A nine-port network analyzer

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This paper presents a feasibility study of replacing six-port reflectometers by five-port reflectometers for vector measurements at microwave frequency bands. A nine-port vector network analyzer using two five-port reflectometers is described. Two new calibration techniques are proposed for calibrating both single reflectometer and double five-port circuits. These procedures require only a short circuit as a standard. The system has been tested in two frequency bands. The comparison of the practical results, obtained by the five-port system, with those measured by six-port reflectometer, proves its efficiency.

هذا البحث يقدم دراسة لاستعمال الوصلات ذات الخمسة منافذ كبديل لتلك ذات الستة منافذ في حال توفر مصدر إشارة ميكروموجية مستقرة مع الزمن و ذلك لقياس سعة وطور بارا مترات التشتت في مجال الذبذبات الميكروموجية. فقد تمت دراسة شبكة ذات تسعة منافذ تحتوي على وصلتين ذات خمسة منافذ. إضافة إلى ذلك يعرض البحث لطرقتي معايرة جديدتين لكل وصلة على حده وللجهاز كله حيث يستخدم عدة أحمال ومعيار واحد فقط و هووصلة قصيرة. كذلك تم فحص الجهاز في مجالي ذبذبات مختلفين. أخيرا تمت مقارنة القياسات العملية مع تلك الناتجة باستعمال الأجهزة ذات الستة منافذ و ذلك باستعمال نفس الأحمال للمعايرة و قد أظهرت هذه المقارنة تقارب جميع النتائج و كفاءة الجهاز.

Keywords: Network analyzer, Scattering parameters, Six-port reflectometers

1. Introduction

The six-port reflectometer was originally designed to be used in instrumentation and measurement applications [1, 2]. In this system, one of the four power detectors is used as a reference to normalize any variation in the source power. During the last decade, the six-port reflectometer has been considered in general applications such as anti-collision radars [3], direction finding systems [4] and direct-conversion receivers [5], where a constant power local oscillator is employed. Consequently, the reference detector may not be required and the six-port reflectometer can be replaced by a simplified five-port version, even for instrumentation when a stable power source is available.

We propose in this paper a theoretical and an experimental study of a nine-port network analyzer using two five-port reflectometers. For good comparison with six-port performance, the used system is a part of a six-port network analyzer (11-port circuit) where the reference power data are not used. We use the same kit for calibrating both six-port and five-port reflectometers. A new procedure for the diode linearization is suggested. The calibration of the five-port is done using a similar approach as in six-port case where an intermediate variable w is introduced [6]. This procedure as well as two new calibration techniques for the w-Γ transform are developed in the calibration section, where only a short circuit is used as a standard. Finally, practical results compared to those obtained by six-port reflectometers in two frequency bands have shown the validity of this proposed system.

2. System description

The nine-port network analyzer fig. 1 is composed of:

- A signal source equipped with a variable attenuator to change the incident power level to the system, especially in the linearization procedure of the schottky diode detectors.
- A power divider to produce the input signal to each reflectometer. It is followed by two isolators at its outputs to increase the isolation between the measurement ports.
- A variable phase shifter to provide different phase relations between the exciting signals of the Device Under Test (DUT).

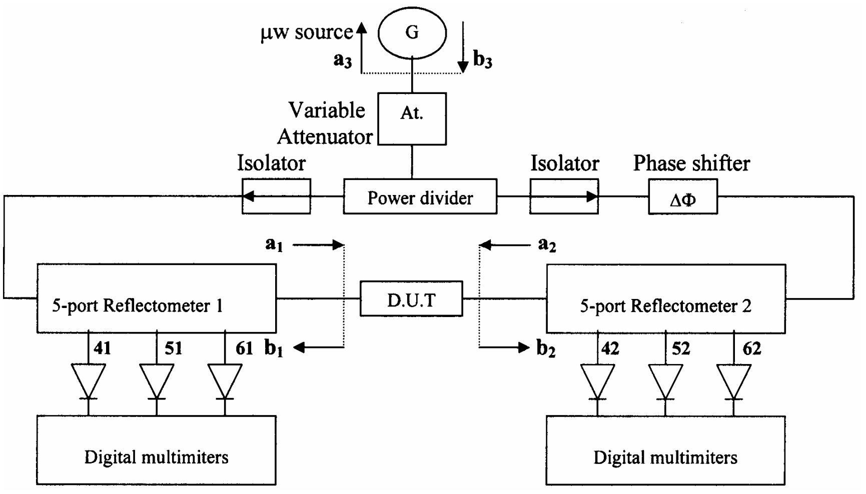

Fig. 1. Nine-port network analyzer.

- Two identical reflectometers to measure the reflection coefficient Γ_1 and Γ_2 at the input of the DUT where schottky diodes are used as power detectors and their output voltages are measured by the digital multimeters.

The scattering parameters of the DUT are deduced from these reflection coefficients Γ_1 and Γ_2, and defined as:

$$\Gamma_1 = \frac{b_1}{a_1} = S_{11} + S_{12}\frac{a_2}{a_1}, \qquad (1)$$

$$\Gamma_2 = \frac{b_2}{a_2} = S_{21}\frac{a_1}{a_2} + S_{22}, \qquad (2)$$

where a_i and b_i (i=1, 2) are the incident and reflected signals at the DUT ports, respectively.

Substituting eqs. (1, 2), the ratio a_1/a_2 can be eliminated and an equation as function of the S-parameters of the DUT and the reflection coefficients Γ_1 and Γ_2 is obtained.

$$\Gamma_1 S_{22} + \Gamma_2 S_{11} - \Delta = \Gamma_1 \Gamma_2, \qquad (3)$$

with,

$$\Delta = S_{11}S_{22} - S_{21}S_{12}.$$

Where Γ_1 and Γ_2 being functions of a_1/a_2, this ratio can be changed by means of the phase shifter. So by generating N eqs. (3) corresponding to N states of the phase shifter, S_{11}, S_{22}, and the product $S_{21}S_{12}$ will be the solution of this equations system.

To determine the S_{12} and S_{21} parameters, two cases are considered:

i) For a reciprocal device, these parameters are calculated from the product $S_{12}\ S_{21}$ as:

$$|S_{12}| = |S_{21}| = \sqrt{|S_{21}S_{12}|}, \qquad (4)$$

$$Arg(S_{12}) = Arg(S_{21}) = 0.5\ Arg(S_{12}S_{21}) \pm n\pi, \qquad (5)$$

n is deduced by comparing the phase shift with the approximate value.

ii) For non-reciprocal device, the parameters S_{12} and S_{21} are calculated from relations (1) and (2); the ratio a_2/a_1 must be determined using a calibration procedure [10].

3. Calibration

The calibration of the nine-port network analyzer is achieved in four stages.

3.1. Power detector linearization

As in case of six-port reflectometer, the detected power at the output of each power detector for each reflectometer can be written as [2]:

$$P_i = K_i |1 + A_i \Gamma|^2 \qquad i = 4, 5, 6, \qquad (6)$$

where:

P_i's are the detected powers of the three Schottky diode detectors,

K_i and A_i, which are functions of source power and five-port circuit, are three real and three complex calibration constants, respectively, and

Γ is the reflection coefficient of the DUT.

Each power detector is calibrated separately using the model proposed in [7]:

$$P = V^{F(V)}. \tag{7}$$

Where $F(V)$ is a polynomial function of the detected voltage V.

Each detector can be linearized either by means of a calibrated power meter or using the following analysis if a calibrated signal generator is available.

For n-output power levels of the signal generator with a constant step, (n-1) equations can be obtained:

$$(P_j - P_{j+1})_{dBm} = F(V_j)*10Log(V_j)\ F(V_{j+1})*10Log(V_{j+1})$$
$$j = 1, ..., n-1. \tag{8}$$

Solving these equations with the least square method, the coefficients of the function $F(V)$ are found.

To test the performance of this method, the power ratio P_{i3} for a given load, which must be constant for any input power level, is calculated before and after linearization. Fig.2. The standard deviations were found to be 0.07 and 0.004, respectively.

3.2. The P-w transform

Using similar analysis as for the six-port reflectometer, the calibration consists of finding the constants K_i and A_i of eq. (6). The P-Γ transform is separated in two stages by introducing an intermediate complex variable w defined by:

$$P_1 = P_4 = |w|^2 . \tag{9}$$

With,

$$w = \sqrt{K_4}\,(1 + A_4\Gamma)\exp(j\phi) \;\; = A\Gamma + B . \tag{10}$$

Substituting the value of w in the expressions of P_5 and P_6 of eq. (6) we get:

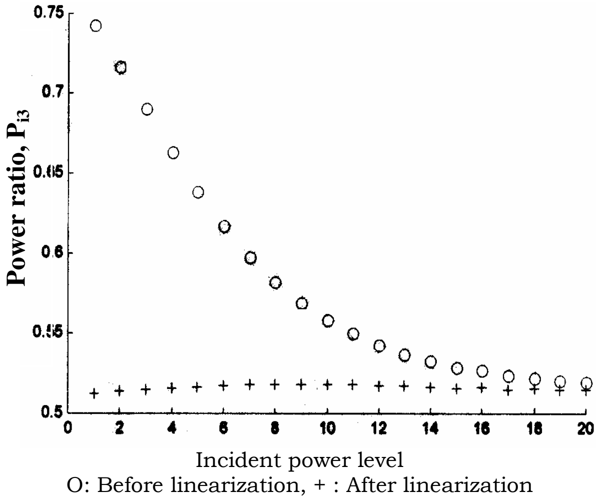

Fig. 2. Power ratio before and after linearization.

$$ZP_2 = ZP_5 = |w - w_1|^2$$
$$RP_3 = RP_6 = |w - w_2|^2 , \tag{11}$$

with:

$$Z = \frac{K_4}{K_5}\left|\frac{A_4}{A_5}\right|^2 , \tag{12}$$

$$R = \frac{K_4}{K_6}\left|\frac{A_4}{A_6}\right|^2 , \tag{13}$$

$$w_1 = \sqrt{K_4}\,\frac{A_5 - A_4}{A_5}\exp(j\phi) , \tag{14}$$

and

$$w_2 = \sqrt{K_4}\,\frac{A_6 - A_4}{A_6}\exp(j\phi), \tag{15}$$

where:

- Z, R and w_1 are three real constants and w_2, A and B are three complex constants, and
- Exp ($j\phi$) is selected in order that w_1 is real and positive.

Using a sliding short circuit and the approach proposed in ref. [8], an initial solution of the P-w transform parameters is obtained. Then these constants can be optimized using the function proposed by [6,9] and the intermediate complex reflection coefficient w is calculated.

$$w = u + j\,v,$$
$$u = \frac{P_1 - ZP_2 + |w_1|^2}{2w_1},$$
$$v = \frac{P_1 - RP_3 + |w_2|^2 - 2uu_2}{2v_2}. \tag{16}$$

3.3. The w – Γ *transform*

To find the two complex constants A and B characterizing the w-Γ transform of each reflectometer, we suggest two new methods for calibrating either the simple or double reflectometer.

3.3.1. Simple reflectometer

3.3.1.1. Calibration with two standards. A perfect matched load ($\Gamma = 0$) permits to get the value of B,

$$w_{ML} = B. \tag{17}$$

Using a perfect short circuit ($\Gamma = -1$), the value of A can be found as:

$$A = B - w_{SC} = w_{ML} - w_{SC}. \tag{18}$$

3.3.1.2. Calibration with one standard. If the perfect matched load is not available, the value of B can be obtained from the w-data of the sliding short, used in the P-w transform. This sliding short circuit describes a circle in the Γ-plane as well as in the w-plane since we have linear conformal transform between w and Γ.

$$|\Gamma|^2 = r^2, \tag{19}$$

and

$$|w - w_o|^2 = R^2, \tag{20}$$

where Γ and w are the reflection coefficients in the Γ and w-planes, respectively, r and R are the radii of the corresponding circles, and w_o is the center of the w-circle.

Substituting w from eq. (10) ($w = A\Gamma + B$) and comparing these equations, we find that the value of B is equal to w_o

$$B = w_o. \tag{21}$$

So, having obtained the values of w of the sliding short from the p-w stage, the center of the circle ($B = w_o$) can be calculated.

The value of A can be obtained as in the first case using eq. (18).

3.3.1.3. Double reflectometer. In this case, the constants B_1 and B_2 are found simultaneously.

Using a matched transmission line between the measurement ports, we get the following equation:

$$\Gamma_1 \Gamma_2 = exp(-2\gamma\,\ell). \tag{22}$$

Substituting for $\Gamma_i = \frac{w_i - B_i}{A_i}$ $i = 1,2$ from eq. (10) we get,

$$B_1 w_2 + B_2 w_1 + (A_1 A_2\, exp(-2\gamma\,\ell) - B_1 B_2) = w_1 w_2. \tag{23}$$

For three states of the variable phase shifter, three eqs. (23) can be generated and the unknowns B_1, B_2 and $(A_1 A_2\, exp(-2\gamma\,\ell) - B_1 B_2)$ can be obtained.

The values of A_1 and A_2 can be calculated as in case of simple reflectometer.

3.4. Calibration of network analyzer

Having calibrated both reflectrometers to measure reflection coefficients and the scattering parameters of reciprocal devices, the calibration of the network analyzer to get the ratio a_2/a_1 can be done using the same procedure as in case of six-port network analyzer [10] since we have the same system configuration.

4. Experimental results

To demonstrate the feasibility of the system and to prove its use as an alternative to six-port network analyzer or other measurement techniques, two measurement systems, in two different frequency bands have been tested. Available reflectometers are calibrated as six-port as well as five-port circuits and the obtained results by both systems are compared.

4.1. Measurements at 94 GHz

The used system is a dual six-port network analyzer [10], operating in the frequency band 75-110 GHz. Linearized schottky diode detectors operating in an AC detection mode are used to increase the measurement accuracy. The same kits are used for the LRL calibration of both six-port reflectometers as well as for the five-port reflectometers using the suggested calibration method. Many measurements were performed:

1. A set of terminations was measured by both six-port and five-port systems: a matched load, two fixed loads and an offset short. The results are presented in table 1.

Table 1
comparison of reflection coefficients of some terminations at 94 GHz

Load	Six-port system	Five-port system
Matched load	0.005	0.012
Fixed load 1	0.41 -143°	0.42 -142°
Fixed load 2	0.826 -22.5°	0.825 -22.8°
Offset short	0.99 108.3°	0.985 109°

A good conformity has been obtained in magnitude as well as in phase. The maximum deviations are within 0.01and 1°, respectively. The largest relative error is obtained for the matched load since its reflection coefficient magnitude is small and comparable to the measurement error.

2. For transmission measurements using the double reflectometer, the product of reflection coefficients of the two matched lines ($\Gamma_1\Gamma_2$= exp (-2γL)) used in the LRL procedure is validated four times. The first line is a thru connection and the length of the second one is 3.074 mm. The average value and the standard deviation of $\Gamma_1\Gamma_2$ are summarized in table 2.

The maximum differences between the values, obtained by the two systems, are 0.001 for the magnitude and 1.0 degree for the phase.

Table 2
Average values and standard deviations of $\Gamma_1\Gamma_2$

Line	Six-port circuit	Five-port circuit
Thru : $\lvert\Gamma_1\Gamma_2\rvert$	1.001 0.006	1.002 0.01
Thru : Arg$(\Gamma_1\Gamma_2)$	0.0025° 0.138	0.278° 0.93
3.074 mm : $\lvert\Gamma_1\Gamma_2\rvert$	0.984 0.0005	0.982 0.01
3.074mm: Arg$(\Gamma_1\Gamma_2)$	176.7° 0.216	177.6° 0.62

4.2. Measurements at 33 GHz

The reflectometer consists of five 3 dB 90° coaxial couplers and has a similar structure as that one used at 94 GHz. The calibration of the six-port is performed with a WR 28 waveguide sliding short circuit, a fixed short circuit and a matched load [11] while the five-port circuit is calibrated using the two methods mentioned above in paragraph (III-c-1). Then, eight equally spaced points of a sliding short of $\lambda/2$ wavelength were measured as well as some other loads. The following results are obtained:

- The center of the circle (w_o) described by the sliding short was found to be approximately equal to the value of w-matched load (w_{ML}) as expected from relation (17). The obtained values are (w_o = 0.136 + i(- 0.0086)) and (w_{ML} = 0.142 + i(- 0.00786)).
- The mean value of the magnitude of Γ is 0.999 with a standard deviation of 0.02 for the six-port case while the corresponding ones for the five-port case are 1.02 and 0.04, respectively. These results are within the maximum allowable measurement errors.
- The theoretical phase shift difference ($\Delta\Phi$) between each two successive points is 45°, the mean and standard deviation of ($\Delta\Phi$) for the eight points for six and five-port reflectometers are (45.5° & 1.7°) and (45.7° and 2.4°), respectively.
- As in case of 94 GHz system, the comparison of measurement of different loads has shown good agreement in both magnitude and phase between the two systems. The maximum deviations are within 0.015 and 1.5°, respectively.

5. Conclusions

The obtained results have shown that the six-port reflectometer can be replaced by a simpler five-port reflectometer, especially when a stable source is available. Also, it has been demonstrated that the 9-port network analyzer can be used for scattering parameters and transmission measurements instead of the double six-port network analyzer, where two additional reference detectors are used. The system has been tested in two different frequency bands for single and double reflectometer. The comparison of results has shown the validity of the proposed calibration techniques, either for the diode linearization or for the system calibration.

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