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Six-Port Reflectometer Realization using Two Microstrip Three-Section Couplers

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Abstract

The single-section couplers are narrow band devices, so in order to broaden the useful bandwidth, three-section couplers are used. In this paper a system of two of three-section couplers is used to construct a six-port reflectometer. The realized six-port reflectometer is calibrated and used to measure different unknown complex terminations. The results of the six-port reflectometer is found to be in good agreement with the measurements of the vector network analyzer (HP-8510C) with an error not exceeding 4% in magnitude and 4° in phase in the frequency range (2.4-4.4GHZ).

1.Introduction

The three-section coupler is a three-quarter wavelength coupler. The analysis is simplified somewhat when one recognizes that the coupler is analytically similar to the quarter-wave transformer [1-2]. Another way of the analysis of the three-section coupler is carried out by taking the advantages of the four fold symmetries of the structures, Fig.1, and the even and odd mode excitations technique[3]. A six port reflectometer is analyzed and designed by using two of the prescribed three-section coupler. The system was first simulated by ready-made software package and then fabricated and tested. The measured S-parameters gave good agreement with the theoretical one. The six-port was calibrated with a matched load and three positions of a sliding short circuit [4] in order to obtain the calibration constants.

2.Analysis and Design of a Three-Section Coupler

Excitations are chosen [3] so that the symmetry plane aa, Fig.1, corresponds to an electric wall (short circuit) or a magnetic wall (open circuit). The same is done for the case of symmetry plane bb corresponding to an electric or magnetic wall. 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. By considering the four different excitations for the three-section coupler and after some derivations the transmission and coupling parameters are [3]:

$$S_{21} = S_{12} = -0.5\left[\frac{g_{a1}^2 - g_{a2}^2}{g_{a1}^2 + g_{a2}^2} + \frac{g_{c1}^2 - g_{c2}^2}{g_{c1}^2 + g_{c2}^2}\right] - j\left[\frac{g_{a1}g_{a2}}{g_{a1}^2 + g_{a2}^2} + \frac{g_{c1}g_{c2}}{g_{c1}^2 + g_{c2}^2}\right] \qquad (1)$$

$$S_{41}=S_{14}=-0.5\left[\frac{g_{a1}^2-g_{a2}^2}{g_{a1}^2+g_{a2}^2}-\frac{g_{c1}^2-g_{c2}^2}{g_{c1}^2+g_{c2}^2}\right]-j\left[\frac{g_{a1}g_{a2}}{g_{a1}^2+g_{a2}^2}-\frac{g_{c1}g_{c2}}{g_{c1}^2+g_{c2}^2}\right] \quad (2)$$

where

$$g_{a1}=Z_c(Z_{oe3}^2T_{e1}T_{e2}T_{e3}-Z_{oe2}Z_{oe3}T_{e1}-Z_{oe1}Z_{oe2}T_{e3}-Z_{oe1}Z_{oe3}T_{e2})$$
(3.a)

$$g_{a2}=Z_{oe2}Z_{oe1}^2T_{e1}T_{e3}+Z_{oe1}^2Z_{oe3}T_{e1}T_{e2}+Z_{oe3}^2Z_{oe1}T_{e2}T_{e3}-Z_{oe1}Z_{oe2}Z_{oe3} \quad (3.b)$$

$$g_{c1}=Z_c(Z_{oo3}^2T_{o1}T_{o2}T_{o3}-Z_{oo2}Z_{oo3}T_{o1}-Z_{oo1}Z_{oo2}T_{o3}-Z_{oo1}Z_{oo3}T_{o2}) \quad (3.c)$$

$$g_{c2}=Z_{oo2}Z_{oo1}^2T_{o1}T_{o3}+Z_{oo1}^2Z_{oo3}T_{o1}T_{o2}+Z_{oo1}Z_{oo3}^2T_{o2}T_{o3}-Z_{oo1}Z_{oo2}Z_{oo3} \quad (3.d)$$

$$T_{e1}=\tan(\beta_{e1}d_1),\ T_{e2}=\tan(\beta_{e2}d_2),\ T_{e3}=\tan(\beta_{e3}d_3) \quad (3.e)$$

$$T_{o1}=\tan(\beta_{o1}d_1),\ T_{o2}=\tan(\beta_{o2}d_2),\ T_{o3}=\tan(\beta_{o3}d_3) \quad (3.f)$$

The relations between the overall coupling coefficients (C_o) and the outer and center coupling coefficients (C_1, C_2) and characteristic impedances are [3]:

$$C_o=C_2-2C_1 \quad (4.a)$$

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

$$Z_{oe_i}=Z_c\sqrt{\frac{1+C_i}{1-C_i}},\quad Z_{oo_i}=Z_c\sqrt{\frac{1-C_i}{1+C_i}},\ i=1,2 \quad (5)$$

Design procedure

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 characteristic impedances are obtained
4. Using any ready-made software, the corresponding physical dimensions can be calculated
5. From Eqs. (1-2), the S-Parameters can be calculated.

The above analysis was used to evaluate a -20 dB three-section maximally flat coupler on RT/Duroid 6006 (ε_r=6.15 , H=0.025") at 3.4 GHz as a center frequency, by using some relations [3] and a ready-made software, the following results are obtained:

Outer Sections	Center Section
$Z_{oe1}=50.62\Omega$	$Z_{oe2}=56.665\Omega$
$Z_{oo1}=49.38\Omega$	$Z_{oo2}=44.118\Omega$
$C_1=-38.13dB$	$C_2=-18.09dB$
$W_1=.928mm$	$W_2=.910mm$
$S_1=3.841mm$	$S_2=.668mm$
$L_1=d_1=7.295mm$	$L_2=2d_2=9.663mm$

3.Six-Port Reflectometer Theory

A six-port reflectometer was designed by using two of the above three-section couplers, Fig.2 each has -20 dB as a coupling coefficient. By using the transmission and coupling relations ($T_n e^{-j\theta_n}$ and $jC_n e^{-j\theta_n}$, respectively, for each directional coupler, n=1,2) and after some mathematical simplification, Fig.2, the power relationships obtained as follow:

$$\frac{P_3}{P_4} = \left|\frac{V_3}{V_4}\right|^2 = \frac{C_1}{C_2} T_2^2 \left|\Gamma_L - \frac{1}{T_2^2} e^{j(2\theta_1+2\delta_1+2\delta_2-2\alpha_1)} e^{-j\beta}\right|^2 \qquad (6)$$

where β is the value of the sliding short circuits connected at port 2 and Γ_L is the reflection coefficient of the DUT port. There are different solutions to make these relationships suitable to represent the six-port reflectometer idea with changing the lengths of the connection between the two couplers (δ_1, δ_2), and the couplers connecting ends (α_1) by taking:

$\alpha_1 = \delta_1 = \delta_2 = \pi/2$ and $C_1 = C_2 = -20dB$

Then, (6) can be reduced to:

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

By choosing three values of β (0,120,240°) three equations of the form of (7) will be obtained and the centers of the circles represented by these equations are: (1.02,0), (−0.51,−0.8833) and (−0.51,0.8833) respectively. Clearly, these centers are uniformly distributed around the origin.

4.Six-Port Reflectometer Realization

Two three-section couplers arranged as shown in Fig.2 are used to construct a six-port reflectometer, in which a sliding short circuit connected to ports 2, two power meters connected to ports 3 and 4, a matched load (50 ohm) connected to port 5, while the source connected to port 1 and the DUT to port 6. The system was realized on RT/Duroid 6006 (ε_r=6.15 , H=0.025") at 3.4 GHz center frequency, Fig.3. The Simulated (simulated by IE3D software package) and the measured S-parameters (Using HP8510C at National Institute for Standards (NIS)) are illustrated in Figs.4-6. It is clear from these figures that, the coupling coefficients S12, S14 varied around -20 dB by 1 dB, while the reflection at input port is around -25 dB or less. Also good isolations and transmission were obtained.

5.Six-port Reflectometer Calibration

With choosing suitable three different values of β, (7) could be rewritten in the form of the six-port traditional equations as:

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

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

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

where A, C and E are three real calibration constants and B, D and F are the corresponding three complex calibration constants. The six-port reflectometer was calibrated with a matched load in addition to three positions of a sliding short circuit connected to the DUT port, respectively, and at the same time the power readings at ports 3 and 4 recorded for the three different values of β. The calibration constants calculated by using the calibration procedure of [3-5]. The realized system was used to measure different unknown terminations and the same unknowns measured using vector network analyzer (HP 8510C) at NIS. The realized system gave good results with error not exceeding 4% in magnitude and 4° in phase in the operating band (2.4-4.4GHz). A comparison between measurements at 3.4 GHz is illustrated in Table-1 as an example.

Table 1 Comparison between 6PR&VNA measurements at F=3.4 GHZ

Load Type	Six-port reflectometer	Vector Network analyzer
Sliding short circuit positions	0.96716∠172.52	0.95321∠169.43
	0.90260∠179.26	0.88352∠177.15
	0.95169∠-9.55	0.96271∠-12.52
	0.93861∠153.98	0.92157∠155.35
	0.90364∠-21.16	0.91426∠-19.28
	0.94515∠-17.3	0.92517∠-20.5

6.Conclusion

The analysis of using two microstrip three-section couplers as a six-port reflectometer is illustrated. The system is realized on Teflon substrate RT/Duroid ($\varepsilon_r = 6.15, H = 0.025"$) at 3.4 GHz as center frequency and then calibrated with perfect matched termination and different three positions of a sliding short circuit so, the calibration constants could be calculated. The measurements of the six-port reflectometer gave good agreement with the measurements of the vector network analyzer (HP8510C) with errors not exceeding 4% in magnitude and 4° in phase especially in the frequency range (2.4-4.4 GHz).

References

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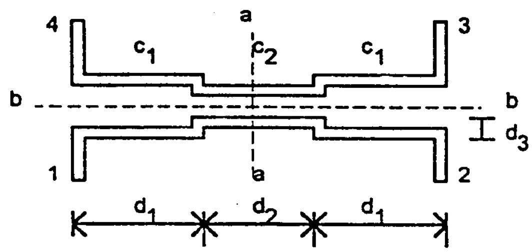

Fig.1 Three sections coupler

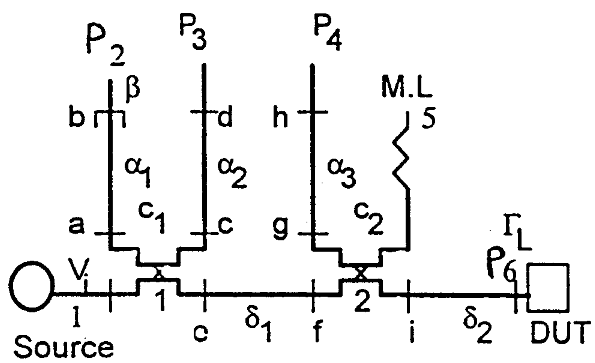

Fig.2 Six-port reflectometer consisting of two three-section couplers

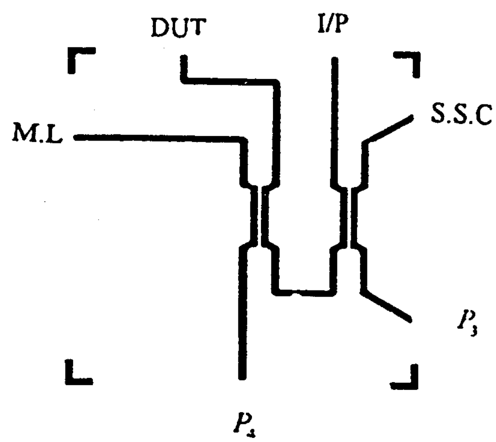

Fig.3 The realized six-port reflectometer (scale 1:1)

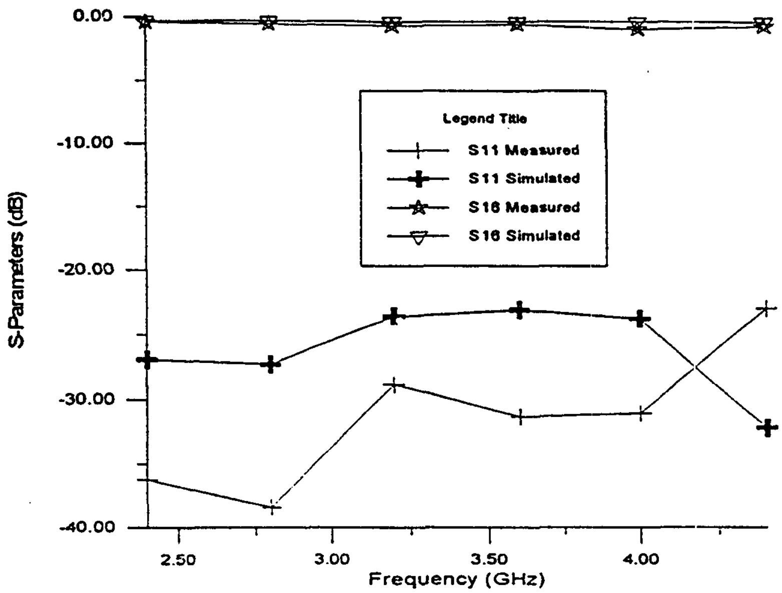

Fig.4 The measured and simulated S11, S16 Parameters.

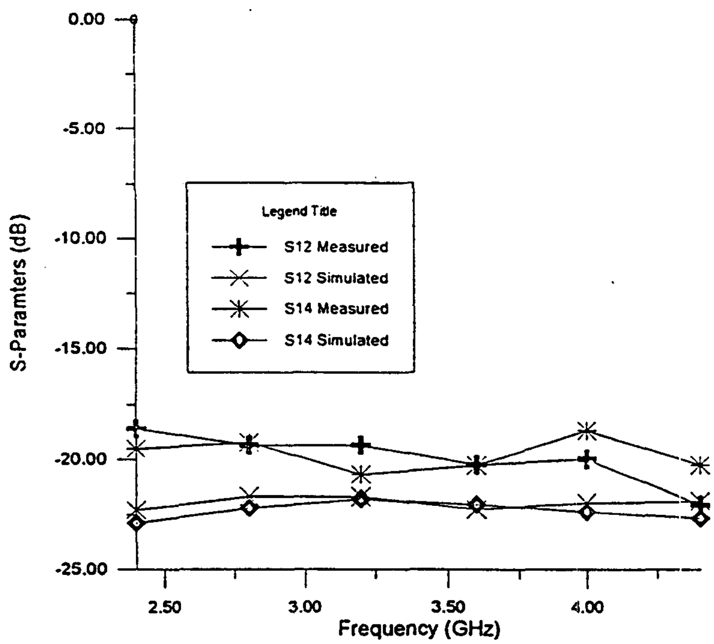

Fig.5 The measured and simulated S12, S14 Parameters.

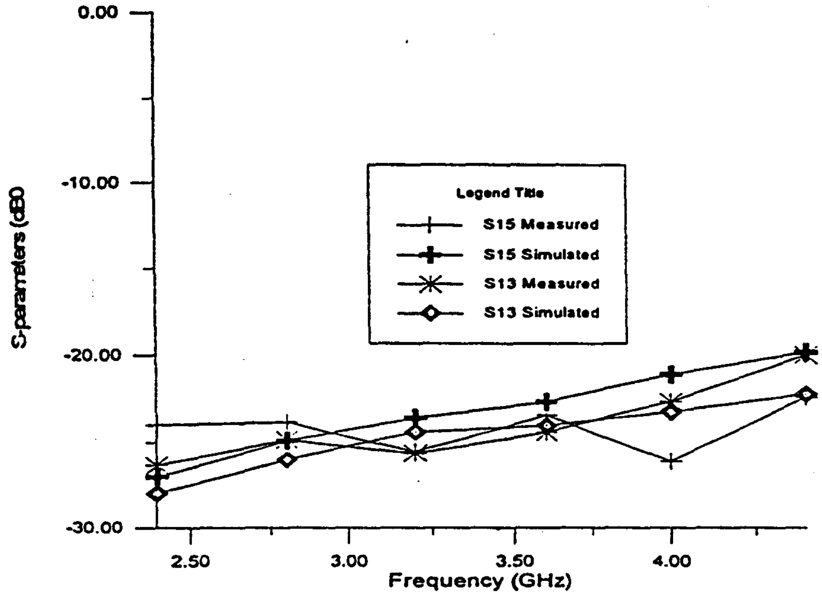

Fig.6 The measured and simulated S13, S15 Parameters.