Seven State PTP for Vector Network Analyzer

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Abstract. *A new, seven-state switched perturbation two-port (PTP) for vector reflection measurement based on scalar measurement only was designed and realized in microstrip structure using PIN diodes. The structure was experimentally tested by means of vector measurements of different impedances in frequency band with relative bandwidth of 2.5 octaves. Good agreement with data obtained using a precise vector network analyzer was achieved. The new calibration method for the PTP was designed and tested on real measured data.*

Keywords

Vector measurement, microwaves, calibration, reflectometer.

1. Introduction

Vector network analyzers (VNA) based on scalar measurement only are commonly known as six-port VNAs, [1] or multi-state reflectometers [4]. A different concept of VNA using a PTP was designed and experimentally verified [2]. The idea consists of a multi-state perturbation two-port inserted between a standard scalar analyzer and the device under test (DUT) Fig. 1.

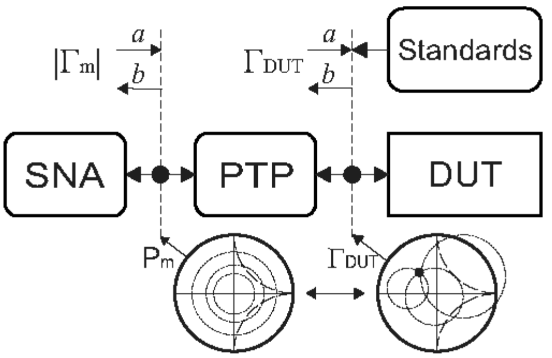


Fig. 1. Block structure of a measurement system with PTP.

The reflection from an unknown DUT is measured by a SNA through a PTP. Magnitudes of such a reflection can be described as circles in the measurement plane. As far as the PTP is known, these circles may be transformed back to DUT plane, intersecting in one point – DUT reflection. All DUT properties should be determined during calibration, using proper standards connected instead of a DUT.

The states of the PTP are controlled by a computer. Several scalar readings obtained at different PTP states allow for obtaining DUT vector characterization. The first PTP [2] was realized from on-the-shelf components and its properties were far from optimum.

A PTP with seven states was suggested in [3], along with selection criteria. Seven states provide for overdetermined measurement. Reflection readings suffer from errors resulting in the fact that the circles after transformation to the DUT plane never intersect in one point only. The idea makes possible to choose the best 3 states of the PTP with respect to the location of the measured reflection coefficient in the Smith chart and frequency. Such a selection makes low measurement uncertainty attainable. Modeling in Maple® software using different criteria for the selection has shown significant improvement in uncertainty of the measurement with respect to results in [2].

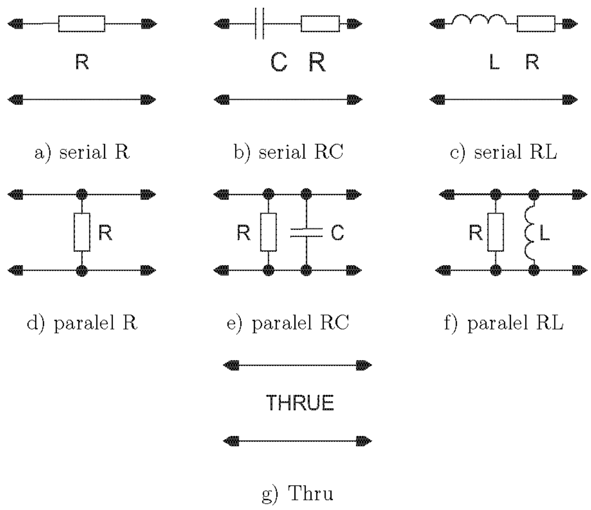


Fig. 2. Seven different internal PTP states realized by simply passive RLC structure.

However, the modeled states of the PTP were composed only from ideal R, L, C components (Fig. 2) and only ideal switches were included in the model. The purpose of this paper is to present the first measurement experience with real circuit structure including switches, bias circuits, etc. In the experiments reflection coefficient of different one-ports were measured on standard VNA and by means of the new seven state PTP circuit. The results were compared with respect to amplitudes and phases.

2. PTP Realization

The realized PTP circuit is based on seven different simple structures, see Fig. 2. The structure was extended to 8 different states using one more parallel R = 100 Ω state. This state improves measurement capability and produces a symmetrical microstrip structure. The structure was designed for the frequency range 240 to 1600 MHz and realized in a 50 Ω microstrip line on Arlon CuClad 233 substrate with thickness 0.254 mm, see Fig. 3. SMD components 0402 were used for realization. Beam lead PIN diodes were used to switch individual parts of the circuit corresponding to the PTP individual states. The whole circuit was placed in an in-house test fixture with APC7 adapters added, see Fig. 4. The reference planes of measurements were located at the planes of APC7 connectors.

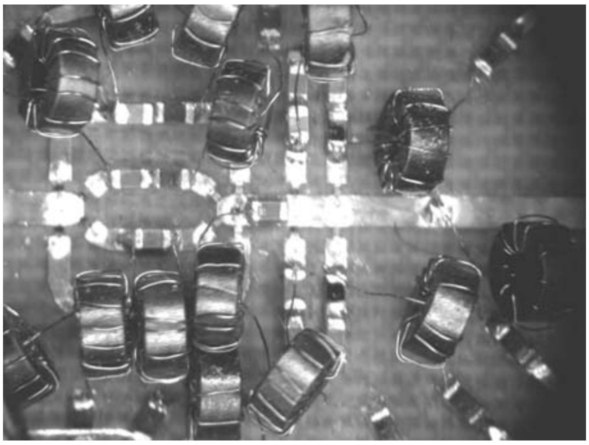


Fig. 3. Detail of the microstrip PTP realization.

Scattering parameters (S-parameters) of all designed states of the PTP were measured using a VNA, and proved to meet design goals [3]. The measurements have shown a good agreement between realization and model simulation.

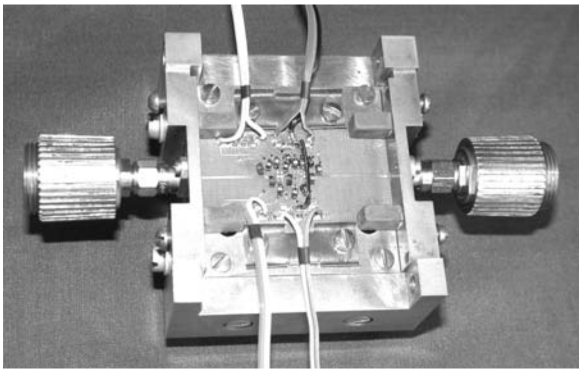


Fig. 4. Test fixture with PTP that was used for verification.

As basic DUTs short, open, load, 50Ω line and 3 dB attenuator terminated with open and short respectively were used, see Fig. 5a).

A piece of 50Ω semi-rigid cable was also added to introduce an element providing fast phase change of measured reflection coefficients (see Fig. 5 b). The long line standard produces 21x360 deg phase difference.

a) b)

Fig. 5. PTP calibration standards and Basic DUTs.

3. Calibration

The measurements using PTP system require in a suitable calibration method. The method should characterize PTP states so that the transformation between from SNA to DUT plane (Fig.1) is possible. A PTP can be described by means of its scattering parameters. The transformation relation has the form

$$P_m = |\Gamma_m|^2 = \left| s_{11} + \frac{s_{21}s_{12}\Gamma_{DUT}}{1 - s_{22}\Gamma_{DUT}} \right|^2 \tag{1}$$

Five fully known standards are needed. The equation (1) is not linear, the calibration process is far from easy. The equation can be linearized by introducing extra variables [1]. More calibration standards are needed and the process is over-determined, but becomes much easier. The transformation between SNA and DUT reference planes (1) can be rearranged to a different form that contains calibration parameters A-G.

$$\begin{gathered} A_i|\Gamma_{DUT}|^2 + B_i \operatorname{Re}(\Gamma_{DUT}) + C_i \operatorname{Im}(\Gamma_{DUT}) + D_i|\Gamma_m|^2 \operatorname{Re}(\Gamma_{DUT}) + \\ + E_i|\Gamma_m|^2 \cdot \operatorname{Im}(\Gamma_{DUT}) + F_i|\Gamma_m|^2|\Gamma_{DUT}|^2 + G_i + |\Gamma_m|^2 = 0 \end{gathered} \tag{2}$$

A different set of calibration parameters A-G is obtained for each PTP state and frequency. The equation (2) is suitable for an over determined calibration method. One PTP state is fully defined by 7 real parameters A-G that are determined during calibration process. 7 different calibration standards are needed. The equation (2) can be rearranged to a matrix form (3) that contains 7 rows for 7 different calibration standards.

$$[x] = -[P] \cdot [L]^{-1} \tag{3}$$

Matrix L depends on the Γ_c (standards) and P_m (reflected power at the SNA ref. plane), see Fig 1.

$$L = \begin{bmatrix} |\Gamma_{c_1}|^2 & \operatorname{Re}(\Gamma_{c_1}) & \operatorname{Im}(\Gamma_{c_1}) & P_{m_1}\operatorname{Re}(\Gamma_{c_1}) & P_{m_1}\operatorname{Im}(\Gamma_{c_1}) & P_{m_1}|\Gamma_{c_1}|^2 & 1 \\ |\Gamma_{c_2}|^2 & \operatorname{Re}(\Gamma_{c_2}) & \operatorname{Im}(\Gamma_{c_2}) & P_{m_2}\operatorname{Re}(\Gamma_{c_2}) & P_{m_2}\operatorname{Im}(\Gamma_{c_2}) & P_{m_2}|\Gamma_{c_2}|^2 & 1 \\ |\Gamma_{c_3}|^2 & \operatorname{Re}(\Gamma_{c_3}) & \operatorname{Im}(\Gamma_{c_3}) & P_{m_3}\operatorname{Re}(\Gamma_{c_3}) & P_{m_3}\operatorname{Im}(\Gamma_{c_3}) & P_{m_3}|\Gamma_{c_3}|^2 & 1 \\ |\Gamma_{c_4}|^2 & \operatorname{Re}(\Gamma_{c_4}) & \operatorname{Im}(\Gamma_{c_4}) & P_{m_4}\operatorname{Re}(\Gamma_{c_4}) & P_{m_4}\operatorname{Im}(\Gamma_{c_4}) & P_{m_4}|\Gamma_{c_4}|^2 & 1 \\ |\Gamma_{c_5}|^2 & \operatorname{Re}(\Gamma_{c_5}) & \operatorname{Im}(\Gamma_{c_5}) & P_{m_5}\operatorname{Re}(\Gamma_{c_5}) & P_{m_5}\operatorname{Im}(\Gamma_{c_5}) & P_{m_5}|\Gamma_{c_5}|^2 & 1 \\ |\Gamma_{c_6}|^2 & \operatorname{Re}(\Gamma_{c_6}) & \operatorname{Im}(\Gamma_{c_6}) & P_{m_6}\operatorname{Re}(\Gamma_{c_6}) & P_{m_6}\operatorname{Im}(\Gamma_{c_6}) & P_{m_6}|\Gamma_{c_6}|^2 & 1 \\ |\Gamma_{c_7}|^2 & \operatorname{Re}(\Gamma_{c_7}) & \operatorname{Im}(\Gamma_{c_7}) & P_{m_7}\operatorname{Re}(\Gamma_{c_7}) & P_{m_7}\operatorname{Im}(\Gamma_{c_7}) & P_{m_7}|\Gamma_{c_7}|^2 & 1 \end{bmatrix} \tag{4}$$

where

$$[x]^T = [A, B, C, D, E, F, G] \quad [P_m]^T = [P_{m_1}, P_{m_2}, P_{m_3}, P_{m_4}, P_{m_5}, P_{m_6}, P_{m_7}] \tag{5}$$

Vector x contains the calibration coefficients A-G for one PTP state and vector P_m contains reflected power at SNA ref. plane. The equation (3) contains the inverse matrix. Therefore the rows of matrix L must be linear independent Linear independency is granted by using different calibration standards. Unfortunately, two or more standards at the same frequency can produce the same reflected power. Therefore, a set of standards is different enough (eg. suitable) if it consists of standards resulting in different power levels. A shape of the transformation function (1) is shown in Fig. 6. This 3-D graph shows *x-y* complex plane and an appropriate reflected power P_m at the SNA ref. plane. At this situation four standards are at the positions corresponding to the same contour line. This configuration produces the same value of the P_m despite of the fact that the standards itself are different.

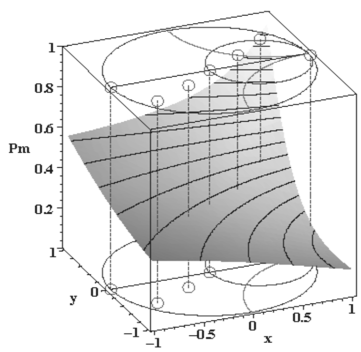


Fig. 6. PTP transformation plane shape for one state at single frequency point.

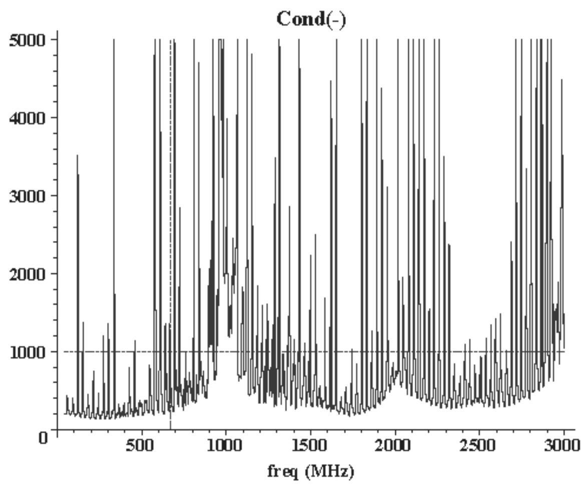


Fig. 7. Condition number for one PTP state and 7 standards.

As a consequence of this configuration there is a linear dependency between rows at the L matrix. It means that the calculation (3) is unstable at some isolated frequencies resulting in a wrong A-G parameters determination. Therefore a new idea of calibration method was designed. A new Long Line aditional caliber was applied, see Fig 5b). It makes possible to produce standards that have very fast phase dependency over the frequency band. Moreover as a criterion that describes quality of a caliber configuration the condition number of the L matrix was used, see (6).

$$cond(L) = \|L\| \cdot \|L\|^{-1}, \tag{6}$$

For example one result is shown in Fig. 7. Using the Long Line does not avoid ill-conditioned measurements, but places them at isolated frequency points where *cond(L)* approaches infinity, but for the majority of points the measurement remains well defined with low *cond(L)*. It makes possible to determine A-G parameters corresponding to wrong configurations using interpolation. The set of calibration standards can be used for all PTP states.

4. Experiments

The device was designed for the band 240 to 1600 MHz and measured in a bit broader band to check real limits of its operation. Measurements in frequency band 45 MHz to 3 GHz on Agilent E 8364A vector network analyzer were arranged in the following way:

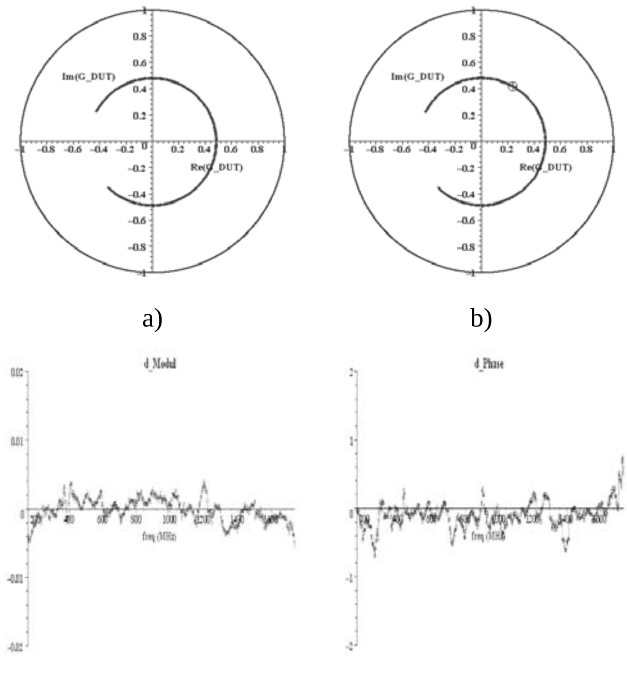
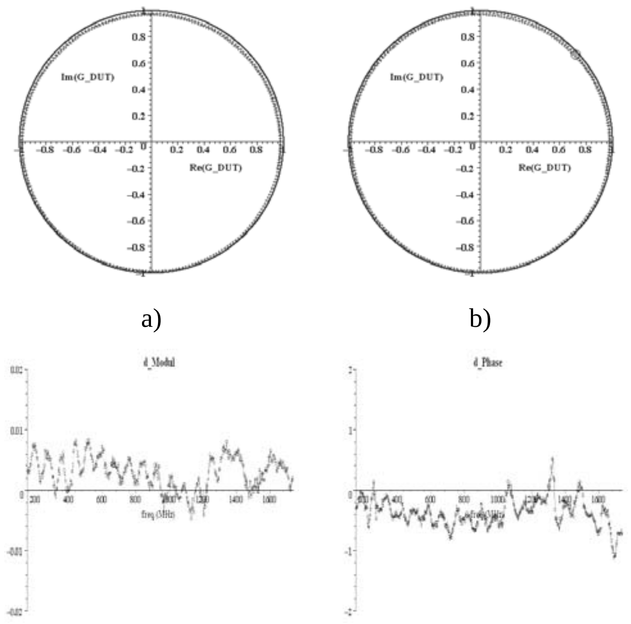


Fig. 8. Comparison of reflection coefficient measured using VNA and via PTP. The DUT is formed as 3-dB attenuator and the short. Frequency range 190-1700 MHz.

Firstly, the S-parameters of the PTP were determined for all individual settings. Secondly, the reflection coefficients of the above mentioned devices were measured. Thirdly, the input reflection coefficients for individual settings of the PTP with a DUT connected at the output were measured. Only magnitudes of these reflection coefficients then were considered for subsequent processing in the verification procedure mentioned in [3].

Quality of measurements was checked comparing the results of the third-type measurements with the data obtained by the transformation of reflection coefficients of DUT determined on VNA through the S-parameters of the PTP. Differences of data were in the order of 0.01 in the magnitude and 1 deg in the phase.



a) b) c) d)

Fig. 9. Comparison of reflection coefficient measured on VNA and via PTP. The DUT is formed as Long Line and the short. Frequency range 190-1700 MHz.

Vector data of DUTs measured by VNA were compared with vector data of DUTs determined by the 7-state PTP via the method [3]. The results for the DUT formed by a cascade of the 3-dB attenuator and the short at the end are plotted in Fig. 8. A detailed comparison of measured results for the Long Line and the short is depicted in Fig. 9.

Concerning the other DUTs in the frequency band 200-1600 MHz the differences did not go beyond 0.01 in magnitude and 1 deg in phase. It means they were in the same order of reproducibility as the connector mounting. Beyond this frequency range the differences gradually rose. Further optimization of the software for PTP settings selection to extend the bandwidth of correct measurement is under way.

5. Conclusion

The key component for a new type of VNA based on scalar measurement only – seven state PTP - was designed, realized and experimentally tested. Excellent operation over the frequency bandwidth of 3 octaves was achieved. Differences of measured data compared to direct measurements on VNA Agilent E8364A corresponded to reproducibility of connector mounting being typically in the order of 0.01 in magnitude and 1 deg in phase. The new calibration method for the PTP was designed and tested on real measured data.

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