Properties of the Symmetrical Five-Port Circuit and Its Broad-Band Design

DONG IL KIM, STUDENT MEMBER, IEEE, KIYOMICHI ARAKI, AND YOSHIYUKI NAITO, SENIOR MEMBER, IEEE

Abstract—The properties of the mismatched symmetrical five-port circuit are discussed, i.e., the equations for the maximum and minimum couplings of a mismatched symmetrical five-port circuit are derived by appropriate approximations. The approximate equations for the maximum and minimum phase differences due to mismatches of a symmetrical five-port circuit are also derived.

Furthermore, a broad-band design theory of a symmetrical five-port circuit with microstrip line is proposed by applying a matching technique which adds a generalized compensating network and matching sections to the fundamental symmetrical five-port circuit. Thus, the bandwidth of the proposed broad-band symmetrical five-port circuit extends to about an octave. The experimental verification has been achieved, and, hence, the validity of the design method is confirmed.

I. INTRODUCTION

RECENTLY, IT WAS proposed that the matched symmetrical five-port circuit could be a very useful component for a six-port network analyzer (six-port measurements), and the basic properties and experimental results for six-port measurements consisting of a matched symmetrical five-port circuit and a directional coupler were reported [1]–[3]. But the detailed analysis for the symmetrical five-port circuit itself was not carried out. While, for the perfectly matched five-port circuit, it is well known that the input power is divided into the other four ports with 6 dB in equal ratios and that the phase differences between the adjacent ports are ±120° [1], [2], [4], it has not been analyzed for a mismatched symmetrical five-port circuit.

On the other hand, there have been proposed symmetrical five-port circuits with planar circuit [1], [2], and with microstrip line [5]. But, for the case with microstrip line, the concrete design theory, optimum circuit parameters, and frequency characteristics are not reported in [5]. Therefore, the broad-band design theory for the symmetrical five-port circuit with microstrip line is not rigidly established, so far.

In this paper, firstly, the properties of the mismatched symmetrical five-port circuit are analyzed in terms of the couplings and phase differences between the adjacent ports. Secondly, the broad-band design method for a symmetrical five-port circuit with microstrip line is presented concretely. As a result, the bandwidth was broadened to an octave by adopting a technique which adds a generalized compensating network and two matching sections to the fundamental symmetrical five-port circuit.

Manuscript received April 4, 1983; revised August 3, 1983.
The authors are with the Department of Electrical and Electronic Engineering, Tokyo Institute of Technology, Meguro-ku, Tokyo 152, Japan.

II. DEVIATIONS OF COUPLINGS AND PHASE DIFFERENCES DUE TO MISMATCH

In the case that the symmetrical five-port circuit is perfectly matched, the input power is split into the four ports, with 6 dB each, when one port is excited. But, when the five-port circuit is mismatched, deviations of couplings occur. The variations of the couplings are found as follows.

The relations between the elements of the scattering matrix S_{ij} and the eigen reflection coefficients Γ_k for the symmetrical five-port circuit are given by

$$\begin{aligned} 5S_{11} &= \Gamma_0 + 2(\Gamma_1 + \Gamma_2) \\ 5S_{12} &= \Gamma_0 + 2\cos(2\pi/5)\Gamma_1 + 2\cos(4\pi/5)\Gamma_2 \\ 5S_{13} &= \Gamma_0 + 2\cos(4\pi/5)\Gamma_1 + 2\cos(2\pi/5)\Gamma_2. \end{aligned} \tag{1}$$

Assuming the losslessness of the circuit and the eigen reflection coefficients as

$$\begin{aligned} \Gamma_0 &= e^{j\theta_0} \\ \Gamma_1 &= e^{j(\theta_0+\theta+\Delta\theta)} \\ \Gamma_2 &= e^{j(\theta_0+\theta-\Delta\theta)} \end{aligned} \tag{2}$$

then

$$5S_{11} = \{1 + 4(\cos\theta\cos\Delta\theta + j\sin\theta\cos\Delta\theta)\}e^{j\theta_0} \tag{3a}$$

or

$$\cos\theta = \frac{25|S_{11}|^2 - 1 - 16\cos^2\Delta\theta}{8\cos\Delta\theta}. \tag{3b}$$

The relations to $|S_{12}|$ and $|S_{13}|$ are derived by substituting (3b) into (1) as follows:

$$|S_{12}|^2 = \frac{1-|S_{11}|^2}{4} \mp \frac{2\sqrt{5}}{25}\sin\theta\sin\Delta\theta \tag{4a}$$

$$|S_{13}|^2 = \frac{1-|S_{11}|^2}{4} \pm \frac{2\sqrt{5}}{25}\sin\theta\sin\Delta\theta. \tag{4b}$$

Since $|\cos\theta| \leqslant 1$, the extent of $\cos\Delta\theta$ is determined from (3b) as

$$\frac{1-5|S_{11}|}{4} \leqslant \cos\Delta\theta \leqslant \frac{1+5|S_{11}|}{4}. \tag{5}$$

Then, the couplings can be calculated by (4). Fig. 1 shows the coupling variations between adjacent parts for sample values of $|S_{11}|$ when the symmetrical five-port is mismatched.

Considering the case that $|S_{11}| < 1/5$, we can get (6) from (3b)

$$|\cos\theta| = \frac{1-25|S_{11}|^2}{8\cos\Delta\theta} + 2\cos\Delta\theta \geqslant \sqrt{1-25|S_{11}|^2}. \tag{6}$$

0018-9480/84/0100-0051$01.00 ©1984 IEEE

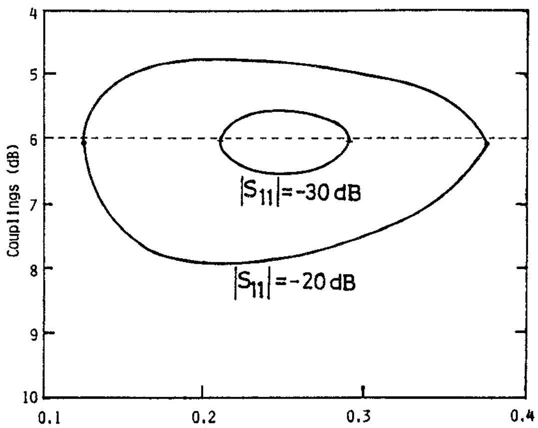


Fig. 1. Coupling deviations when mismatched.

TABLE I
MAXIMUM AND MINIMUM VALUES OF COUPLINGS DUE TO MISMATCH

$\|S_{11}\|$	$\|S_{12}\|_{max}$ or $\|S_{13}\|_{max}$ approx.	$\|S_{12}\|_{max}$ or $\|S_{13}\|_{max}$ exact	$\|S_{12}\|_{min}$ or $\|S_{13}\|_{min}$ approx.	$\|S_{12}\|_{min}$ or $\|S_{13}\|_{min}$ exact
-15dB	4.002dB	3.982dB	10.550dB	10.755dB
-20	4.761	4.751	7.935	7.955
-25	5.259	5.257	6.979	6.982
-30	5.573	5.573	6.529	6.530
-40	5.873	5.873	6.174	6.174

Therefore

$$\sin\theta|_{max} = 5|S_{11}|$$
$$\sin\theta|_{min} = -5|S_{11}| \qquad (7)$$

since

$$\cos\theta|_{min} = \sqrt{1-25|S_{11}|^2}.$$

Assuming that $|S_{11}|$ is sufficiently small and $\sin\Delta\theta \simeq \sqrt{15}/4$, then we can get

$$|S_{12}|^2_{max} \simeq \frac{1-|S_{11}|^2}{4} + \sqrt{\frac{3}{2}}|S_{11}|$$
$$|S_{12}|_{min} \simeq \frac{1-|S_{11}|^2}{4} - \sqrt{\frac{3}{2}}|S_{11}|. \qquad (8)$$

The maximum and minimum values of $|S_{13}|$ are also found in the same manner as the above. Note that $|S_{13}|$ has a minimum value when $|S_{12}|$ has a maximum value, and vice versa. Hence, the maximum and minimum couplings of the mismatched symmetrical five-port circuit are calculated by (4) exactly and (8) approximately. Table I shows the maximum and minimum couplings calculated exactly and approximately by (4) and (8), respectively. Here we can see that the above approximations are quite valid, and, hence, approximated values of the maximum and minimum couplings agree well with the exact values.

Now we consider the phase difference between the adjacent ports due to mismatches of a symmetrical five-port. The phase difference between the adjacent ports $\phi(=\angle S_{12} - \angle S_{13})$ equals $\pm 120°$ when the five-port circuit is perfectly matched. But the mismatches of the five-port cause deviations of the difference between the adjacent ports from $\pm 120°$, and the phase difference between the adjacent ports can be calculated exactly as follows:

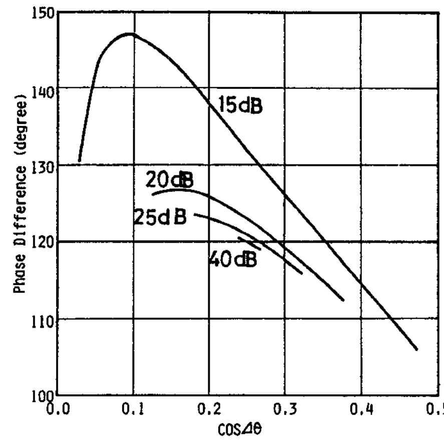


Fig. 2. Phase differences between adjacent ports when mismatched.

$$\phi = \tan^{-1}\left\{\frac{\sqrt{5}\cos\theta\sin\Delta\theta - \sin\theta\cos\Delta\theta}{1-\sqrt{5}\sin\theta\sin\Delta\theta - \cos\theta\cos\Delta\theta}\right\}$$
$$-\tan^{-1}\left\{\frac{-\sqrt{5}\cos\theta\sin\Delta\theta - \sin\theta\cos\Delta\theta}{1+\sqrt{5}\sin\theta\sin\Delta\theta - \cos\theta\cos\Delta\theta}\right\}. \qquad (9)$$

If the degree of mismatch $|S_{11}|$ is given, the extent of $\cos\Delta\theta$ is determined from (5) and $\cos\theta$ from (3b), and then the phase difference between adjacent ports can be calculated by (9). Fig. 2 shows the phase differences for sample values of $|S_{11}|$.

Since (9), however, is very complicated, it is very difficult to anticipate the extent of the phase differences when the reflection level $|S_{11}|$ is given. Assuming that the tolerance limit of the reflection level $|S_{11}|$ of the five-port circuit is below -20 dB, i.e., $|S_{11}|$ is sufficiently small, the maximum and minimum values of the phase difference are located at both ends of the range of $\cos\Delta\theta$, as was shown in Fig. 2. The phase differences at the edges are as follows;

$$\phi = -2\tan^{-1}\left\{\frac{\sqrt{3+2|S_{11}|+5|S_{11}|^2}}{1-|S_{11}|}\right\} \text{ at } \cos\Delta\theta = \frac{1-5|S_{11}|}{4} \qquad (10a)$$

$$\phi = -2\tan^{-1}\left\{\frac{\sqrt{3-2|S_{11}|-5|S_{11}|^2}}{1+|S_{11}|}\right\} \text{ at } \cos\Delta\theta = \frac{1+5|S_{11}|}{4}. \qquad (10b)$$

Approximately, then, we can replace (10a) and (10b) as the maximum and minimum values of the phase differences, respectively, and by further approximations, the following equations are obtained:

$$\phi_{max} \simeq \frac{2\pi}{3} + \frac{2}{\sqrt{3}}|S_{11}| \quad \text{(rad)}$$
$$\phi_{min} \simeq \frac{2\pi}{3} - \frac{2}{\sqrt{3}}|S_{11}| \quad \text{(rad)}. \qquad (11)$$

TABLE II
MAXIMUM AND MINIMUM VALUES AND THEIR DIFFERENCES OF PHASE DIFFERENCES BETWEEN ADJACENT PORTS DUE TO MISMATCH

$\lvert S_{11}\rvert$	$\cos\Delta\theta$	ϕ_{max} and ϕ_{min}		$\Delta\phi$	
		approx.	exact	approx.	exact
-20dB	0.125	126.62°	*126.22°	13.23°	14.20°
	0.159	-	127.09		
	0.375	113.38	112.89		
-30dB	0.2105	122.09	122.05	4.18	4.19
	0.2895	117.91	117.86		
-40dB	0.2375	120.66	120.66	1.32	1.33
	0.2625	119.34	119.33		

*It is not the maximum value exactly.

The difference $\Delta\phi$ of ϕ_{max} and ϕ_{min} is

$$\Delta\phi = \frac{4}{\sqrt{3}}|S_{11}| \qquad \text{(rad)}. \tag{12}$$

Therefore, ϕ_{max}, ϕ_{min}, and $\Delta\phi$ can be expressed by (11) and (12) in very simple and concise forms. Table II shows the maximum and minimum values and their difference for the phase differences between the adjacent ports due to mismatches of a symmetrical five-port circuit. From Table II, we can see that the values of phase differences calculated by (11) and (12) agree well with the exact values, and, hence, it is confirmed that the above approximations are reasonable.

III. BROAD-BAND DESIGN OF SYMMETRICAL FIVE-PORT CIRCUIT WITH MICROSTRIP LINE

The simplest symmetrical five-port circuit with microstrip line is shown in Fig. 3, which operates as a matched one at the center frequency when the normalized characteristic admittance Y is 1.1 and the section length l is 0.211 λ_g on the ring. The frequency characteristics of the circuit with $Y=1.1$ and $l=0.211\ \lambda_g$ are shown in Fig. 4, and with any other circuit parameters the frequency characteristics of the circuit are worse than those with $Y=1.1$ and $l=0.211\ \lambda_g$. The circuit shown in Fig. 3 is referred to as *the fundamental symmetrical five-port circuit* with microstrip line since it is the simplest and optimized one in circuit parameters.

In general, it is required in the actual characteristics of a circuit that the reflection or couplings are to be within certain tolerance limits over a broad frequency band even though the circuit may not operate perfectly at the center frequency. Throughout this paper, we take the tolerance limit of -20 dB for maximum reflection because the extents of the couplings and the phase differences between the adjacent ports are given by the reflection levels as was shown in Section II. From the above point of view, the bandwidth of the fundamental symmetrical five-port circuit extends only to 10 percent. If broad bandwidth is required in its application, e.g., in the case of use in six-port measurements, it is needed to broaden the bandwidth of the fundamental symmetrical five-port circuit or to change the circuit form.

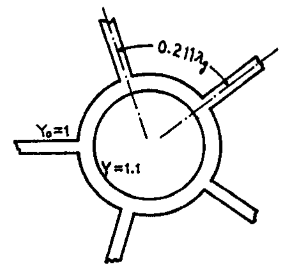


Fig. 3. Configuration of the fundamental symmetrical five-port circuit.

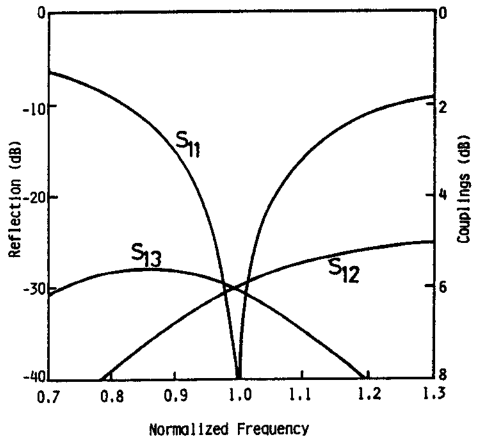


Fig. 4. Response curves for the fundamental symmetrical five-port circuit.

Considering the required characteristics of the circuit including broadbanding, we define an evaluation function F as follows:

$$F = \sum_{j=1}^{N} a_j \left\{ |S_{11}|^2 + \left(|S_{12}|+0.5\right)^2 + \left(|S_{13}|-0.5\right)^2 \right\}_{f_j} \tag{13}$$

where N is the number of sampling points, f_j's are the sampled normalized frequencies, and a_j's are the weighting coefficients for broad-band design. Thus the values of the circuit parameters can be obtained numerically so as to minimize F and broaden the bandwidth as much as possible where the responses of the circuit are within the extent of the given tolerance limits. Powell's minimizing method [6] was used for the above optimization. This optimization method was proposed in [7] and [8], by which excellent designs of directional couplers and power dividers were obtained.

First, to broaden the bandwidth of the fundamental symmetrical five-port circuit, we calculated the equivalent admittance Y_{eq} [2], [9], [10] for the fundamental symmetrical five-port circuit, which is shown in Fig. 5. The equivalent admittance has the property that if a two-port matching network matches into this admittance, then the same network connected at each port will match the five-port circuit. It is well known [10], [11] that quarter-wave matching sections are very effective to match the circuit with the equivalent admittance as was shown in Fig. 5. Hence, we performed optimization for the circuit to which the double quarter-wave matching sections are added. The optimum circuit parameters are obtained as shown in Table III,

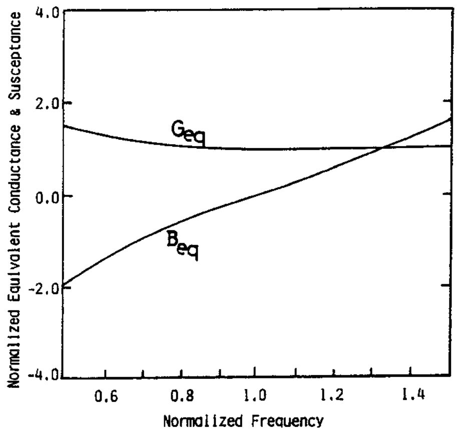


Fig. 5. Equivalent admittance for the fundamental five-port circuit ($Y_{eq} = G_{eq} + jB_{eq}$).

TABLE III
OPTIMUM CIRCUIT PARAMETERS WHEN TWO QUARTER-WAVE MATCHING SECTIONS ARE ADDED

Section	Characteristic Admittance/Y_0	Section's Length/λ_g
on the Ring	3.0	0.2103
1st Matching Section	1.561	0.25
2nd Matching Section	0.872	0.25

where the normalized characteristic admittance Y on the ring is specified as an easily fabricable value in advance. It is the same reason as the case of [7]. The frequency characteristics for the optimized symmetrical five-port circuit with the parameters shown in Table III are shown in Fig. 6. Here, we can see that adding quarter-wave sections to the fundamental symmetrical five-port circuit is quite effective for broadbanding, but the bandwidth cannot exceed the limit of about 35 percent in the case of adding double quarter-wave matching sections.

Since it is recognized from the above investigation that there exists a bandwidth limit of about 35 percent in the case of adding quarter-wave matching sections only, we tried to add a generalized compensating circuit which has couplings between the adjacent ports. Therefore, we constructed the compensating network as shown in Fig. 7. Fig. 8 shows the equivalent circuit for the eigen excitation to a symmetrical circuit like a circulator or a five-port circuit after adding a generalized compensating network. Here, Y_i is the eigen admittance for the fundamental or original circuit, Y_i^l is the effective eigen admittance for the admittance Y_l between adjacent ports, and Y_r is the common admittance for each eigen excitation. Let Y_{mn}^l $(m, n = 1,2)$ be the elements of the admittance matrix $[Y]$ which represents the admittance matrix of the circuit Y. Then, the effective eigen admittance Y_i^l for each eigen excitation is given as follows:

$$Y_0^l = Y_{11}^l + Y_{22}^l + 2Y_{12}^l$$

$$Y_1^l = Y_4^l = Y_{11}^l + Y_{22}^l + \frac{\sqrt{5}-1}{2} Y_{12}^l$$

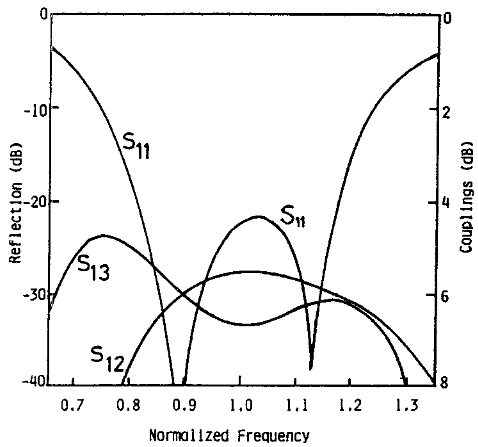


Fig. 6. Response curves for the five-port circuit with two quarter-wave matching sections. (Circuit parameters are shown in Table III.)

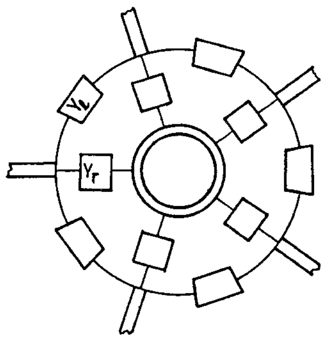


Fig. 7. Construction of generalized compensating circuit.

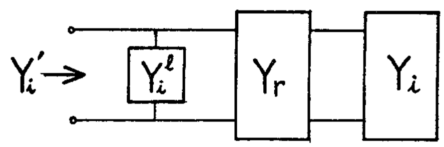


Fig. 8. Equivalent circuit for the eigen excitation after the construction of generalized compensating circuit.

and

$$Y_2^l = Y_3^l = Y_{11}^l + Y_{22}^l - \frac{\sqrt{5}+1}{2} Y_{12}^l. \tag{14}$$

Since we use microstrip line for Y_r and Y_l, $[Y^l]$ is given by

$$[Y^l] = \begin{bmatrix} -jY_l \cot\theta & jY_l/\sin\theta \\ jY_l/\sin\theta & -jY_l\cot\theta \end{bmatrix} \tag{15}$$

where θ is the electrical length of the section Y_l. Thus the eigen admittance Y_i', after generalized compensation, is readily obtained from Fig. 8. Let the elements of the F chain-matrix for two matching sections adding to each port be A, B, C, and D. Then, the eigen admittance Y_i^T for the symmetrical five-port circuit with the generalized compensating and matching networks are given by

$$Y_i^T = \frac{C + jY_i'D}{A + jY_i'B}. \tag{16}$$

The scattering matrix of the symmetrical five-port circuit under investigation as shown in Fig. 9 is readily obtained from (16).

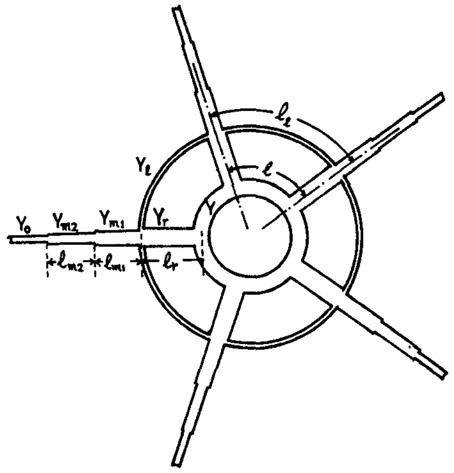


Fig. 9. Symmetrical five-port circuit with generalized compensating and matching networks.

TABLE IV
OPTIMUM CIRCUIT PARAMETERS WHEN GENERALIZED COMPENSATING AND MATCHING NETWORKS ARE ADDED

Section	Characteristic Admittance/Y_0	Section's Length/λ_g
Y	3.500	0.1916
Y_r	3.768	0.1159
Y_ℓ	0.450	0.3373
Y_{m1}	2.259	0.1850
Y_{m2}	1.244	0.1850

By optimization after substituting the elements of the scattering matrix for the circuit shown in Fig. 9 into (13), a bandwidth above an octave is obtained. However, some of the optimized circuit parameters, especially the normalized characteristic admittance Y and Y_l, cannot entirely be fabricated since they are too high or too low. So we reoptimized the circuit after specifying Y and Y_l as 3.5 and 0.45, respectively, which are easily realizable with microstrip line. The optimized circuit parameters are shown in Table IV, while the frequency characteristics for the circuit with the optimized circuit parameters are shown in Fig. 10. The optimized symmetrical five-port circuit with the generalized compensating network and two matching sections is referred to as *the broad-band symmetrical five-port circuit*, since its bandwidth is extremely broadened in comparison with the fundamental symmetrical five-port circuit and extends to 64 percent. Thus it is confirmed that the generalized compensating and matching networks are very effective for broadbanding the fundamental five-port circuit, and it is remarkable that each matching section used is much shorter than a quarter wavelength.

On the other hand, the circuit shown in Fig. 11 is obtained by specifying l as zero and removing Y_{m2}. Then, this circuit is the same as the circuit proposed by de Ronde [5]. Although it is reported in [5] that the circuit has an octave bandwidth within the tolerance limits below -20 dB of reflection and 0.5 dB of unbalance for couplings, it could not be obtained from our results. In practice, we performed the optimization for the circuit shown in Fig. 11, after specifying l as zero and removing Y_{m2} from the

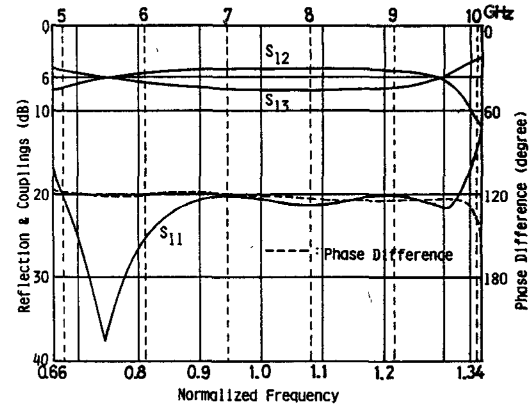


Fig. 10. Response curves for the optimized broad-band symmetrical five-port circuit with generalized compensating and matching networks. (Circuits parameters are shown in Table IV.)

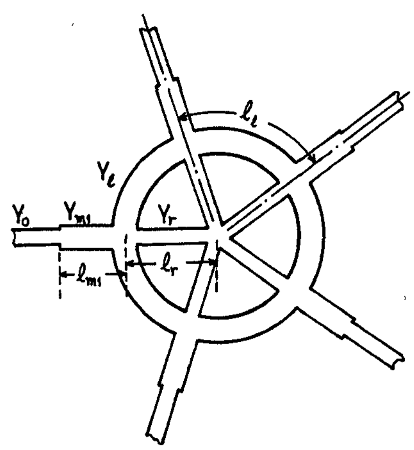


Fig. 11. Symmetrical five-port circuit when the length l of the section Y is specified as zero and Y_{m2} is removed.

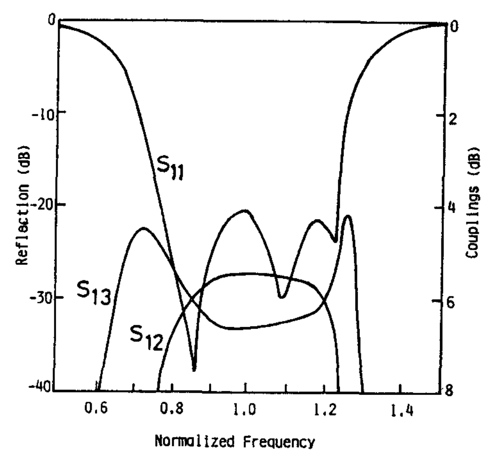


Fig. 12. Response curves for the optimized symmetrical five-port circuit when the length l of the section Y is specified as zero and Y_{m2} is removed. (Circuit parameters are shown in Table V.)

circuit shown in Fig. 9. As the result, the optimized circuit parameters are shown in Table V, while the frequency characteristics for the optimized circuit are shown in Fig. 12. Therefore, the bandwidth of this circuit extends to 45 percent only.

Furthermore, we also performed the optimization for the

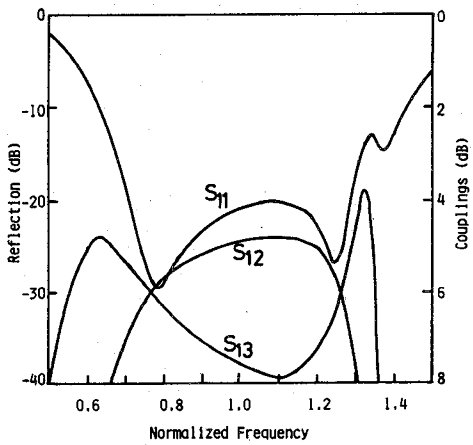


Fig. 13. Response curves for the optimized symmetrical five-port circuit when the length l of the section Y is specified as zero and two matching sections are taken. (Circuit parameters are shown in Table VI.)

TABLE V
OPTIMUM CIRCUIT PARAMETERS WHEN THE LENGTH OF THE SECTION Y IS SPECIFIED AS ZERO AND Y_{m2} IS REMOVED

Section	Characteristic Admittance/Y_0	Section's Length/λ_g
Y_r	5.625	0.2470
Y_l	2.800	0.3104
Y_{m1}	2.181	0.2500

TABLE VI
OPTIMUM CIRCUIT PARAMETERS WHEN THE LENGTH OF THE SECTION Y IS SPECIFIED AS ZERO AND TWO MATCHING SECTIONS ARE TAKEN

Section	Characteristic Admittance/Y_0	Section Length/λ_g
Y_r	1.249	0.1976
Y_l	4.000	0.2484
Y_{m1}	3.043	0.2319
Y_{m2}	1.283	0.2500

circuit shown in Fig. 11 after adding one more matching section Y_{m2} at each port. In this case, above an octave bandwidth could be obtained but some of the circuit parameters are actually unrealizable because the characteristic admittances are too high, e.g., $Y_r = 4.5$, $Y_l = 10.73$, and $Y_{m1} = 6.53$ in normalized admittance. Hence, we performed the optimization again after specifying Y_l as 4.0 as a realizable characteristic admittance. The optimized circuit parameters that result are shown in Table VI and the frequency characteristics for the optimized circuit are shown in Fig. 13, for which the bandwidth widens to 57 percent. Moreover, the bandwidth of the circuit for the case of $l = 0$ is narrower than that of the case of $l \neq 0$. It is regarded as a natural result from the degree of freedom of the circuit, so the bandwidth of the broad-band symmetrical five-port circuit is wider than that of the circuit proposed by de Ronde.

IV. EXPERIMENTAL RESULTS

To confirm that the design method of the broad-band symmetrical five-port circuit is valid, we have fabricated the proposed broad-band symmetrical five-port circuit with microstrip line at the center frequency 7.4 GHz and tested its frequency characteristics. The effective dielectric constant ϵ_r, the wavelength λ_g, and the line width W in the microstrip line were calculated by the equations of Schneider [12]. The calculated values for constructing the broad-band symmetrical five-port circuit are tabulated in Table VII. The dielectric substrate used here has the dielectric constant ϵ_r of 2.6 and the thickness h of 0.254 mm. The circuit fabricated and used for experiments is shown in Fig. 14.

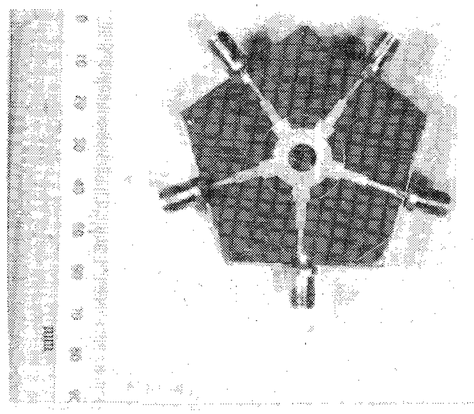
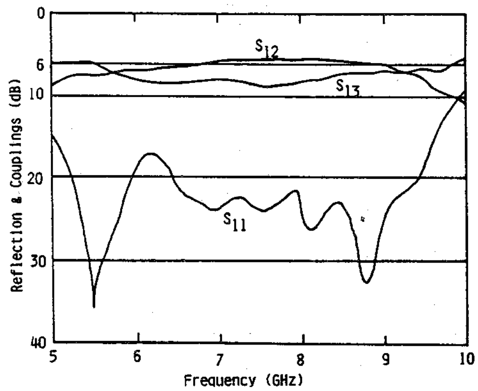
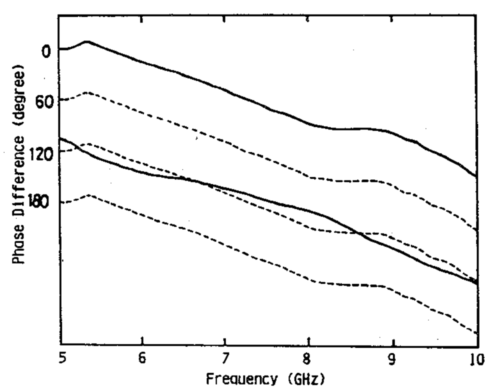


Fig. 14. Photograph of the broad-band symmetrical five-port circuit.



(a)



(b)

Fig. 15. Measured frequency characteristics for the broad-band symmetrical five-port circuit. (a) Couplings and reflection. (b) Phase differences between the adjacent ports.

Fig. 15 shows the measured frequency characteristics

TABLE VII
VALUES FOR CONSTRUCTION OF THE BROAD-BAND SYMMETRICAL FIVE-PORT CIRCUIT

Section	Characteristic Admittance/Y_o	Line Impedance	ε_{eff}	λ_g (mm)	W/h	W (mm)
Y_o	1.000	50.000 Ω	2.1733	33.916	2.783	0.7070
Y	3.500	14.286	2.4107	32.203	13.97	3.5478
Y_r	3.7682	13.269	2.4213	32.132	15.20	3.8615
Y_ℓ	0.4500	111.111	1.9894	35.450	0.5936	0.1508
Y_{m1}	2.2587	22.137	2.3389	32.694	8.306	2.1096
Y_{m2}	1.2441	40.193	2.2209	33.551	3.826	0.9719

obtained from the fabricated broad-band symmetrical five-port, while the theoretical responses are shown in Fig. 10. Here, the measured frequency characteristics for the couplings and reflection agree reasonably well with theoretical ones. The experimentally obtained bandwidth is about 58 percent because of the fabrication error and the circuit loss, while the designed bandwidth is 64 percent. On the other hand, the phase differences between adjacent ports contain some errors because of the errors of the reference planes and the fabrication, and the circuit loss. Therefore, it is expected that the experimental frequency characteristics of the broad-band symmetrical five-port circuit would be better when carefully and elaborately manufactured.

V. CONCLUSION

The properties of the symmetrical five-port circuit are presented in terms of the couplings and the phase differences between the adjacent ports when the circuit is mismatched.

On the other hand, a broad-band design theory of the symmetrical five-port circuit with microstrip line was demonstrated, where the technique of the construction of the generalized compensating and matching networks to the fundamental symmetrical five-port circuit was adopted. The experiments for the fabricated broad-band five-port circuit were carried out, the results of which agreed reasonably well with the numerically designed ones, and, hence, the validity of the broad-band design method was confirmed. Although the specific properties of the symmetrical five-port circuit have been proposed to make six-port measurements, its wider applications should be desired, e.g., six-phase phase-modulator.

REFERENCES

[1] G. P. Riblet and E. R. B. Hansson, "The use of a matched symmetrical five-port junction to make six-port measurements," in *1981 IEEE MTT-S Int. Microwave Symp. Dig.*, June 1981, pp. 151–153.

[2] E. R. B. Hansson and G. P. Riblet, "The matched symmetrical five-port junction as the essential part of an ideal 6-port network," in *Proc. Eur. Microwave Conf.*, (Amsterdam), 1981, pp. 501–506.

[3] G. P. Riblet and E. R. B. Hansson, "Aspects of the calibration of a single six-port using a load and offset reflection standards," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 2120–2125, Dec. 1982.

[4] C. G. Montgomery *et al.*, *Principles of Microwave Circuit.* New York: McGraw-Hill, 1948.

[5] F. C. de Ronde, "Octave-wide matched symmetrical, reciprocal 4- and 5-ports," in *1982 IEEE MTT-S Int. Microwave Symp. Dig.*, 1982, pp. 521–523.

[6] M. J. D. Powell, "A method for minimizing a sum of squares of nonlinear function without calculating derivatives," *Computer J.*, vol. 7, pp. 303–307, 1965.

[7] D. I. Kim and Y. Naito, "Broad-band design of improved hybrid-ring 3-dB directional couplers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 2040–2046, Nov. 1982.

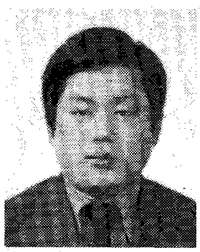
[8] D. I. Kim *et al.*, "Optimum design of the power dividers with ferrite toroids for CATV and/or MATV systems," *IEEE Trans. Consumer Electron.*, vol. CE-28, no. 1, pp. 27–38, Feb. 1983.

[9] G. P. Riblet, "The measurement of the equivalent admittance of 3-port circulators via an automated measurement system," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 402–405, May 1977.

[10] G. P. Riblet, "A directional coupler with very flat coupling," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 70–74, Feb. 1978.

[11] R. Levy and J. Helszajn, "Specific equations for one and two section quarter-wave matching networks for stub-resistor loads," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 55–62, Jan. 1982.

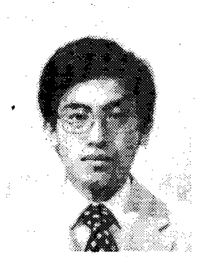
[12] M. V. Schneider, "Microstrip lines for microwave integrated circuits," *Bell Syst. Tech. J.*, pp. 1421–1445, May–June 1969.



Dong Il Kim was born in Nonsan, Korea, on February 26, 1952. He received the B.E. and M.E. degrees in nautical science and electronic navigation from the Korea Maritime University, in 1975 and 1977, respectively. Currently, he is studying toward the Ph.D. degree at the Tokyo Institute of Technology, where he has been working on the broad-band and optimum design of power dividing circuits and millimeter-wave integrated circuits.

He is a Lecturer at Korea Maritime University, and he is currently on leave from the Korea Maritme University.

Mr. Kim is a member of the Institute of Electronics and Communication Engineers of Japan, the Korea Institute of Navigation, and the Japan Institute of Navigation.



Kiyomichi Araki was born in Nagasaki, Japan, on January 7, 1949. He received the B.S. degree in electrical engineering from Saitama University, Urawa, Japan, in 1971, and the M.S. and Ph.D. degrees in physical electronics engineering, both from the Tokyo Institute of Technology, Tokyo, Japan, in 1973 and 1978, respectively.

From 1978 to the present, he has been a Research Associate at the Tokyo Institute of Technology. From September 1979 to August 1980, he was a Post-Doctoral Fellow at the University of Texas, Austin, where he was engaged in the design and development of millimeter-wave devices.

Dr. Araki is a member of the Institute of Electronics and Communication Engineers of Japan, from which he received a Young Engineer Award in 1979.

Yoshiyuki Naito was born in Oita, Japan, on November 22, 1936. He received the B.S. degree in electrical engineering and the D.Eng. degree, from the Tokyo Institute of Technology, Tokyo, Japan, in 1959 and 1964, respectively.

Since 1964, he has been with the Tokyo Institute of Technology. From September 1965 to October 1966, he was a Post-Doctoral Fellow at the Polytechnic Institute of Brooklyn, Brooklyn, NY. Currently, he is a Professor with the Faculty of Engineering. His research has chiefly been concerned with microwave circuit elements and properties and applications of magnetic material and antennas.

Dr. Naito received an Inada Award in 1961 and a Treatise Award in 1966 from the Institute of Electronics and Communication Engineers of Japan. He is a member of the Institute of Electronics and Communication Engineers of Japan.