SIX-PORT REFLECTOMETER STRUCTURE USING TWO MICROSTRIP THREE–SECTION COUPLERS

Mohra, Ashraf Shouki
Electronics Research Institute, Dokki-Cairo, Egypt
Email: Mohra@eri.sci.eg

Abstract
In this paper, a new structure of the six-port reflectometer is presented by using two microstrip three-section couplers. The six-port reflectometer was analyzed, simulated and then realized on teflon substrate at the operating frquency 3.5GHz. The six-port reflectometer was calibrated and then used to measure different unknown complex impedances. The measured results was found to be in good agreement with that obtained using the vector network analyzer with an error not exceeding 4% in magnitude and 4° in phase especially in the frequency range (2.5 up to 4.5 GHZ). This bandwidth is larger as compared to the six-port reflectometer realized by using two single-section couplers.

مقياس الإنعكاس ذو الستة منافذ بإستخدام
إثنين من المقرنات الشريطية ذات الثلاثة مقاطع

المقرن الإتجاهى الشريطى ذو المقطع الواحد يعيبه صغر عرض النطاق الترددى له ولزيادة عرض النطاق الترددى له يتم إستخدام المقرن الشريطى ذو الثلاثة مقاطع. فى هذه المقالة تم إستخدام إثنين من المقرنات ذات الثلاثة مقاطع لعمل مقياس إنعكاس ذو ستة منافذ. تم تصميم مقياس الإنعكاس ذو الستة منافذ على مادة التيفلون العازلة عند التردد العامل 3.5 جيجا هرتز. تم معايرة مقياس الإنعكاس ذو الستة منافذ بإستخدام حمل قياسى متوافق بالإضافة إلى ثلاثة أوضاع مختلفة لدائرة قصر كهربى متغيرة الطول ومن ثم تم الحصول على ثوابت المعايرة. كما تم قياس عدد من المعاوقات المركبة المجهولة باستخدام كلا من مقياس الإنعكاس ذو الستة منافذ والمحلل الشبكى الإتجاهى ووجدت النتائج متوافقة مع وجود نسبة خطأ لاتتجاوز 4% بالنسبة للمقدار و4 درجة لزاوية الطور فى النطاق الترددى (2.5–4.5 جيجا هرتز).

Introduction

The network analyzers based on the six-port technology[1]; Fig.1, was introduced as an alternative to the convential expensive network analyzers using heterodyning system. It is defined as a device which allows the phase and the magnitude of an unknown complex impedance to be measured directly at the operating frequency in terms of power measurements alone using standard impedances and a calibration procedure. The calibration procedure is carried out in order to take into consideration the imperfections of the reflectometer hardware and imperfect matching and isolation between different ports. The six-port reflectometer has many advantages such as, the absence of any need to frequency conversion and phase meters; the absence of electronic errors for all practical purposes; the ability to measure transmission characteristics by introducing a second six-port (dual six-port) and low price as compared to the vector network analyzer. The main disadvantage of the six-port reflectometer is the limited bandwidth, but this disadvantage can be overcome by using a number of six-port reflectometers operating at different frequencies with microprocessor control. The six-port reflectometers have different configurations [2]-[3], such as, a section of three coupled transmission lines, these lines may be waveguides, coaxial lines, striplines, microstrip lines; a system consists of four couplers, these couplers may be single-section couplers or three-section couplers; a five-port junction with a coupler; probes and directional couplers; a group of quadrature hybrids; a six-port magic junction; planar symmetric six-port junction, etc.

In this paper, the analysis and design of a new structure of the six-port reflectometer that is constructed from two three-section directional couplers are given. The three-section coupler, Fig.2, is a three-quarter wavelength coupler. The analysis is simplified when one recognizes that the coupler is analytically similar to the quarter-wave transformer [4]. Another method of the analysis is taking the advantage of the four fold symmetries of the structures, Fig.2, with the even and odd modes excitations technique [3],[5]. The designed six-port reflectometer was first simulated by (IE3D) ready made software package and then fabricated using the photolithographic technique and thin-film technology. The measured S-parameters were found to be in good agreement with the theoretical results. The six-port reflectometer was first calibrated using matched load and three positions of a sliding short circuit [6]-[8], so the calibration constants are obtained. Then, it was used to measure different unknown terminations and gave good agreement with the measurements of the vector network analyzer (HP8510C) within an acceptable error.

Analysis of the Three-Section Coupler

The analysis of the microstrip three-section coupler was done such that, the excitations are chosen [4], [5] where, the symmetry plane aa, Fig.2, corresponds to an electric wall (short circuit) or a magnetic wall (open circuit). The same is done for the case of symmetry plane bb. When bb corresponds to an electric wall, the mode of propagation on the coupled lines is the odd mode that has a characteristic impedance Z_{oo} and propagation constant β_o. When bb corresponds to a magnetic wall, the mode of propagation is the even mode that has a characteristic impedance Z_{oe} and propagation constant β_e. The propagation constants are different because the medium is nonhomogeneous. Due to symmetry, the outer sections of the three-section coupler are identical. By considering the four different excitations for the three-section coupler (considering ideal reflection and isolation), the transmission and coupling parameters are as follows:

$$S_{21} = S_{12} = -0.5(a_1 + a_2) - j(a_3 + a_4) \tag{1}$$

$$S_{41} = S_{14} = -0.5(a_1 - a_2) - j(a_3 - a_4) \tag{2}$$

where

$$a_1 = (g_{a1}^2 - g_{a2}^2)/(g_{a1}^2 + g_{a2}^2) \tag{3.a}$$

$$a_2 = (g_{c1}^2 - g_{c2}^2)/(g_{c1}^2 + g_{c2}^2) \tag{3.b}$$

$$a_3 = (g_{a1} g_{a2})/(g_{a1}^2 + g_{a2}^2) \tag{3.c}$$

$$a_4 = (g_{c1} g_{c2})/(g_{c1}^2 + g_{c2}^2) \tag{3.d}$$

$$g_{a1} = Z_C (Z_{oe1}^2 T_{e1}^2 T_{e2} - 2 Z_{oe1} Z_{oe2} T_{e1} - Z_{oe1}^2 T_{e2}) \tag{3.e}$$

$$g_{a2} = Z_{oe2} Z_{oe1}^2 T_{e1}^2 + 2 Z_{oe1}^3 T_{e1} T_{e2} - Z_{oe1}^2 Z_{oe2} \tag{3.f}$$

$$g_{c1} = Z_C (Z_{oo1}^2 T_{o1}^2 T_{o2} - 2 Z_{oo1} Z_{oo2} T_{o1} - Z_{oo1}^2 T_{o2}) \tag{3.g}$$

$$g_{c2} = Z_{oo2} Z_{oo1}^2 T_{o1}^2 + 2 Z_{oo1}^3 T_{o1} T_{o2} - Z_{oo1}^2 Z_{oo2} \tag{3.h}$$

$$T_{e1} = \tan(\beta_{e1} d_1),\ T_{e2} = \tan(\beta_{e2} d_2) \tag{3.i}$$

$$T_{o1} = \tan(\beta_{o1} d_1), T_{o2} = \tan(\beta_{o2} d_2) \quad (3.j)$$

where 1,2 refer to outer and center sections, respectively. The relations between the overall coupling coefficient (C_o), the coupling of the outer section (C_1), the coupling of the center section (C_2) and the characteristic impedances for each section are given by [4], [9]:

$$C_o = C_2 - C_1 \quad (4.a)$$

$$C_2 = 10C_1 \quad (4.b)$$

$$Z_{oei} = Z_c \sqrt{\frac{(1+C_i)}{(1-C_i)}} \qquad i=1,2 \quad (5.a)$$

$$Z_{ooi} = Z_c \sqrt{\frac{(1-C_i)}{(1+C_i)}} \qquad i=1,2 \quad (5.b)$$

The Three-Section Coupler Design Procedure

From the previous analysis, the design procedure for the three-section coupler can be summarized as follows:

1. Define the required overall coupling (C_o)
2. From Eq. (4), the corresponding values of the coupling coefficients for the center and the outer sections can be calculated
3. From Eq. (5), the even and odd mode characteristic impedances are evaluated, and then by using any ready-made software (such as APPCAD), the geometrical dimensions can be obtained namely W_i / H and S_i / H, d_i (i=1,2) where W_i is the width of the microstrip line, S_i is the separation between the coupled lines, d_i is the coupling length and H is the dielectric substrate thickness.
4. Using Eqs. (1)-(3), the S-parameters can be calculated.

The above procedure was used to design a -20 dB three-section coupler on Teflon substrate RT/Duroid 6006 (ε_r=6.15 , H=0.025") at 3.5 GHz center frequency. The even and odd mode impedances, the overall coupling coefficient and the geometrical dimensions for outer-section and center-section of the designed coupler were found to be as follows:

Outer Sections	Center Section
$Z_{oe1} = 50.62\Omega$	$Z_{oe2} = 56.665\Omega$
$Z_{oo1} = 49.38\Omega$	$Z_{oo2} = 44.118\Omega$
$C_1 = -38.13 dB$	$C_2 = -18.09 dB$
$W_1 = .928 mm$	$W_2 = .910 mm$
$S_1 = 3.841 mm$	$S_2 = .668 mm$
$d_1 = 7.295 mm$	$d_2 = 9.663 mm$

The three-section coupler was simulated using IE3D software package, and the simulated results are shown in Fig.3. From the simulated results, it is clear that each of the reflection coefficient (S_{11}) and the isolation coefficient (S_{31}) are less than -25dB over the whole operating range (2.5-4.5GHz). Also, the coupling coefficient (S_{41}) is around –20 dB along the operating bandwidth with maximum deviation of 0.5dB. From these results, it is clear that , the three-section coupler gives broader bandwidth when compared with the single section coupler.

Six-Port Reflectometer Theory

A six-port reflectometer was designed by using two of the above three-section couplers, Fig.4. By using the transmission and coupling coefficients $T_{on}e^{-j\theta_n}$ and $jC_{on}e^{-j\theta_n}$, respectively, for each directional coupler, n=1,2 and after mathematical manipulation, the power relationships will be as follow:

$$\frac{P_3}{P_4} = \left|\frac{V_3}{V_4}\right|^2 = \frac{C_{o1}}{C_{o2}} T_2^2 \left| \Gamma_L - \frac{1}{T_2^2} e^{j(2\theta_1 + 2\delta_1 + 2\delta_2 - 2\alpha_1)} e^{-j\beta} \right|^2 \quad (6)$$

where β is the electrical length of the sliding short circuit connected to port 2, θ is the total electrical length for each coupler and Γ_L is the reflection coefficient of the DUT. There are different solutions to make Eq.(6) suitable to represent three circles with uniform center distribution. By changing the lengths of the interconections between the two couplers (δ_1), between the second coupler and the DUT (δ_2) and the couplers connecting terminalss (α_1), different solutions can be obtained. As an example, take $\alpha_1 = \delta_1 = \delta_2 = \pi/2$ and $C_{o1} = C_{o2} = -20 dB$, then, Eq.(6) will be reduced to the following form:

$$\frac{P_3}{P_4} = 0.9801 \left| \Gamma_L - 1.020 e^{-j\beta} \right|^2 \quad (7)$$

By adjusting three positions for β such as ($\beta = 0^\circ, 120^\circ, 240^\circ$), we will have three equations each represent a circle with centers $(1.02,0)$, $(-0.51,-0.8833)$ and

$(-0.51, 0.8833)$, respectively. It is clear that, these centers are uniformly distributed around the origin, which is one of the required condition to have accurate measurements for the reflection coefficient when using the six-port reflectometer [3].

Six-Port Reflectometer Realization

The six-port reflectometer was fabricated on Teflon substrate RT/Duroid 6006 (ε_r=6.15, H=0.025") at 3.5 GHz center frequency (using the previous geometrical dimensions of the three-section coupler). The simulated and the measured S-parameters are illustrated in Figs.5-7. It is clear from these Figures that; the coupling coefficients (S_{21}), and (S_{41}) are around –20 dB with maximum deviation of 2.0 dB, while the reflection at input port (S_{11}) is less than -25 dB. Also good isolations (S_{31}, S_{51}) and transmission (S_{61}) were found.

Six-Port Reflectometer Calibration

By choosing three different values for β ($\beta_1 = 0^\circ, \beta_2 = 120^\circ$ and $\beta_3 = 240^\circ$), Eq.(7) can be rewritten in the form of the six-port reflectometer traditional equations as:

$$(P_3 / P_4)_{\beta_1} = |A|^2 |\Gamma_L + B|^2 \quad (8.a)$$

$$(P_3 / P_4)_{\beta_2} = |C|^2 |\Gamma_L + D|^2 \quad (8.b)$$

$$(P_3 / P_4)_{\beta_3} = |E|^2 |\Gamma_L + F|^2 \quad (8.c)$$

where A, B, C, D, E and F are the calibration constants. The six-port reflectometer was calibrated with four terminations (matched load and three positions of a sliding short circuit) connected to port 6, respectively, and at the same time, the power readings at ports 3 and 4 recorded for the three different values of β for each termination. By using the calibration procedure of [7]-[9], the calibration constants are calculated, Table (1). The realized six-port reflectometer and the vector network analyzer (HP8510C) were used to measure the same unknown terminations. The discripancy between both results did not exceed 4% in magnitude and 4° in phase especially in the operating band (2.5-4.5 GHz). Table (2) illustrates some of these results at the center frequency 3.5GHz as an example.

Comparsion with the six-port reflectometer of [10]

In [10], the author used four three-section directional coupler to construct the six-port reflectometer, while, in this paper we used only two three-section coupler. In fact, the use of four three-section couplers gives more redundant equations that help in getting more accurate solutions for the reflection coefficient. Obtaining three different positions for the sliding short circuit that are separted by 120° needs good experience, since the circle centers, that respresent the power ratios reading depend on these positions. Table (3) illustrates a comparison between the results obtained by the realized six-port reflectometer and that was presented in [10]. In this paper, the reduction in size is about 50% when compared with that of [10], and at the same time the reflection coefficient (S_{11}) is better. The errors in magnitude and phase angle for the realized six-port reflectometer did not exceed 4% and 4°, respectiveley.

Conclusion

The analysis of using two microstrip three-section directional couplers as a six-port reflectometer was illustrated. The six-port reflectometer was realized on Teflon Substrate RT/Duroid ($\varepsilon_r = 6.15, H = 0.025''$) at 3.5 GHz and then calibrated using a perfect matched load and three different positions of a sliding short circuit. The measurements of the realized six-port reflectometer gave good agreement with that obtained using the vector network analyzer with errors not exceeding 4% in magnitude and 4° in phase especially in the frequency range (2.5-4.5 GHz).

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Figures

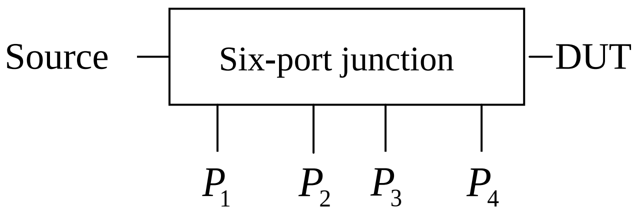

Fig.1 Six-port reflectometer

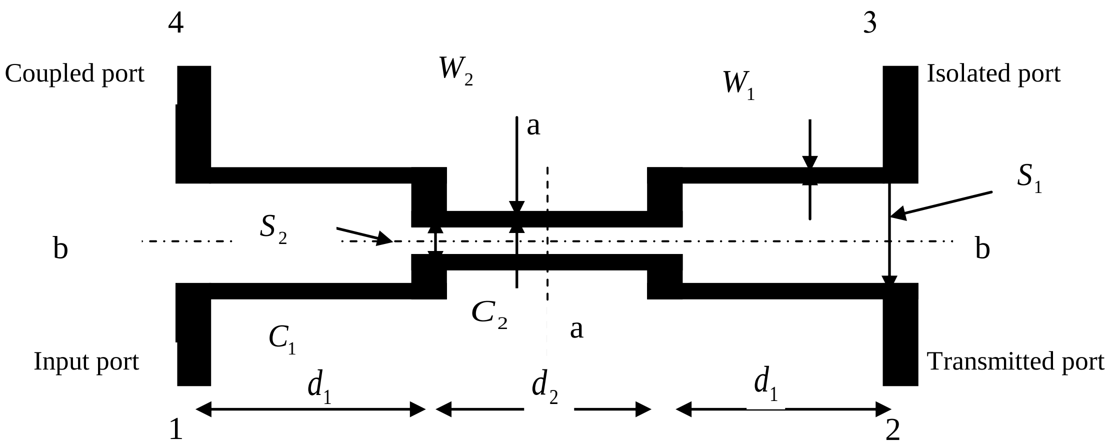

Fig.2 The three-section microstrip coupler

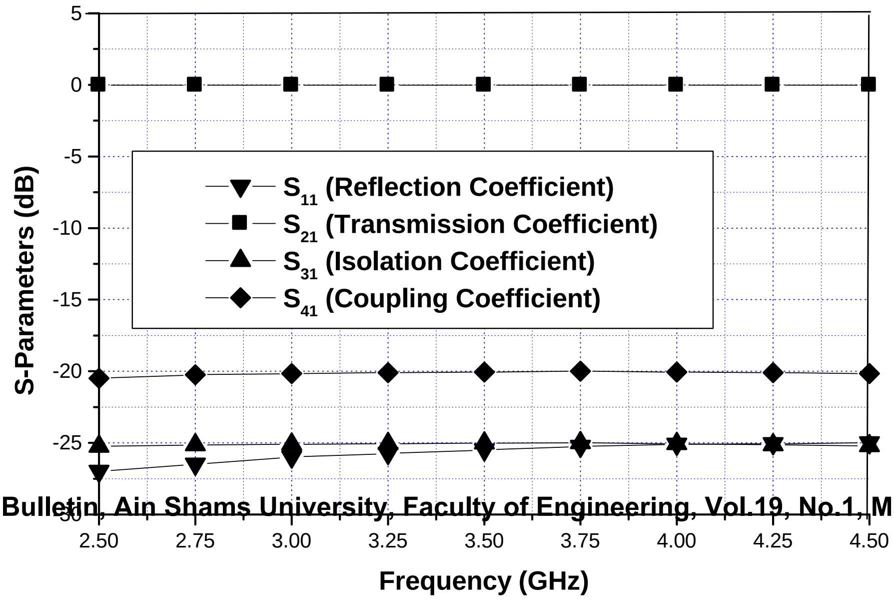

Fig.3 The simulated S-parameters for the microstrip three-section coupler

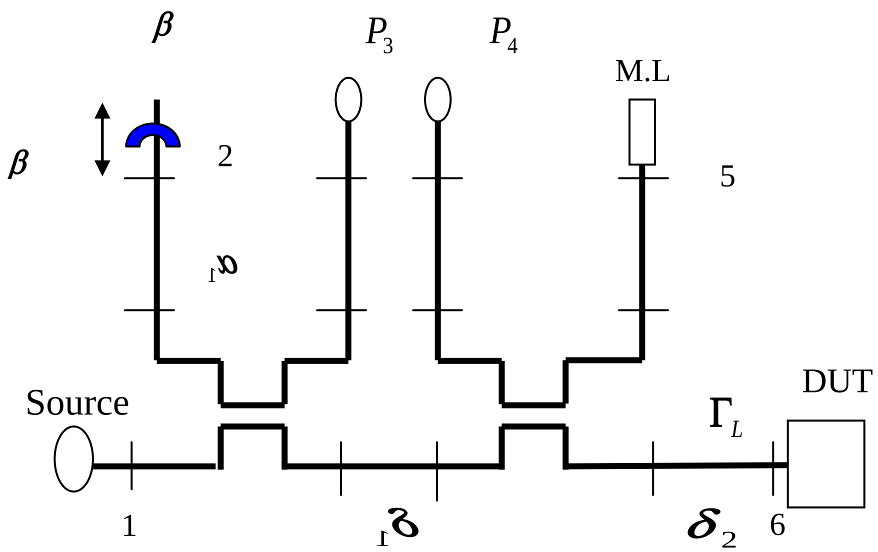

Fig.4 Six-port reflectometer using two microstrip three-section couplers

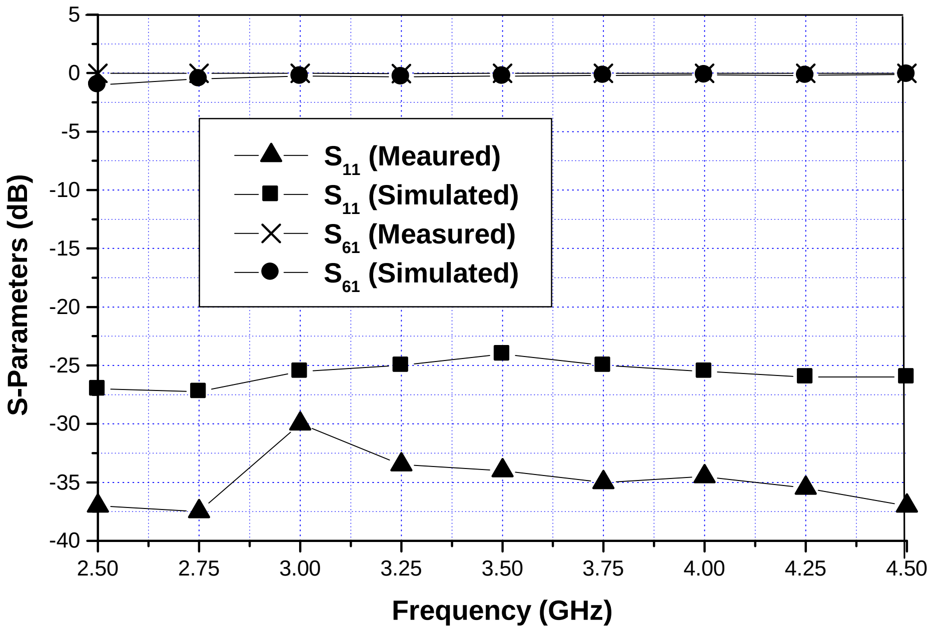

Fig.5 The measured and simulated S_{11} and S_{61} for the realized six-port reflectometer

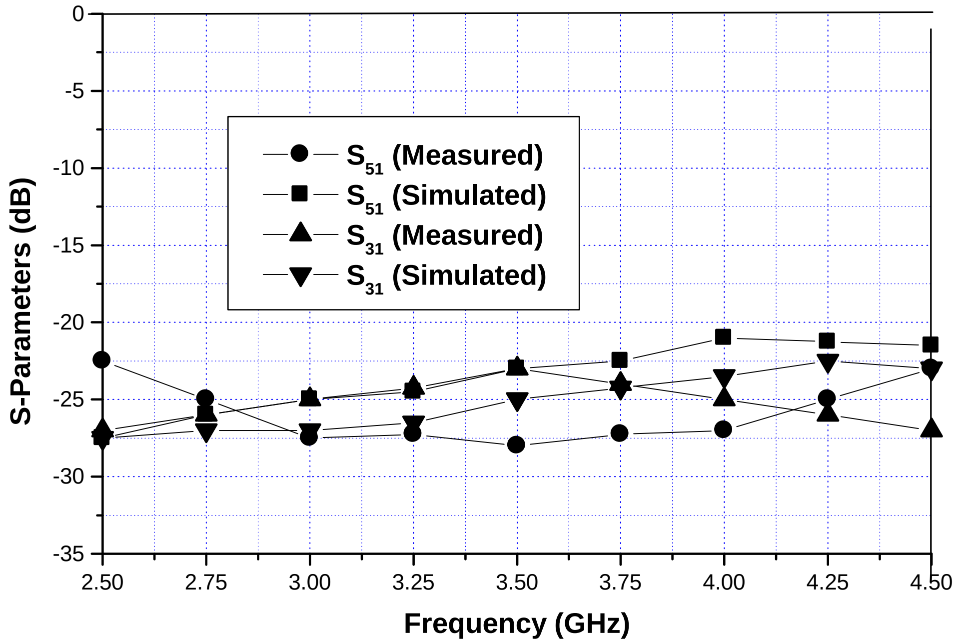

Fig.6 The measured and simulated S_{51} and S_{31} for the realized six-port reflectometer

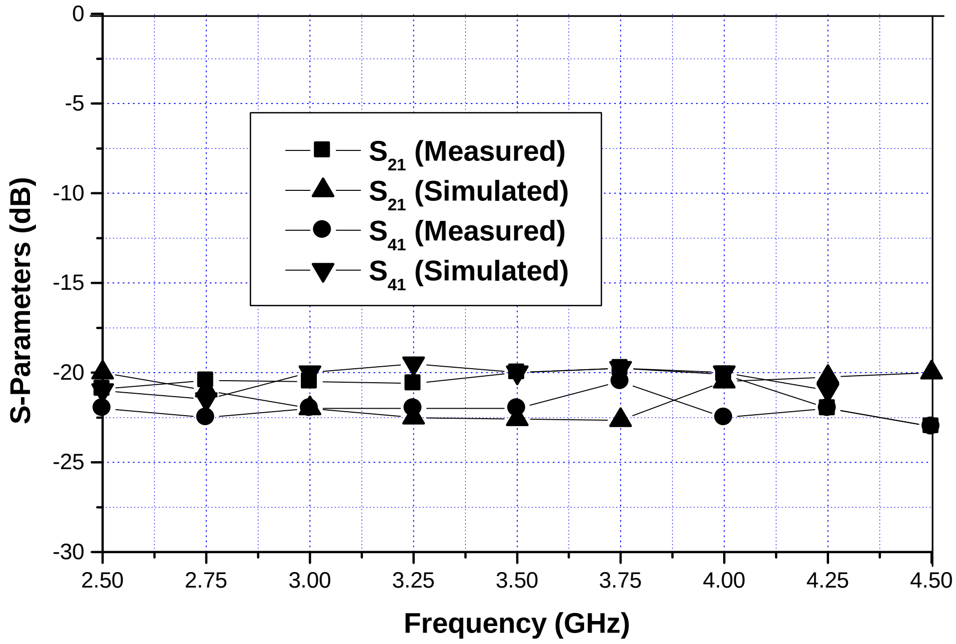

Fig.7 The measured and simulated S_{21} and S_{41} for the realized six-port reflectometer

Table (1) Calibration constants at F=3.5 GHz

$\|A\|$ =0.123585	B=-0.25355-J0.35255
$\|C\|$ =0.523571	D=-2.353251+J2.3537
$\|E\|$ =0.235184	F=3.525157-J2.53468

Table (2) Comparison between the results at

Load	Network analyzer	Realized Six-port reflectometer	Six-port reflectometer at [10]
50 ohm +3dB att.	0.0061∠-28.5	0.0059∠-30.5	0.0062∠-29.5
Sliding short circuit	0.95321∠169.43 0.88352∠177.15 0.96271∠-12.52 0.92157∠155.35 0.91426∠-19.28 0.92517∠-20.5	0.96716∠172.52 0.90260∠179.26 0.95169∠-9.55 0.93861∠153.98 0.90364∠-21.16 0.94515∠-17.3	0.94523∠170.75 0.87352∠175.23 0.95276∠-10.50 0.91157∠153.53 0.91899∠-20.22 0.91573∠-22.50

Table (3) The difference between the results of the realized six-port reflectometer and that of reflectometer at [10]

Item to be compared	Realized six-port Reflectometer	Six–port reflectometer of [10
Number of required couplers	2	4
Number of sliding short circuits	1	2
Number of fixed short circuit	----	1
Number of power meter	2	4
Reflection coefficient (S_{11}), dB	<-30	<-15
Error in magnitude of unknown termination	4%	3%
Error in phase of unknown termination	4°	2.8°
Reduction in size	50% relative to [10]	