelling through a 50 Ω transmission line towards the measuring port will be absorbed. Thus, the voltage measurement is equivalent the measurement of a wave quantity. Since no expensive wave couplers are used, the reflected wave (measured in channel B superposed with the incident wave) is also superposed in the reference channel A. To solve this problem a three-port model including both measuring channels and the signal source is developed and considered for calibration. The vector voltmeters are **not** able to measure all 4 S-parameters within one run, thus a transfer relais was added. The transfer relais is able to swap the DUTs input and output port avoiding a manual turning of the DUT while the measurement is running. The relais switches the ports by an electrical control signal.

Opening the box makes the wiring between all used devices visible, thereby the locations where the voltages are measured and both 50 Ω impendances, which terminate the measurement channels, can be identified. Figure 3 show the wiring and the RF-components within the box.

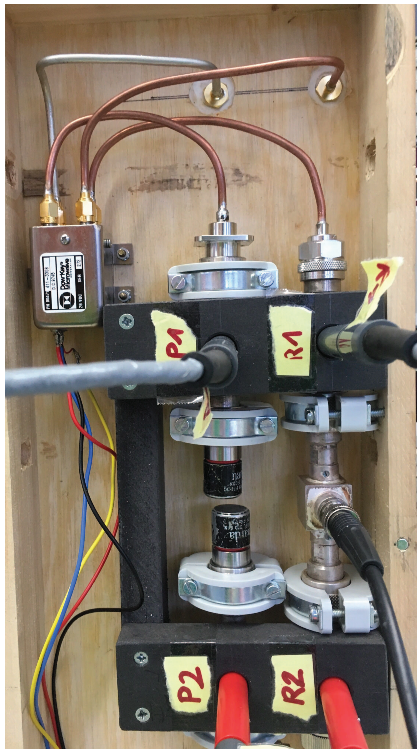

Fig. 3. Internal wiring

By using old instruments which were present anyway and seemed to had served their time, the measurement concept of an vector analyzer can be explained in detail. The cost for the network analyzer was reduced to virtually zero, besides the working hours of the student.

IV. Data Acquisition and Calibration

All devices are connected via an USB GPIB interface to a PC. MATLAB communicates with all devices using the MATLAB Instrument Control Toolbox. The measurement routine is running a frequency sweep automatically. The frequency range is chosen by the user in a graphical unser interface.

If one vector voltmeter detects an error during the measurement, the programm recognizes it by checking the SRQ line in the GPIB data communication and repeats the measurement at the same frequency. The error reason is shown to the user in order to understand the measurement failure (e.g. that the transmitted wave is just to low to get an evaluable result), also an advice is given how to solve the occured problem. The acquired data is used for calculating the S-Parameters of the DUT.
Although the used vector voltmeters provide scattering parameter as direct (false) output only the voltage magnitude in channel A (reference) and channel B and the phase relation between both channels are measured and transferred to MATLAB. Making the wrong assumption that the wave reflected by the DUT is absorbed and **not** superposing the wave in the reference channel A the calculation of the S-Parameters (which is also used by the vector voltmeters) is quite simple:

$$S11, S22 = \frac{U_{B,1} - U_{A,1}}{U_{A,1}} \tag{1}$$

$$S12, S21 = \frac{U_{B,2}}{U_{A,2}} \tag{2}$$

with $U_{B,n}$ and $U_{A,n}$ being the voltages in channel B and A of the vector voltmeter n. Obviously all numbers are complex and have a frequency dependent phase relation to each other. As only a T-junction instead of couplers is used and as the reflected wave is not absorbed but superposing the voltages in the reference channel A of both voltmeters, the calculation result of the formulas above will be wrong. Thus a new formula must be derived.
The voltages at all measurement locations can be derived from all S-Parameters by graph theory. Fig. 4 shows the schematic including the S-Parameters of the three-port T-junction and the terminations and the incident and reflected wave at all ports. It is obvious that the wave b_3 in the reference channel B is

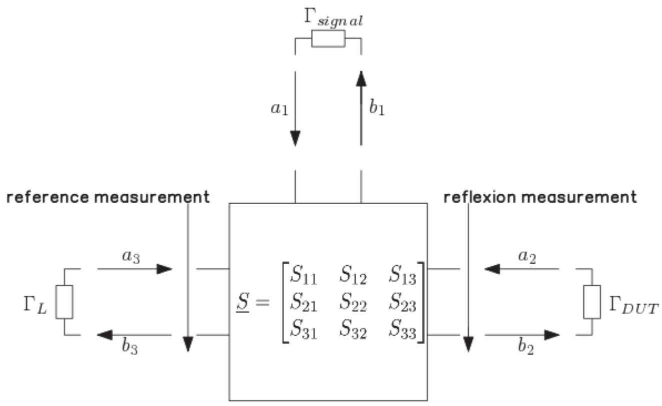

Fig. 4. 3-port including signal source, load impedance and DUT

composed of $S_{3,1} \cdot a_1$ which is also the incident wave at the DUT (when the T-junction is symmetric and $S_{21} = S_{31}$) and of $S_{3,2} \cdot a_2$ which is the reflected power from the DUT transferred to port 3. (The incident power a_3 at port 3 is assumed zero as the termination of this port is considered as ideal which, in addition, holds not true.)
One strategy can be to determine all S-Parameters of all components before bringing the measurement setup in operation. The drawback will be that the RF-characteristics of all components mounted in the circuitry differs slightly which increases the measurement uncertainity. In addition aging of the RF components makes the results even worse.
A better solution would be a calibration as it is known from classical network analyzers [5]. In general a VNA measurement is assumed to be influenced by an error two-port network as it is depicted in fig. 5.

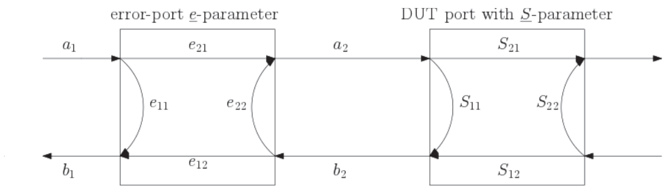

Fig. 5. VNA measurement including an error two-port network and a DUT circuitry

In this error model only four parameters needs to be found. As one of these parameter (e_{21} or e_{12}) can be chosen freely, only three measurements are needed to solve for the three dependent parameters of a one-port measurement. This is possible by measuring three known reflection standards (open, short, load). In order to calibrate a two-port VNA measurement a 7-term error model must be used. Thus, the one-port reflection standards are used twice at both measuring ports and the seventh missing equation (setting the second error model on the right side into relation to the first one on the left side) is realized by a thru-connection between measuring port 1 and 2.
Regarding fig. 4 it is obvious that much more parameters are unknown. These parameters could not be determined independently but algebraic combinations of the parameters for calibrating the measurement can be found. The reflected wave at port is determined by graph theory and yield an inflated formula

$$b_3 = a_1 \cdot \frac{\overbrace{S_{31}}^{\mathcal{A}} + \Gamma_{DUT} \cdot \overbrace{(S_{32} \cdot S_{21} - S_{22} \cdot S_{31})}^{\mathcal{B}}}{\underbrace{1 - S_{33} \cdot \Gamma_L}_{\mathcal{C}} + \underbrace{((S_{22} \cdot S_{33} - S_{23} \cdot S_{32}) \cdot \Gamma_L - S_{22})}_{\mathcal{D}} \cdot \Gamma_{DUT}} \tag{3}$$

The calculation shows that only constant parts and a linear dependencies of Γ_{DUT} are present in the nominator and denominator. Thus the formula can be represented as Möbius transformation. The voltage at the reference plane of the coltage measurement can be determined as follows

$$U_3 = a_1 \cdot (\Gamma_L + 1) \cdot \sqrt{Z_0} \cdot \frac{\mathcal{A} + \mathcal{B} \cdot \Gamma_{DUT}}{\mathcal{C} + \mathcal{D} \cdot \Gamma_{DUT}} \tag{4}$$

$$= a_1 \cdot \frac{A_3 + B_3 \cdot \Gamma_{DUT}}{C_3 + D_3 \cdot \Gamma_{DUT}} \tag{5}$$

where the reflection of the termination Γ_L is combined to new Möbius coefficients with $A_3 = (\Gamma_L + 1) \cdot \sqrt{Z_0} \cdot \mathcal{A}$.

In a second derivation it can be found that the voltage at port 2 of the three-port has the sam eform and can be given with

$$U_2 = a_1 \cdot \frac{A_2 + B_2 \cdot \Gamma_{DUT}}{C_2 + D_2 \cdot \Gamma_{DUT}} \tag{6}$$

Assuming that the source wave $a_1 = 1$ the coefficients can be solved from the three measurement of the match, the short and the open standard. The students can derive the equations by thereself after some algebraic derivations.

$$C_i = 1 \tag{7a}$$

$$D_i = \frac{\frac{U_{i,Match} - U_{i,Open}}{U_{i,Match} - U_{i,Short}} - \frac{\Gamma_{Match} - \Gamma_{Open}}{\Gamma_{Match} - \Gamma_{Short}}}{\Gamma_{Open} \cdot \frac{U_{i,Match} - U_{i,Open}}{U_{i,Match} - U_{i,Short}} - \Gamma_{Short} \cdot \frac{\Gamma_{Match} - \Gamma_{Open}}{\Gamma_{Match} - \Gamma_{Short}}} \tag{7b}$$

$$A_i = U_{i,Match} - \frac{U_{i,Match} - U_{i,Open}}{\Gamma_{Match} - \Gamma_{Open}} \cdot ...$$
$$(1 + D_i \cdot \Gamma_{Open}) \cdot \Gamma_{Match} \tag{7c}$$

$$B_i = \frac{(U_{i,Match} - A_i) \cdot (1 + D \cdot \Gamma_{Match})}{\Gamma_{Match}} - A_i \cdot D_i \tag{7d}$$

Now, the unknown reflection of the DUT can be derived by combination of U_2 and U_3. One of these formulas is solved to the wave quantity a_1 and put into the other equation which yields the following quadratic equation which must be solved analytically

$$\Gamma_{DUT}^2 + \frac{\frac{U_{A,1}}{U_{B,1}} \cdot (B_2 + D_3 \cdot A_2) - B_3 + D_2 \cdot A_3}{\frac{U_{A,1}}{U_{B,1}} \cdot B_2 \cdot D_3 - B_3 \cdot D_2} \cdot \Gamma_{DUT} + ...$$
$$\frac{\frac{U_{A,1}}{U_{B,1}} \cdot A_2 - A_3}{\frac{U_{A,1}}{U_{B,1}} \cdot B_2 \cdot D_3 - B_3 \cdot D_2} = 0 \tag{8}$$

The same procedure is repeated for the transmission calculation. The students have the possibility to derive the formulas and to program them into the MATLAB-file of the graphical unser interface. Thus the students train their ability to use a matrix oriented tool like MATLAB for computer-aided engineering.

Surely any student knows that a calibration is made to reduce measurement errors, but it is hard to tell what is necessary to perform a complete calibration and what errors are effectively removed. So first of all the students are taught which components of the measuring unit can cause a variance. Wires and connections affect the measurment results, such as cable delay or capacitive behavior of test probes. With the three-port calibration presented above, all this errors are eliminated which has the same effect than a classical three-term error model calibration of a conventional network analyzer.

V. Calibration standards

The calibration of the previous chapter can be executed with all kind of calibration standards as it is shown in the upper part of fig. 6. In order to show students how standards could look like different standards were processed on small daughter PCBs which could be connected to a mother board with cable connectors for the network analyzer. The standards are designed in coplanar transmission line technology and clearly visible for students as it is shown in fig. 6, too.

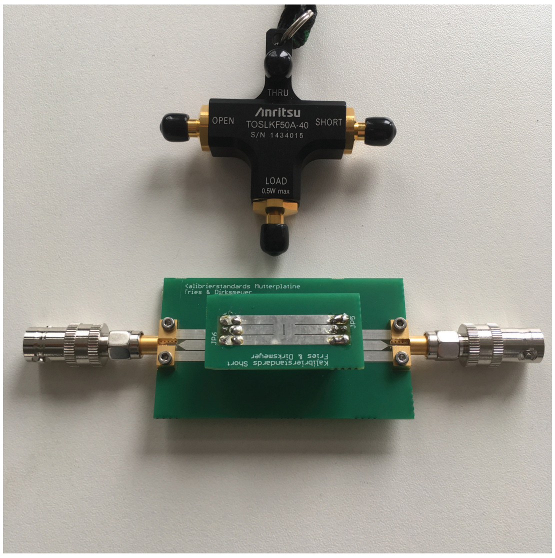

Fig. 6. Custom calibration standard and the selfmade below

VI. Conclusion

In order to teach students topics like scattering parameters, the function of a network analyzer, the calibration process and a general understanding in radio frequency measuring a student lab course was created in a practical way.

After a detailed description of the custom-made network analyzer students are sensitized for predictable error sources. Also the scattering parameters are introduced. Besides a general definition, formulas to calculate the parameters by using raw data (voltage in channels A and B and phase relation) are given to the students or could be developed by their own. With the understanding of the network analyzers wiring and functions, students can discover where the voltages for transmission and reflexion measurement are trapped, making the origin of scattering parameters descriptively derivated.

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