American Journal of Engineering and Applied Sciences

Original Research Paper

A Six-Port Reflectometer Calibration Using Wilkinson Power Divider

Traii Moubarek and Ali Gharsallah

Department of Physics, Faculty of Sciences of Tunis, El Manar City, Tunisia

Article history
Received: 28-12-2015
Revised: 08-03-2016
Accepted: 15-03-2016

Corresponding Author:
Traii Moubarek
Department of Physics, Faculty of Sciences of Tunis, El Manar City, Tunisia
Email: traii_moncef@yahoo.fr

Abstract: A new calibration method for a six-port reflectometer which minimizes the effect of power measurement errors is presented. It is based on the power divider correlator to obtain estimates of the six-port calibration constants. The calibration procedure is to determine the constants that govern the operation of the six-port from the measurement of power or output ports tensions by placing five to eleven standard loads in succession to DUT. A load and four offset shorts are used as reflection standards. Computer simulation results are presented to show that the described procedure substantially reduces the overall error in the calibration constants.

Keywords: Calibration Program Six-Port Junction, Reflectometer, Power Divider

Introduction

Recently, considerable improvement has been made in microwave components and new devices have become available. Current techniques employ a so-called arbitrary six-port junction embodying wideband 180° hybrids, quadrature hybrids, power splitter/combiners, etc…

The six-port reflectometer serves as standard measurement system to determine the complex reflection coefficient of the commercial working standards (Abou Chahine *et al*., 2000). Up to now, a large number of millimetric six-port circuits has been described. Their circuits differ in the six-port junctions, the power detection technique and the power detectors used (Abou Chahine *et al*., 1993). Some circuits present a new type of four-port automatic network analyzer containing one power detector and one variable reference load (Brantervik and Kollberg, 1985). Others use a dielectric waveguide structure (Hjipieris *et al*., 1990), or discrete waveguide components (Cronson and Fong-Tom, 1982). These methods are very easy and reliable but difficult to automate. Most circuits pointed out that there exist exact relations between some system parameters and integral quantities of the detected power values for a number of reference plane positions (Yakabe, 1994). Such techniques require additional microwave hardware and auxiliary control circuits specifically made for such calibration purposes. Another type uses Schottky diodes (Cronson and Fong-Tom, 1982) that can be Utilized with homodyne detection technique (Simon, 1991). However, it would be entirely impractical for a DMR to perform a calibration procedure. To overcome these drawbacks, a new convenient calibration method with power divider correlator is adjusted and used. The reflectometer is based on four coupled equal-mode impedance micro-strip lines, whose principle of operation is presented in (Collier and El-Deeb, 1979) and its design in (El-Deeb, 1989). The calibration procedure is to determine the constants that ensure the operation of the six-port from the measurement of voltage output ports. For this reason, we place five to eleven standard loads according to the DUT that before we know their reflection coefficient (El-Deeb, 1991).

The calibration technique and analysis of the six-port with power divider are described. The six-port network responses at output ports are determined by ADS software and standards values to demonstrate the validity of the six-port circuit developed.

Six-port Theory

The fundamental operation and theory of the six-port reflectometer has been described in detail in previous papers, many algorithms that have been developed for calibrating six-port refiectometers, the six-port-to-four-port reduction technique given by Engen (1978) is among the most widely used.

Six-port block diagram is shown in Fig. 1, the circuit is composed of microwave synthesizer to excite a six-port circuit, linear six-port network with four outputs measurement port 3...6 and the Device Under Test (DUT) which placed at port 2.

Science Publications

© 2016 Traii Moubarek and Ali Gharsallah. This open access article is distributed under a Creative Commons Attribution (CC-BY) 3.0 license.

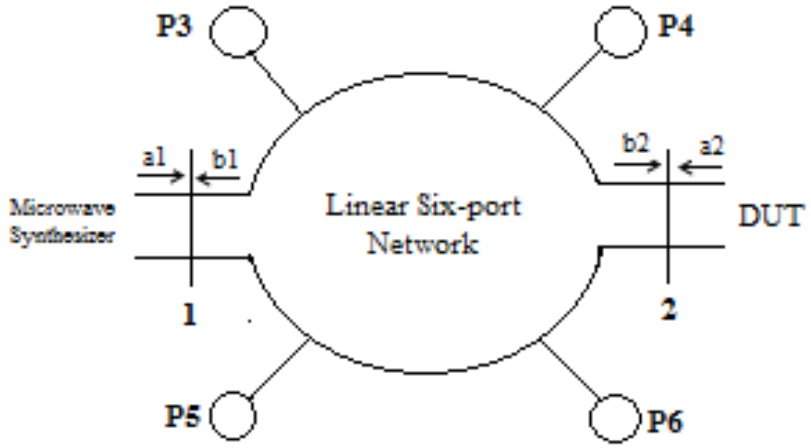

Fig. 1. Six-port block diagram for measuring complex microwave parameters

Assuming that the intervening structure is linear and all ports properly terminated, the wave amplitude emerging at any port can be expressed as a linear combination of two independent inputs to the network (Bialkowski *et al*., 2007).

The power detector responses are proportional to the modulus squared of the port voltages V_3 to V_6, such that:

$$|V_3| = |b_2|^2 \tag{1}$$

$$|V_4| = |a_2|^2 \tag{2}$$

The response of the six-port reflectometer is contained into additional voltage readings:

$$|V_5|^2 = |a_2 + b_2|^2 \tag{3}$$

$$|V_6|^2 = |a_2 + jb_2|^2 \tag{4}$$

If V_3 is taken as the reference level, we divide Equation 2-4 by Equation 1, we obtain:

$$\left|\frac{V_4}{V_3}\right|^2 = |\Gamma_2|^2 \tag{5}$$

$$\left|\frac{V_5}{V_3}\right|^2 = 1+|\Gamma_2|^2 + 2|\Gamma_2|\cos\phi \tag{6}$$

$$\left|\frac{V_6}{V_3}\right|^2 = 1+|\Gamma_2|^2 + 2|\Gamma_2|\sin\phi \tag{7}$$

Where:

ϕ = The phase angle between a_2 and b_2

Γ_2 = The complex reflection coefficient of the DUT

The equivalent reflection coefficient Γ_2 then becomes:

$$\Gamma_2 = \frac{1}{2}\left(\left|\frac{V_5}{V_3}\right|^2 - \left|\frac{V_4}{V_3}\right|^2 - 1\right) + \frac{j}{2}\left(\left|\frac{V_6}{V_3}\right|^2 - \left|\frac{V_4}{V_3}\right|^2 - 1\right) \tag{8}$$

The previous equation show that the proposed six-port circuit based in Wilkinson power divider and four power detector can successfully generate responses at ports 3 to 6 in terms of voltage not power. In any case, an analysis in terms of port voltages is necessary to take into accounts the situation when zero-conductance detectors are used. Nevertheless, when the detector conductance are finite (Woods, 1979).

Six-Port Calibration with Power Divider Technique

The six-port reflectometer comprises a signal source port, a measurement port and four sidearm ports to which power detectors are connected (Woods, 1977; Haddadi *et al*., 2006).

In the present investigation, our aim is to determine the reflection coefficient of the device under test in terms of magnitude and phase at operating frequency band between 1-3 GHz.

Thus, the key problem is, how to determine the eleven frequency dependent system parameters at operating frequency, with fewer calibration standards and with less computational effort.

Figure 2 shows the block diagram of six-port calibration system:

For the six-port correlator with two power divider, an RF source provides a signal a_1. This signal is divided by means of a first coupler to feed one of the complex correlator inputs and a second coupler to feed the

DOI: 10.3844/ajeassp.2016.274.280

measurement port associated with the access of the DUT. The signal reflected by the latter is injected through the second coupler to the other complex correlator input. We finally get four DC voltages rated from V_1 to V_4 to calculate the reflection coefficient Γ in the access plan DUT (Pozar, 2005).

Wilkinson Power Divider

Power dividers provide equal amplitude, isolation between the output ports and equal phase splitting, as is depicted in Fig. 3. The proposed power divider is composed of two coupled transmission lines with characteristic impedances, each one quarter-wavelength long and lumped resistors. The output signals are 3 dB below the input signal and they are also in phase (i.e., 0 degree phase shift between the outputs), where the power delivered to the two output ports is equal (Woods, 1977). For an equal split Wilkinson, we connect resistors between each output transmission line.

Subsequently, we present the schematic and the results of the ADS simulation of the Wilkinson Power Divider respectively.

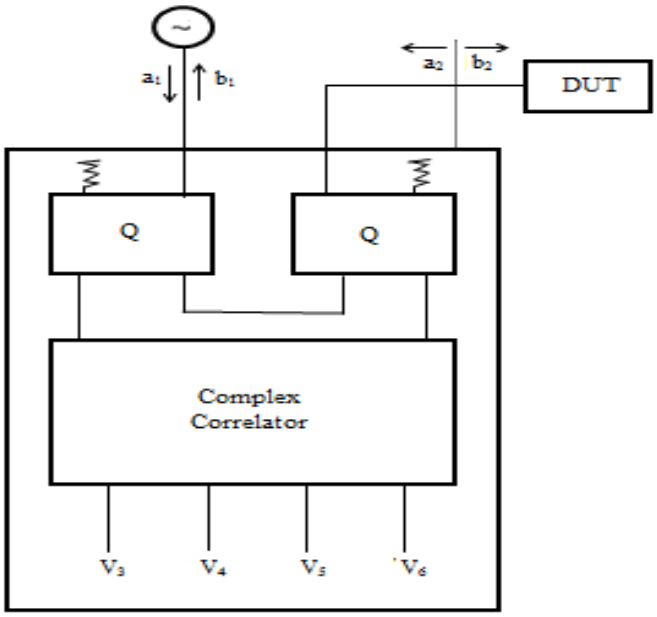

Fig. 2. Block diagram six-port correlator with two power

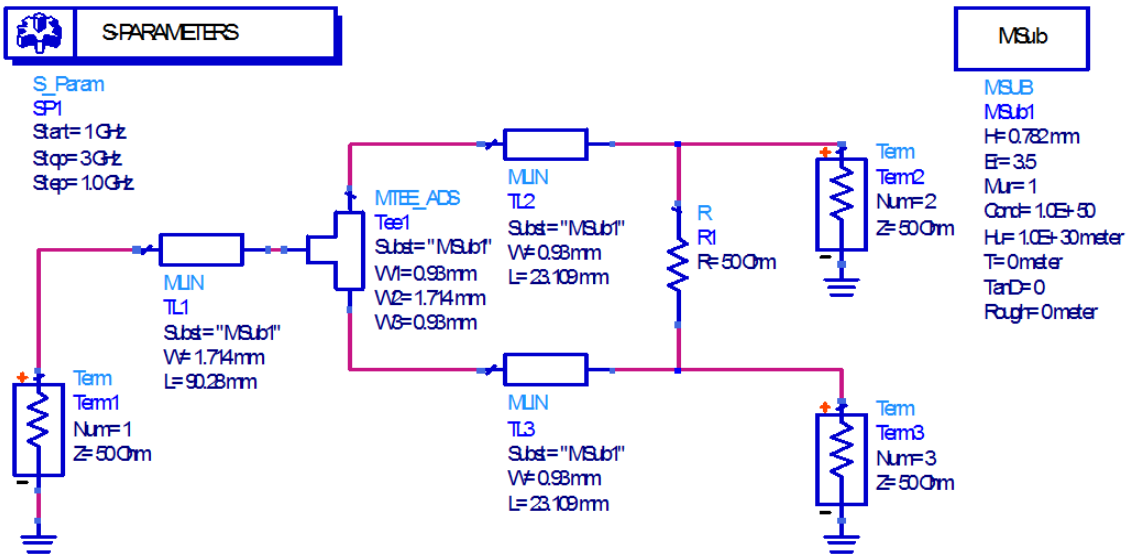

Fig. 3. Schematic of Wilkinson power divider circuit

The Wilkinson power divider at figure above is designed such that the input power is equally distributed among the output ports. Thus, a 2 to 1 power divider passes 50% (-3 dB) of the power to each output. This means $P_2 = P_3 = 1/2$, it is verified that the input and outputs are ideally adapted.

Simulation results in Fig. 4 above show that all the features of a conventional Wilkinson power divider, such as an equal power split, impedance matching at all ports and a good isolation between the two output ports. The structure can be used as a power divider for equivalent power division of calibration six-port circuit.

The calibration of a six-port is to determine the constants that govern the operation of the circuit. These constants allow us to determine the complex relationship between the two waves present at the input, from the values of the four outputs. The calibration procedure is as follows:

- Log in succession of the standards to six-port and quads meet the outputs
- Matrix formalization of the problem
- Determination of calibration constants by resolution matrix
- Polynomial modeling output voltages allow us to move to a formalization of the problem matrix

In addition to simulation of the Wilkinson power divider, a schematic of six-port reflectometer was up illustrated in figure below.

Two couplers are added to the complex correlator type Wilkinson so that only one source connected to port 1 also supplies port 2, where is connected the Device Under Test (DUT) with reflection coefficient S_{11}. Thus, we obtain a very simple structure for the SPR (Fig. 5).

Results

Figure below shows the amplitudes detected by the four outputs $V_1 \ldots V_4$ at the central frequency f = 2 GHz.

The voltage at a power detector port is a vector summation of a portion waves presented at port. The output voltage waveforms of the diode detectors are shown in the following equation:

$$V_{out,i} = \frac{1}{2}\left(|a_i|^2 + |b_i|^2\right) + |a_i|.|b_i|.\cos(2\prod \Delta f t + \Delta\varphi_i) \quad (9)$$

where, a_i. b_i, waves corresponding to a and b at port 1 and 2 respectively.

The obtained amplitudes change according to the load. We find better results than those obtained with other calibration methods; these results will be presented in more detail by determining the input matrices.

The operation of SPR requires preliminary steps of calibration. For this, we used a matched load and the loads consisting of lumped element (resistance and self in series). To establish the calibration, we perfectly know the load impedance at the DUT to move to the reflection coefficient of the DUT.

Replacing the load with a variable short-circuit, in this case, were taken at each time phase in accordance with the piston position to determine its reflection coefficient.

Five characteristic impedance points were determined; these data are used during calibration of the device with technical computing language (Matlab).

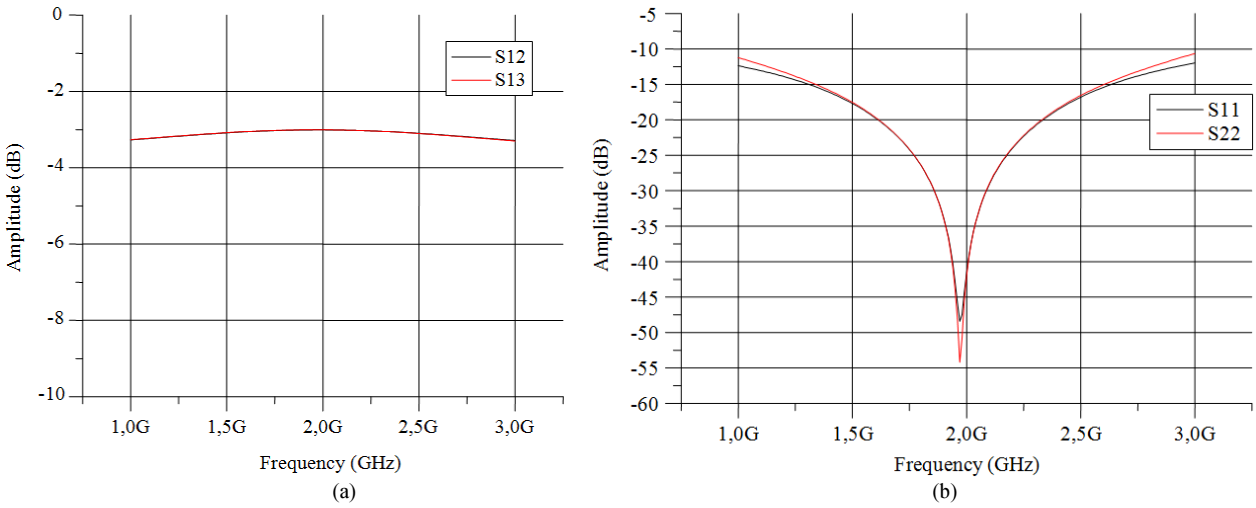

Fig. 4. Frequency response of Wilkinson power divider with ADS simulator

DOI: 10.3844/ajeassp.2016.274.280

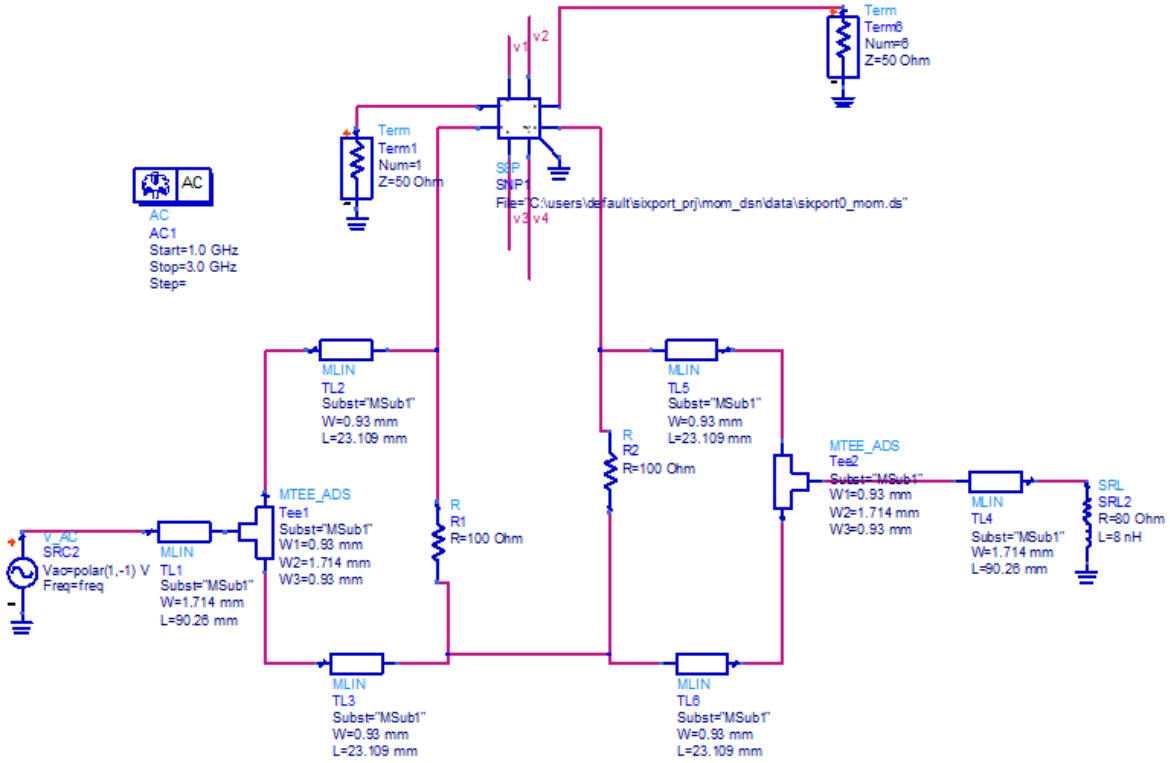

Fig. 5. Schematic of calibrating six-port circuit with ADS software

Table 1. Correspondence between reflection coefficient and impedance standards

k	Rel(Γ)	Im(Γ)	R(Ohm)	L(nH)
0	0	0	CA	CA
1	1	0	CO	CO
2	-1	0	CC	CC
3	0,5	0,5	50	7,9E-9
4	0,4	0,7	20,588	6,5E-9
5	0,3	0,3	70,68	4,1E-9

Table 2. Standards values of the outputs

k	Re(Γ)	Im(Γ)	V_1(v)	V_1^2 (v²)	V_2(v)	V_2^2 (v²)	V_3(v)	V_3^2 (v²)	V_4(v)	V_4^2 (v²)
0	0	0	0,802	0,643204	0,682	0,465124	0,783	0,613089	0,796	0,633616
1	1	0	0,739	0,546121	0,629	0,395641	0,709	0,502681	0,667	0,444889
2	-1	0	1,11	1,2321	1,13	1,2769	1,198	1,435204	1,324	1,752976
3	0,5	0,5	0,5999	0,35988001	0,777	0,603729	0,539	0,290521	0,849	0,720801
4	0,4	0,7	0,536	0,287296	0,834	0,695556	0,464	0,215296	0,918	0,842724
5	0,3	3	0,664	0,440896	0,739	0,546121	0,617	0,380689	0,826	0,682276

The five standards are shown in the following Table 1:

We connect six loads on access of measuring reflection coefficient of a successive manner and we take the outputs every time.

The values obtained are shown in the following Table 2:

$$\Gamma_k = I_K + jQ_K (K = 1,\ldots,5) \tag{10}$$

Γ_k, represent the five standard loads and the sixth is the matched load (k = 0). It divides these data into the corresponding matrices.

For a matched load (I = Q = 0), the resulting matrix system is written as follows: $V_0 = B_0$:

$$V_0 = \begin{bmatrix} V_{10} \\ V_{20} \\ V_{30} \\ V_{40} \end{bmatrix} \rightarrow V_0 = \begin{bmatrix} 0.643 \\ 0.465 \\ 0.613 \\ 0.633 \end{bmatrix} \tag{11}$$

For the remaining loads Γ_k the following system is obtained:

$$V_M = \begin{bmatrix} 0.546 & 0.39 & 0.5 & 0.44 \\ 1.23 & 1.277 & 1.435 & 1.752 \\ 0.358 & 0.6 & 0.29 & 0.72 \\ 0.287 & 0.71 & 0.215 & 0.842 \\ 0.44 & 0.546 & 0.38 & 0.68 \end{bmatrix} \quad (12)$$

$$\text{real}(\Gamma) = \begin{bmatrix} 1 \\ -1 \\ 0.5 \\ 0.4 \\ 0.3 \end{bmatrix} \rightarrow \text{Im}(\Gamma) = \begin{bmatrix} 0 \\ 0 \\ 0.5 \\ 0.7 \\ 0.3 \end{bmatrix} \quad (13)$$

Discussion of Results

The results presented in the previous section show that the proposed calibration method is valid. This method based on power divider correlator requires knowledge of six loads for a second order modeling and eight loads for a third order. There are no constraints regarding strong signals as there are in former works. The standard deviation of the amplitudes detected by the four outputs increased as the power of RF generator decreased. This fact is not due to the calibration constants, though it caused by quantization noise. The method described here was used to calibrate the six-port reflectometer on 1-3 GHz frequency band.

Conclusion

A calibration method for a six-port reflectometer which minimizes the effect of power measurement errors is presented. The proposed four-port correlator requires only two power dividers and lumped components. Regarding calibration considerations, a major improvement in the technique has been made to achieve simulation in the 1-3 GHz frequency range. This solution makes a good compromise between the number of calibration standards, the computational cost and the accuracy.

Acknowledgement

The Authors acknowledge the support of the University of Tunis EL Manar.

Author's Contributions

Traii Moubarek: Conception and simulation of the six-port circuit with ADS and calibration of the system with Matlab software, secondly the first author contributes to the writing of the manuscript.

Ali Gharsallah: Organize the study and gives many important ideas related with this contribution.

Ethics

The authors undertake to meet all the ethical issues that may occur after the publication of this manuscript.

References

Abou Chahine, S., B. Huyart and L. Jallet, 2000. A convenient calibration procedure of four-port reflectometers: Application on six-port reflectometer and heterodyne network analyzer. Proceedings of the 17th National Radio Science Conference, Feb. 22-24, IEEE Xplore Press, Minufiya, pp: B7/1-B7/8. DOI: 10.1109/NRSC.2000.838844

Abou Chahine, S., B. Huyart, E. Bergeault and L. Jallet, 1993. A six-port reflectometer calibration using schottky diodes operating in AC detection mode. IEEE Trans. Instrument. Measure., 42: 505-510. DOI: 10.1109/19.278612

Bialkowski, M.E., A.M. Abbosh and N. Seman, 2007. Compact microwave six-port vector voltmeters for ultra-wideband applications. IEEE Trans. Microw. Theory Tech., 55: 2216-2223. DOI: 10.1109/TMTT.2007.906539

Brantervik, K. and E.L. Kollberg, 1985. A new four-port automatic network analyzer: Part I-Description and performance. IEEE Trans. Microwave Theory Tech., 33: 563-568. DOI: 10.1109/TMTT.1985.1133030

Collier, R.J. and N.A. El-Deeb, 1979. On the use of a microstrip three-line system as a six-port reflectometer. IEEE Trans. Microwave Theory Tech., 27: 847-853. DOI: 10.1109/TMTT.1979.1129747

Cronson, H.M. and R.A. Fong-Tom, 1982. A 94-GHz diode-based single six-port reflectometer. IEEE Trans. Microwave Theory Tech., 30: 1260-1264. DOI: 10.1109/TMTT.1982.1131235

El-Deeb, N.A., 1989. An improved design of systems based on three coupled microstrip lines. IEEE Trans. Microwave Theory Tech., 37: 795-798. DOI: 10.1109/22.18857

El-Deeb, N.A., 1991. Calibration and performance of an automatic microstrip six-port reflectometer. IEEE Trans. Instrument. Measure., 40: 51-54. DOI: 10.1109/19.69954

Engen, G.F., 1978. Calibrating the six-port reflectometer by means of sliding terminations. IEEE Trans. Microwave Theory Tech., 26: 951-957. DOI: 10.1109/TMTT.1978.1129527

Haddadi, K., H. El Aabbaoui, C. Loyer, D. Glay and N. Rolland *et al*., 2006. Wide-band 0.9 GHz to 4 GHz four-port receiver. Proceedings of the 13th IEEE International Conference on Electronics, Circuits and Systems, IEEE Xplore Press, Nice, pp: 1316-1319. DOI: 10.1109/ICECS.2006.379724

Hjipieris, G., R.J. Collier and E.J. Griffin, 1990. A millimeter-wave six-port reflectometer using dielectric waveguide. IEEE Trans. Microwave Theory Tech., 38: 54-61. DOI: 10.1109/22.44156

Pozar, D., 2005. Microwave Engineering. 3rd Edn., John Wiley and Sons Inc., Hoboken, ISBN-10: 047164451X, pp: 700.

Simon, J., 1991. A W-band homodyne vector network analyzer with variable measurement port distance. IEEE Trans. Instrum Meas., 40: 446-448. DOI: 10.1109/TIM.1990.1032982

Woods, D., 1977. Multiport-network analysis by matrix renormalisation employing voltage-wave S-parameters with complex normalisation. Proc. IEE, 124: 198-204. DOI: 10.1049/piee.1977.0037

Woods, D., 1979. Analysis and calibration theory of the general 6-port reflectometor employing four amplitude detectors. Proc. IEE, 126: 221-228. DOI: 10.1049/piee.1979.0051

Yakabe, T., 1994. Complete calibration of a six-port reflectometer with one sliding load and one short. IEEE Trans. Microwave Theory Techniques, 42: 2035-2039. DOI: 10.1109/22.330115