A New Six-Port Microwave Network: Six-Port Magic Junction

ISAO OHTA, MEMBER, IEEE

***Abstract*—A new six-port junction, which consists of an H-plane symmetrical waveguide Y junction with a coaxial line on one side of its axis and a circular waveguide on its other, is proposed. The scattering matrix of the junction in an ideal case is derived using the symmetry properties of the structure. If both the coaxial and the circular waveguide arm are matched without destroying the symmetry, the arms of the junction are automatically matched and isolated as well, similar to the side arms of a conventional magic T. Therefore, it is called a six-port magic junction. These properties are confirmed by experiment in X-band. Lastly, some interesting applications based on the properties of the six-port junction are discussed.**

I. Introduction

In the past, various multiport junctions have been invented and employed for dividing and combining microwave signals, measuring circuit impedances, and so forth [1]. A turnstile junction, a Purcell's junction, and a waveguide impedance bridge [1]–[3] are well-known examples of six-port junctions.

This paper treats a new six-port junction consisting of an H-plane symmetrical Y junction with a coaxial line and a circular waveguide orthogonal to the H plane, as shown in Fig. 1. In Section II, after deriving the scattering matrix of the junction in an ideal case, we discuss some interesting properties. If both the coaxial and the circular waveguide arm are matched without destroying the symmetry, the junction is completely matched and has a strong analogy with a conventional magic T. In particular, there is no coupling between the three coplanar rectangular waveguide arms; nor is there any between the coaxial and circular arms. Therefore, it is called a *six-port magic junction*. In Section III, we obtain experimental corroboration by measuring the scattering parameters of a junction built as a trial. Section IV is devoted to a description of some unique applications to which the properties lend themselves.

II. Construction and Properties

Although the proposed junction, as can be seen in Fig. 1, has only five physical ports, it constitutes a six-port junction because of the two orthogonal TE_{11} modes in the circular guide (if each guide can support only a dominant

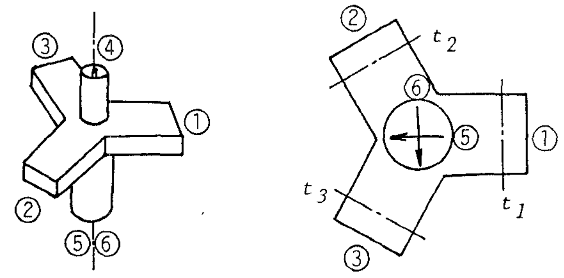

Fig. 1. (a) Schematic configuration of the newly proposed six-port junction. (b) Terminals in the circular guide for two polarizations.

mode). Fig. 1 also shows the numbering scheme of the ports and three symmetrically located reference planes, $t_1 - t_3$, in the three rectangular guides. The plane in the coaxial arm is designated as t_4, and the planes in the circular arm for two polarizations as t_5 and t_6.

Using the symmetrical structure outlined above, we will derive the scattering matrix of the junction. When a TEM wave is incident in port 4, the field within the junction has third-order rotational symmetry with respect to the common guide axis of the coaxial arm and the circular arm. This field can excite equal TE_{10} modes of like phase in ports 1–3, but no dominant-mode wave (TE_{11} mode) in the circular arm. Thus

$$S_{54} = S_{64} = 0 \tag{1}$$

$$S_{14} = S_{24} = S_{34} = \alpha. \tag{2}$$

Considering the physical symmetry of the construction of the junction, we obtain

$$S_{12} = S_{13} = S_{23} = \beta \tag{3}$$

$$S_{11} = S_{22} = S_{33} = \gamma. \tag{4}$$

Ports 5 and 6 are orthogonal to each other. Hence,

$$S_{65} = S_{56} = 0. \tag{5}$$

Moreover, since a wave (TE_{10} mode) entering port 1 cannot excite a wave polarized in the direction of port 6, we have

$$S_{61} = 0. \tag{6}$$

We can also derive the following equations from symmetry:

$$S_{25} = S_{35} = -\delta \cos 60° \tag{7}$$

$$S_{26} = -S_{36} = \delta \cos 30° \tag{8}$$

Manuscript received May 23, 1987; revised December 16, 1987. This work was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Japan.

The author is with the Department of Electronics Engineering, Himeji Institute of Technology, Himeji 671-22, Japan.

IEEE Log Number 8819964.

0018-9480/88/0500-0859$01.00 ©1988 IEEE

where

$$S_{15} = \delta. \tag{9}$$

Finally, let it be assumed that suitable matching elements are added to the coaxial and circular arms of the junction without destroying the symmetry such as to make the reflection coefficients at these arms vanish, that is,

$$S_{44} = S_{55} = S_{66} = 0. \tag{10}$$

If we use (1)–(10) and take account of the reciprocal theorem, the scattering matrix of the junction may be written as

$$[S] = \begin{bmatrix} \gamma & \beta & \beta & \alpha & \delta & 0 \\ \beta & \gamma & \beta & \alpha & -\delta/2 & \sqrt{3}\delta/2 \\ \beta & \beta & \gamma & \alpha & -\delta/2 & -\sqrt{3}\delta/2 \\ \alpha & \alpha & \alpha & 0 & 0 & 0 \\ \delta & -\delta/2 & -\delta/2 & 0 & 0 & 0 \\ 0 & \sqrt{3}\delta/2 & -\sqrt{3}\delta/2 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

For a lossless structure we can obtain the following relations through the unitary properties of the scattering matrix:

$$3|\alpha|^2 = 1 \tag{12a}$$

$$(3/2)|\delta|^2 = 1 \tag{12b}$$

$$|\gamma|^2 + 2|\beta|^2 + |\alpha|^2 + |\delta|^2 = 1 \tag{12c}$$

$$\gamma\beta^* + \beta\gamma^* + |\beta|^2 + |\alpha|^2 - |\delta|^2/2 = 0 \tag{12d}$$

$$(\gamma + 2\beta)\alpha^* = 0 \tag{12e}$$

$$(\gamma - \beta)\delta^* = 0. \tag{12f}$$

By proper choice of reference planes t_1–t_6, we can make both α and δ positive real numbers. Therefore, (12a) and (12b) can be solved as follows:

$$\alpha = 1/\sqrt{3} \tag{13}$$

$$\delta = \sqrt{2/3}. \tag{14}$$

Substituting (13) and (14) into (12c) gives

$$\beta = \gamma = 0. \tag{15}$$

The remainder of the equations in (12) are automatically satisfied by (13)–(15). Thus the scattering matrix can be exhibited in the form

$$[S] = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{\sqrt{3}} & \sqrt{\frac{2}{3}} & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 & 0 & 0 \\ \sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{6}} & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 & 0 & 0 \end{bmatrix} \tag{16}$$

Next, in order to gain a better understanding of the junction, let us take up the following particular cases.

Case 1

When a wave is incident in the coaxial arm only, the scattered waves in all ports are given by

$$[b] = [S][0,0,0,a,0,0]^t = (a/\sqrt{3})[1,1,1,0,0,0]^t \tag{17}$$

Case 2

When a right- or left-hand circularly polarized wave enters the circular arm, the scattered wave vector becomes

$$[b] = [S]\left[0,0,0,0,a/\sqrt{2}, \pm ja/\sqrt{2}\right]^t$$

$$= (a/\sqrt{3})\left[1, e^{\pm j2\pi/3}, e^{\mp j2\pi/3}, 0,0,0\right]^t \tag{18}$$

where the upper signs correspond to a right-hand circular polarization and the lower signs to a left-hand circular polarization.

Equations (16), (17), and (18) enable us to state as follows:

1) If the coaxial and circular arms of the junction (ports 4 ~ 6) are matched, the other three rectangular ports are matched also; that is, the junction is completely matched.
2) In the matched junction there is no coupling between the three coplanar rectangular arms or between the coaxial and circular arms.
3) A wave entering the coaxial arm of the matched junction is equally divided into three waves in the rectangular arms. Conversely, when equal-amplitude and in-phase waves are incident in the three rectangular arms, they completely combine and emerge from the coaxial arm.
4) A circularly polarized wave entering the circular arm is split into three waves propagating in the rectangular arms with an equal amplitude and in a three-phase relationship. Their phases advance by $2\pi/3$ radians with respect to the direction ports $1 \to 2 \to 3$ for a right-hand circular polarization, and delay by the same value for a left-hand circular polarization. In reverse, if three equal-amplitude waves with the relative phase difference of $2\pi/3$ radians enter the three rectangular arms, they are combined into a right- or left-hand circularly polarized wave in the circular arm.

The above statements show that the properties of this junction are very analogous to those of a conventional magic T apart from the number of the ports. In particular, the three coplanar rectangular arms are isolated from one another by matching of the junction at the coaxial and circular arm, just as the two coplanar side-arms of a conventional magic T are isolated by matching at the E- and H-plane arms. This is why the junction is called a six-port magic junction. Furthermore, the analogy between the two junctions may be understood better by considering a magic T with a coaxial arm as the H-plane arm [4], as illustrated in Fig. 2.

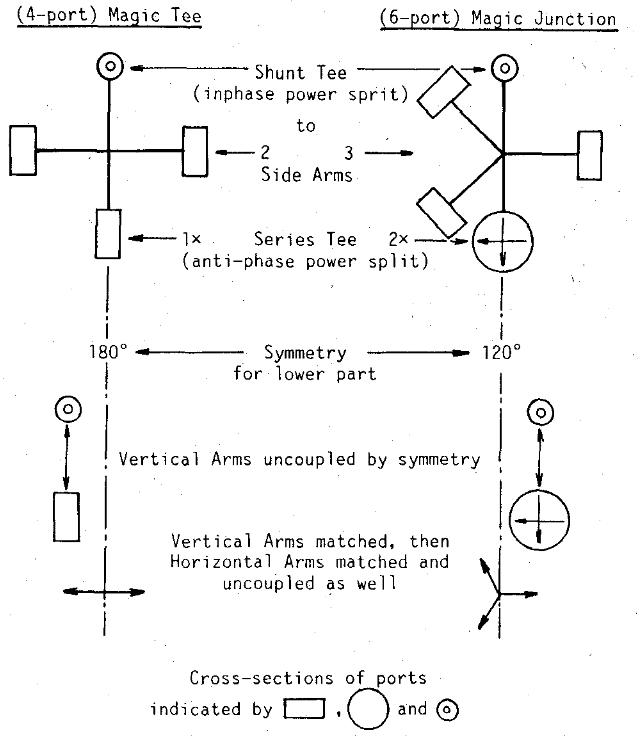

Fig. 2. Analogy between magic T and six-port magic junction.

III. Experimental Results

In order to provide experimental corroboration, a test junction was constructed and tested. Its photographs are shown in Fig. 3. The basic waveguides employed were a 22.9×10.2 mm I.D. rectangular waveguide and a 22 mm I.D. circular waveguide, whose material was brass. A type N connector (MM 1404CC; Murata's trade name, the specific *VSWR* is 1.13 max.) was employed as a coaxial line. The key point of designing a six-port magic junction is to maintain symmetry and eliminate the coaxial and circular arm reflections simultaneously. In the present paper, this matching was done by adjusting the dimensions of a drilled frustum of a cone and a thin ring which were fixed on the dielectric supporting the probe of the coaxial connector, and varying the probe insertion and the length of the dielectric support as in Fig. 4. The ring was used for fitting two frequency ranges in which the reflected waves in the coaxial and circular arms vanished.

Fig. 5 exhibits $X-Y$ recordings of the scattering-matrix parameters made with a scalar network analyzer. They are in agreement with the values in (16) over a bandwidth. The bandwidth for the return loss in the coaxial arm, S_{44}, is relatively narrow. This results from emphasizing the broad-band matching of the circular arm. It is difficult to match both the coaxial and the circular arm simultaneously over a broad band. Accordingly, in the first place, the dimensions of the frustum, the ring, and the dielectric support were determined so as to match the circular arm over a desirable frequency range. Second, the reflection in the coaxial arm was reduced by adjusting the probe insertion. Finally, the two matching frequency ranges were fitted by a slight modification of the height of the ring. Therefore, the bandwidth for return loss in the coaxial arm is narrower than in the circular arm. Conversely, if the circular arm is matched by a symmetrical matching element (e.g., a thin inductive circular window) after a broad-band matching of the coaxial arm, we may obtain a network with a wide bandwidth for S_{44}.

The maximum frequency band of the junction, however skillfully matching elements may be devised, can hardly exceed a frequency band for which only the TE_{11} mode propagates in the circular waveguide, because the TEM mode of the coaxial line easily couples with the second mode of the circular waveguide (TM_{01}). This band of the test junction, shown in Fig. 3, is from 8.0 to 10.4 GHz.

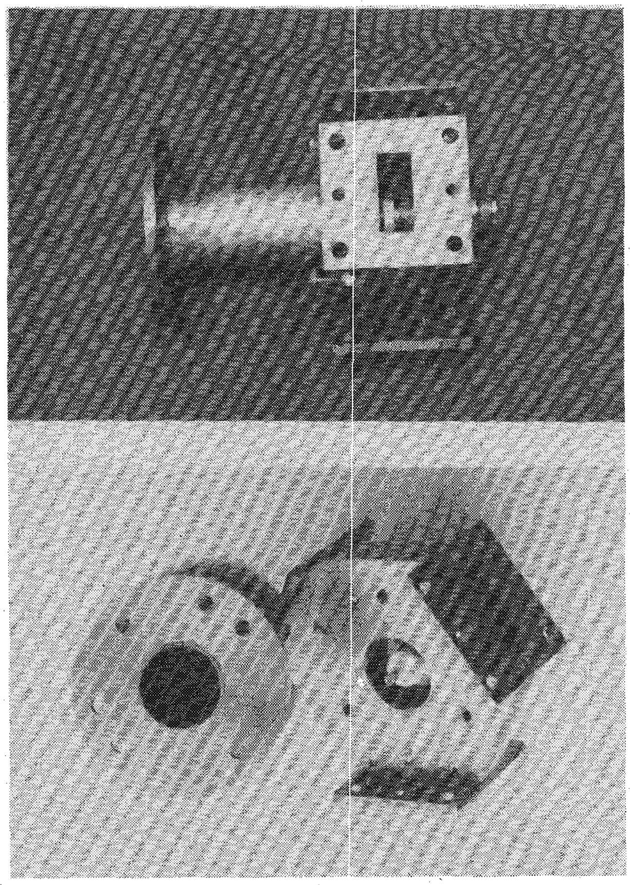

Fig. 3. Photographs of an X-band junction built as a trial.

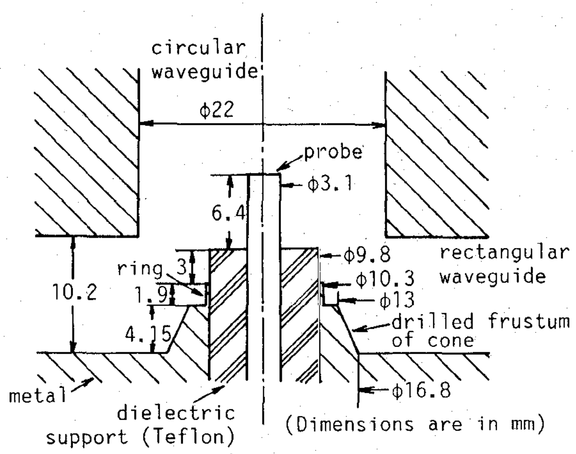

Fig. 4. Dimensions of experimental matching element.

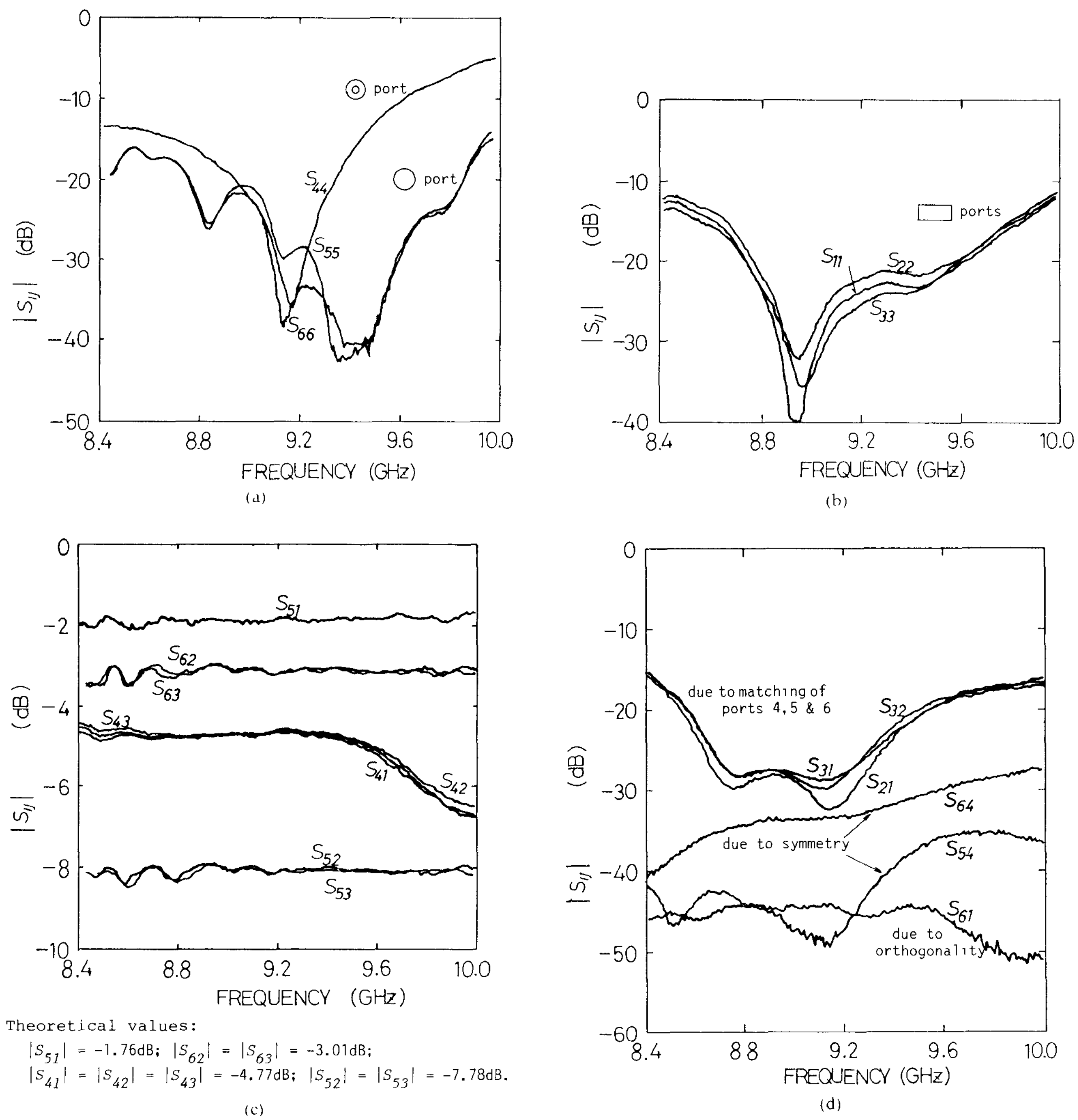

Fig. 5. Measured frequency characteristics of $|S_{ij}|$ of the six-port magic junction shown in Fig. 3. (a) Measured return loss of the coaxial arm and the circular arm. (b) Measured return loss of the three rectangular arms. (c) Measured coupling between the coaxial arm and the three rectangular arms, and between the circular arm and the three rectangular arms. (d) Measured isolation between the three rectangular arms, between the coaxial arm and the circular arm, and between one rectangular arm and one plane of polarization in the circular arm.

IV. Applications

The above-mentioned properties of the six-port magic junction lend themselves to some interesting applications in the microwave field. Some of the applications will be discussed in the following.

A. Three-Way Power Divider/Combiner

This application appears to be a natural consequence of the previous discussion. However, it should be emphasized that each port is matched to its transmission line and the three coplanar rectangular arms are isolated from one another.

B. Unequal Three-Way Power Divider

When a linearly polarized wave is fed into the circular arm, its power is split into three unequal powers emerging from the rectangular arms with ratios determined by the direction of polarization. If the plane of polarization of the incident wave with a unit amplitude, as illustrated in the Fig. 6 insert, makes an angle θ with respect to that in port

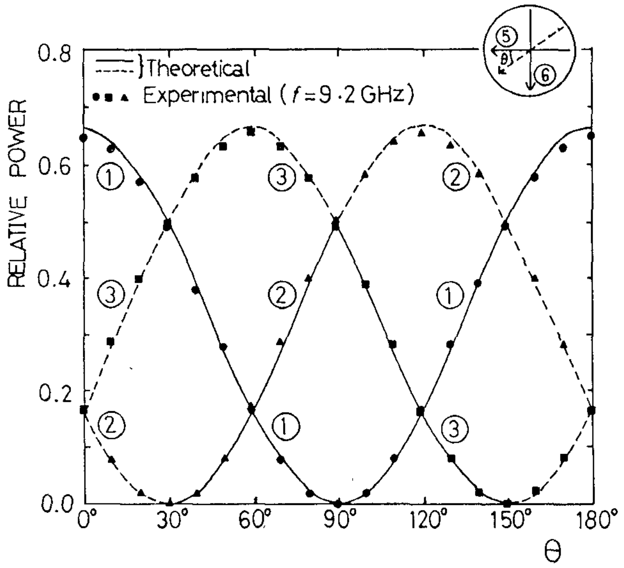

Fig. 6. Power division ratios versus direction of polarization of a wave incident in the circular arm.

5, the scattered waves in all ports may be written as

$$[b] = [S][0,0,0,0,\cos\theta,\sin\theta]^t = \sqrt{2/3}\,[\cos\theta,\cos(\theta-2\pi/3),\cos(\theta-4\pi/3),0,0,0]^t. \quad (19)$$

The graph in Fig. 6 shows a plot of the computed power split ratio at each rectangular arm as a function of the angle θ. In the figure the solid and broken curves indicate the split ratios of waves with a relative phase of 180°. The black dots show the measured power split ratios at 9.2 GHz. They show good agreement with the theoretical curves.

C. Circular Polarizer

When ports 1, 2, and 3 are terminated in short circuits which are longer by $\lambda_g/6$ in the direction ports $1 \to 2 \to 3$ (λ_g being the guide wavelength in the rectangular arm), the scattering matrix of the junction reduces to the following three-port matrix with respect to ports 4, 5, and 6:

$$\begin{bmatrix} S_{44} & S_{45} & S_{46} \\ S_{54} & S_{55} & S_{56} \\ S_{64} & S_{65} & S_{66} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 0 & \sqrt{2} & -j\sqrt{2} \\ \sqrt{2} & 1 & j \\ -j\sqrt{2} & j & -1 \end{bmatrix}. \quad (20)$$

It is evident from (20) that a TEM wave incident in the coaxial arm is completely converted into a right-hand circularly polarized wave in the circular arm. If the short circuits are set shorter by $\lambda_g/6$ in the same direction, the junction behaves as a left-hand circular polarizer. Moreover, exchanging the above short circuits for three reflection-type amplifiers with an identical characteristic, we can form an active circular polarizer.

D. Impedance Bridge

A typical circuit connection for this application is constructed as follows. An RF signal is fed into port 5, an "unknown" impedance and two known impedances are connected to ports 1, 2, and 3, respectively, and a detector receives the output from the coaxial arm 4. Supposing port 6 is terminated in a matched load and an incident signal has a unit amplitude, the signal reaching the detector is given by

$$b_4 = (\sqrt{2}/3)\{\Gamma_L - (\Gamma_2 + \Gamma_3)/2\} \quad (21)$$

where Γ_L and $\Gamma_{2,3}$ are the reflection coefficients of the unknown impedance and the two known impedances, respectively.

If the known impedances are produced by two movable shorting plungers which are adjusted to give a null signal at the detector, we can determine the value of the unknown Γ_L as follows:

$$\Gamma_L = (\Gamma_2 + \Gamma_3)/2 = \cos\{(\theta_2 - \theta_3)/2\}\, e^{j(\theta_2+\theta_3)/2} \quad (22)$$

where

$$\Gamma_{2,3} = e^{j\theta_{2,3}}.$$

A valuable feature of this method of measurement is that the standard impedances required are only two movable shorting plungers.

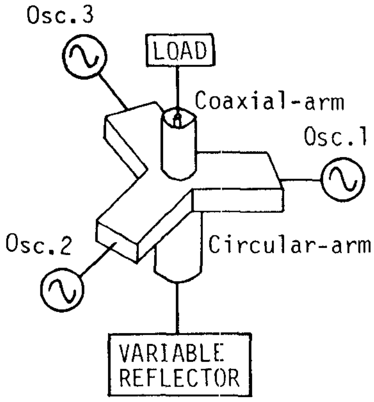

Fig. 7. Block diagram of a power combining system of three oscillators. The sum of their outputs is delivered to a load in the coaxial arm at in-phase synchronism.

E. Parallel Running System of Three Oscillators

We consider a power combining system with three oscillators symmetrically connected to the three rectangular arms as shown in Fig. 7. If the coaxial and the circular arm are terminated in a (matched) load and a variable reflector with third-order rotational symmetry, respectively, this system falls into in-phase synchronism or either of two three-phase synchronisms (the relative phase difference betwen the three oscillators is equal to 120°). The synchronism, however, is decided in conformity with the stability criterion derived from the reflection coefficients (or impedances) of the circuits attached to the coaxial and circular arms, and the circuit parameters of the oscillators, including their nonlinearity. For example, let it be assumed that the circuit impedances are adjusted to stabilize the in-phase synchronization. Then, since the three oscillators oscillate in phase, their outputs completely combine in the (matched) load of the coaxial arm. Further, each oscillator behaves as if it were independently terminated in the same load [5]. In this case, the load (variable reflector) in the circular waveguide seems to be unnecessary, but actually it plays an important role, described below. Supposing the synchronized steady state is disturbed for one reason or another, a part of the oscillator output enters the circular guide, is reflected by the variable reflector, and returns to the oscillators again. If the phase of these reflected waves, and hence of the variable reflector, is adjusted to suppress the disturbance, the in-phase synchronism is held permanently.

On the other hand, if circuit impedances are adjusted to stabilize a three-phase synchronization, a combined wave in a right- or left-hand circular polarization is delivered to a load in the circular arm [6].

V. Conclusions

A new six-port microwave network possessing new properties has been proposed and some applications utilizing the network have been discussed. Moreover, it is suggested that this network be called a six-port magic junction, because the properties are very analogous to those of a conventional magic T; in particular the three coplanar rectangular waveguides do not couple with one another. A further increase in the bandwidth of the junction would be an important subject for more practical purposes.

Acknowledgment

The author would like to thank the reviewers for their valuable comments regarding the manuscript and Prof. T. Kaneko of Himeji Institute of Technology for his helpful advice.

References

[1] C. G. Montgomery, R. H. Dicke, and E. M. Purcell, *Principles of Microwave Circuits*. New York: McGraw-Hill, 1948.

[2] M. A. Meyer and H. B. Goldberg, "Applications of the turnstile junction," *IRE Trans. Microwave Theory Tech.*, vol. MTT-3, pp. 40–45, Dec. 1955.

[3] M. Chodorow, E. L. Ginzton, and F. Kane, "A microwave impedance bridge," *Proc. IRE*, vol. 37, pp. 634–639, June 1949.

[4] W. A. Tyrrell, "Hybrid circuits for microwaves," *Proc. IRE*, vol. 35, pp. 1294–1306, Nov. 1947.

[5] I. Ohta and I. Hagino, "A symmetrical power combining system of three oscillators," *Trans. IECEJ*, vol. J68-C, pp. 1116–1122, Dec. 1985 (in Japanese).

[6] I. Ohta, H. Takagi, K. Takemura, and I. Hagino, "Power combining oscillator systems with a circularly polarized output wave," in *IEC Japan, Nat. Convention Rec.*, May 1986 (in Japanese).

Isao Ohta (M'86) received the B.Eng., M. Eng., and D.Eng. degrees in electrical engineering from Osaka University, Osaka, Japan, in 1965, 1967, and 1978, respectively.

Since 1967 he has been a Research Instructor in the Department of Electronics at Himeji Institute of Technology, Himeji. His current research interests are microwave networks such as printed-circuit directional couplers and the six-port magic junction, and nonlinear phenomena pertaining to microwave oscillators and their applications.

Dr. Ohta is a member of the Institute of Electronics, Information and Communication Engineers of Japan.