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A Five-Port Matched Pseudo-Magic Tee*

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Summary—**The five-port matched pseudo-magic tee consists of an input waveguide, two load arm waveguides which are coupled into the input waveguide with +90° and −90° phase shifts, respectively, and an output waveguide which is split into two load waveguides by a septum.**

The improvements include a much broader matching and isolation bandwidth, higher isolation between arms, better matching into arms, and a variety of modifications for different applications.

These characteristics have been obtained by employing frequency-insensitive phase shifters. Hence, frequency coverage is mainly limited by mechanical asymmetry and the characteristics of the directional coupler in the magic tee.

While this type of hybrid junction is not a true magic tee because the load arms are not used as the input arm, it does have several applications which an ordinary magic tee does not have.

***X*-, *K*-, and *M*-band models were examined experimentally, and highly sensitive and accurate impedance measurements were made.**

INTRODUCTION

CONVENTIONAL magic tees are not as well matched nor as well isolated over as broad a frequency range as one would like. The sensitivity and accuracy of impedance bridges and the sensitivity of microwave mixers are quite often limited by the aforementioned factors. Several attempts at modifying conventional matched magic tees have been made. However, the main difficulties, which arise from the fundamental restrictions of the structure itself, have remained.

A solution of this problem has been obtained in the following ways.

PRINCIPLES OF OPERATION

The new-type magic tee (type 1) is shown in Fig. 1(a) and 1(b) (page 218). Input-microwave power is split equally by a septum in the input waveguide and then introduced into load arm waveguides 1 and 2 through directional couplers. The waves reflected from loads 1 and 2 meet at the output arm.

One can see that the waves going into loads 1 and 2 are out of phase with each other, if the condition $L_{i1}=L_{i2}$ is satisfied. Hence, the wave coming from the output arm has zero amplitude if loads 1 and 2 are identical and $L_{o1}=L_{o2}$. The geometrical conditions $L_{i1}=L_{i2}$ and $L_{o1}=L_{o2}$ are satisfied independently of the input frequency. This condition has enabled us to build a frequency-insensitive magic tee.

The matching conditions of the input waveguide depend mainly upon the matched load of the directional couplers. The necessity for the matched loads at waveguide junctions of the load arms is easily seen by circuit theory.[1] The mismatches at the junction cause fre-

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quency-sensitive reflections. Although the basic principle of this tee is simple, there are several construction difficulties.

Another version of the magic tee, as sketched in Fig. 2(a) (type 2), was much more practical and easier to build. Here an input waveguide, which was separated by a septum in the first model, is replaced by a single waveguide and a single directional coupler, and is coupled to the two load arms by two lines of coupling holes symmetrically arranged about the A-A plane, as shown in Fig. 3. The holes are located at the position of maximum H field of the input waveguide so that the input wave couples to the load arms magnetically with $+90°$ and $-90°$ phase shifts, as shown in Fig. 2(a) and Fig. 4.

In this case, one can see that the phase shifts are obtained only by one directional coupler, instead of by the complicated waveguide bends of Type 1.

This hybrid circuit can be analyzed with the use of the scattering matrix.

The scattering matrix of the five-port network of Fig. 3, which is symmetric about the A-A plane, can be written as follows:

$$\begin{pmatrix} S_{11} & S_{12} & iS_{13} & -iS_{13} & iS_{15} \\ S_{12} & S_{22} & iS_{23} & -iS_{23} & iS_{25} \\ iS_{13} & iS_{23} & S_{33} & S_{34} & S_{35} \\ -iS_{13} & -iS_{23} & S_{34} & S_{44} & S_{35} \\ iS_{15} & iS_{25} & S_{35} & S_{35} & S_{55} \end{pmatrix}$$

where $V_{01}=S_{11}V_{i1}+S_{12}V_{i2}+S_{13}V_{i3}+S_{14}V_{i4}+S_{15}V_{i5}$.

V_{0n} is the voltage amplitude of the wave out of test arm n, and V_{im} is the voltage amplitude of the wave incident on test arm m.

From reciprocity, it follows that $S_{ij}=S_{ji}$. From the symmetry of the tee we obtain

$$S_{35} = S_{45}.$$

Finally, from the phase relations and the symmetry of the tee, we deduce the conditions

$$S_{13} = -S_{14}$$

$$S_{23} = -S_{24}.$$

Here the phase relations are included in the matrix elements. From column 3, row 4, the following relations are obtained:

$$+S_{13}^2 \quad +S_{23}^2 \quad +S_{33}^2 \quad +S_{34}^2 \quad +S_{35}^2 \quad = 1.$$

$$+S_{13}^2 \quad +S_{23}^2 \quad +S_{34}^2 \quad +S_{44}^2 \quad +S_{35}^2 \quad = 1.$$

Therefore,

$$S_{33} = S_{44}.$$

From column 1, row 2,

$$S_{11}S_{12} + S_{12}S_{22} + 2S_{13}S_{23} + S_{15}S_{25} = 0.$$

If $S_{11}=S_{22}=0$, then

$$2S_{13}S_{23} + S_{15}S_{25} = 0.$$

From the geometrical symmetry of a tee and field symmetry of arms 3 and 4, one can see immediately that

$$S_{15} = S_{25} = 0.$$

Hence,

$$S_{13}S_{23} = 0.$$

From column 1, row 3,

$$S_{11}S_{13} + S_{12}S_{23} - S_{13}S_{33} + S_{13}S_{34} - S_{15}S_{15} = 0.$$

If $S_{11}=S_{33}=0$, then $S_{12}S_{23}+S_{13}S_{31}=0$.

Suppose the coupling is directive:

$$S_{13} \neq 0 \quad \text{and} \quad S_{23} = 0,$$

then

$$S_{34} = 0.$$

The opposite directivity, $S_{13}=0$, $S_{23}\neq 0$, is not allowed because $S_{12}\neq 0$ should be satisfied in any case. One can summarize the results as follows:

Directive coupling is required such that $S_{23}=0$, $S_{13}\neq 0$, as in a magic tee. Complete isolation between load arms 3 and 4 is obtained if ports 1, 2, 3, and 4 appear matched looking out of the tee.

Experimental Results

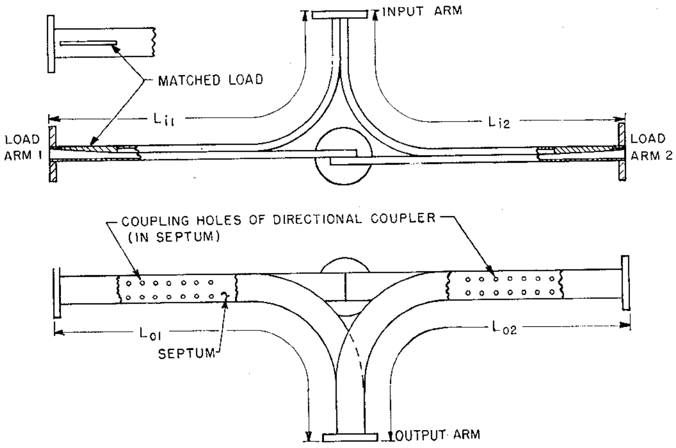
X-, K- and M-band tees of type 2 shown in Fig. 2(a) were built and tested. Photographs of those tees are shown in Fig. 2(b).

A K-band tee of type 1, shown in Fig. 1(a), was also built and tested. Fig. 1(b) is a photograph of the part of this K-band magic tee which does not include directional couplers.

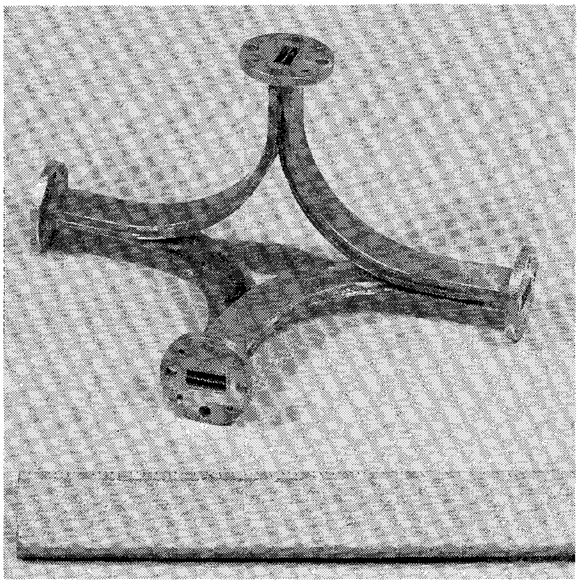
One of the type 2 X-band tees was analyzed in detail by a reflectometer setup which covered the frequency range from 8.2 kMc to 12.5 kMc. The isolation between ports 1 and 5, with matched loads at ports 2, 3, and 4, was examined. The results are shown in Fig. 5. The small leakage, which appeared on the low-frequency end of Fig. 5, was due to imperfect matching of the loads at port 2. The reflectometer was too insensitive to measure a real value of isolation at which unbalanced signals were far below the noise signal. The voltage standing wave ratios at input and output arms were less than 1.3 and 1.10, respectively, over the frequency range from 8 kMc to 11 kMc.

A more severe test of isolation was made by shorting ports 3 and 4. This test serves to emphasize any unbalancing in the two load arms, even though the tee would never be used this way in practice. As the data in Table I shows, the isolation is extremely high, even in this case.

The detailed characteristics of the tee are shown in Table I. In this case, slight adjustment of the balancing,

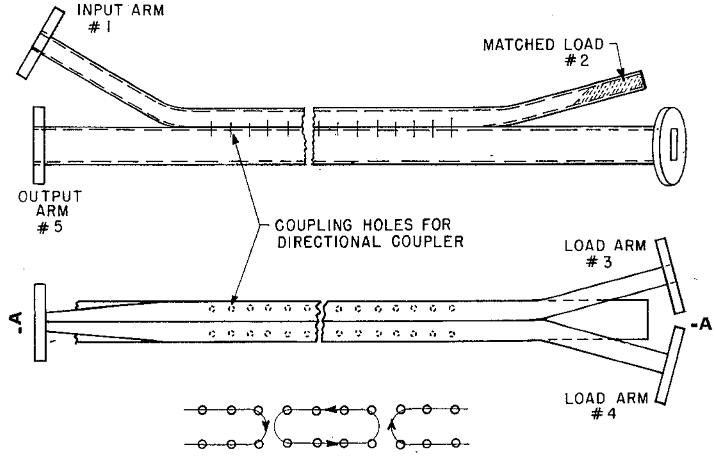


(a)

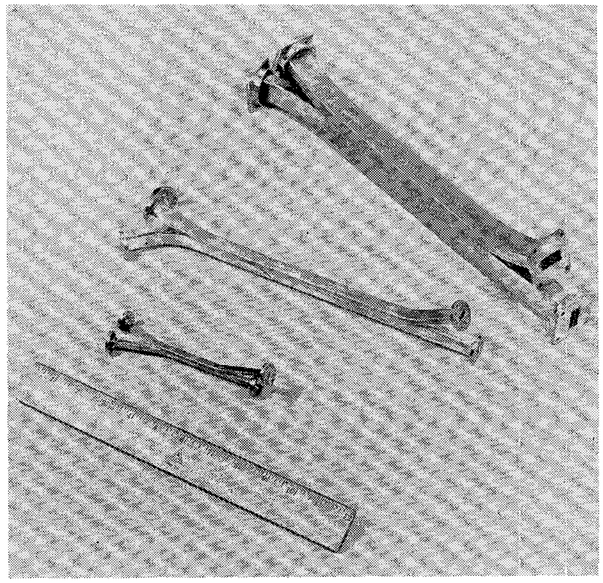


(b)

Fig. 1—(a) Structure of split waveguide-type matched magic tee (type 1). (b) Photograph of split waveguide-type magic tee.



(a)



(b)

Fig. 2—(a) Structure of five-port split waveguide-type matched magic tee (type 2). (b) Photograph of five-port split waveguide-type matched magic tee.

which compensated for the mechanical asymmetry (less than 60 mils), was made for each frequency. An isolation 30 db better than the conventional magic tee was obtained.

The same type of test on the type 1 K-band tee was made. Fig. 6 shows the results of this test.

An M-band tee, which is shown in Fig. 2(b), was made, and quite uniform characteristics over the frequency range 45–58 kMc were obtained. The isolation between the input and output arms was greater than 35 db.

Conclusion

Experiments show no reason to prevent the use of this type of magic tee in the shorter millimeter wave region. Furthermore, this type of magic tee is no more difficult to build than directional couplers and matched loads at the same frequencies.

The tee is well matched in any arm, particularly in the load arm, if arm 1 is used as the input. But if one of the load arms 3 or 4 is used as an input, there is no longer isolation between arms 3 and 4. This is different from the usual magic tee.

It does have power dissipation at the matched load of arm 2. However, it need not be 11.5 db as in our test model. The circuits with 3-db directional couplers are easy to design and build.

The characteristics of the circuit are independent of the coupling loss. Hence, the coupling loss must be chosen to meet the application.

The directivity of the directional couplers contributes to the isolation between the load arms, as one can see from the previous discussion. However, the balancing characteristics do not depend upon the directivity. They depend only on the symmetric arrangement of coupling holes.

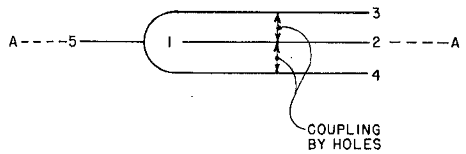


Fig. 3—A simplified schematic of the five-port magic tee.

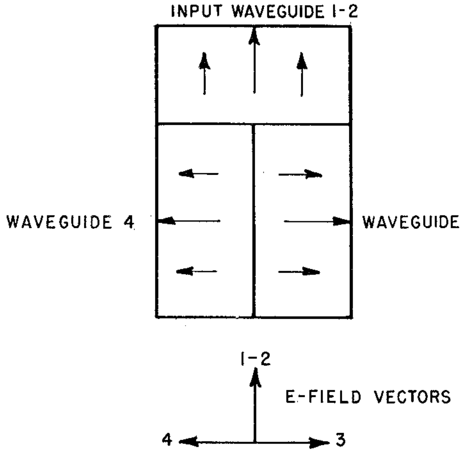


Fig. 4—Electric field phase relation in the cross section of a tee.

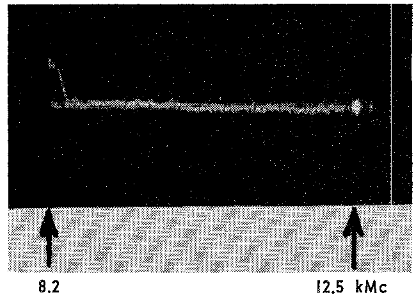


Fig. 5—The frequency characteristics of isolation between ports 1 and 5, with matched loads at ports 2, 3, and 4.

TABLE I
CHARACTERISTICS OF THE FIVE-PORT MATCHED PSEUDO-MAGIC TEE

Frequency in KMC	Isolation* (excluding the coupling loss)† Between Ports 1 and 5 (ports 3 and 4 are shorted) in db	VSWR Port 5‡	Port 1§
8.0	40	1.10	1.3
8.6	75	1.10	1.25
9.0	75	1.09	1.25
9.5	70	1.08	1.20
10.0	75	1.07	1.02
10.5	70	1.14	1.20
10.9	70	1.05	1.00
11.1	70	1.14	1.07

* 70~75 db was the limit of measurement by our instruments.
† The total coupling loss of the directional coupler was 11.5 db in this specific model.
‡ Matched loads at ports 3 and 4.
§ Match load at port 2 and short circuit at ports 3 and 4.

The standard magic tee can be converted to a very-broadly-banded matched magic tee using a lossy pad as a matching device. If we compare the modified regular magic tee with our pseudo-magic tee, we can see the following differences.

The modified standard magic tee has as big a loss between output and load arms as between input and load arms. On the other hand, the loss in our pseudo-tee is almost entirely between input and load arm and there is very little loss between the load arms and the output arm.

Furthermore, since the coupling loss in the directional coupler effectively contributes to the isolation between load arms 3 and 4, much greater isolation could be achieved in this way than by the regular magic tee.

This type of pseudo-tee was therefore effectively used to make an extremely sensitive impedance bridge, and measurements were made rapidly and accurately for the various impedances.

In several applications, the coupling loss in the input arm is even desirable. For example, in a balanced mixer, the local oscillator is normally isolated from the rest of the circuit with an attenuator. Here, the attenuator is already included in the tee.

One can modify the five-port tee in several ways. For example, the modification shown in Fig. 7 enables us to introduce simultaneously two signals of different frequencies from different waveguides.

This circuit is effectively used to monitor a high-power balanced circuit. The input power from port 5 is divided equally into arms 3 and 4. Only a fraction of unbalanced power from arms 3 and 4 is detected at arm 1 through small coupling holes.

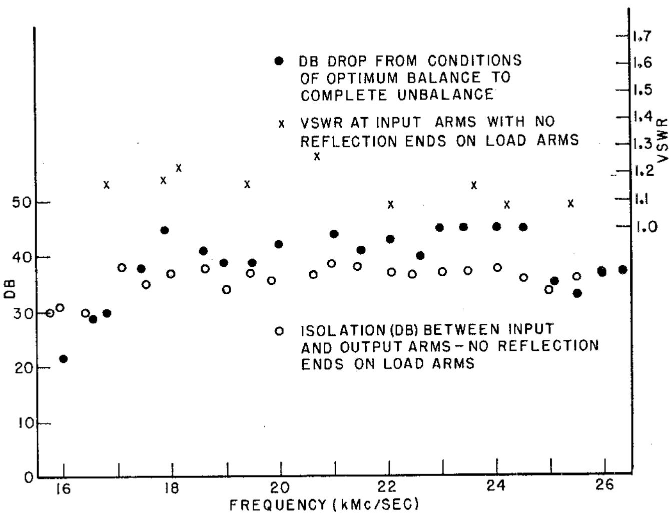


Fig. 6—The frequency characteristics of split waveguide-type magic tee (type 1).

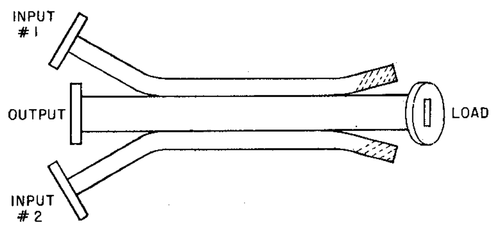


Fig. 7—Modified magic tee.