Applications of the Turnstile Junction

MAURICE A. MEYER† AND HAROLD B. GOLDBERG†

Summary—The Turnstile Junction is a six-terminal pair microwave network, consisting of four coplanar rectangular arms and a circular arm, orthogonal to the rectangular arms, which is excited in two orthogonal TE 1, 1, modes.

The characteristics of the network are such that they lend themselves to some very important and unique applications in the microwave field.

Making use of the symmetry conditions and the field division properties of the Junction, this paper describes the operation of the Junction under various conditions, with particular emphasis on the applications to which these characteristics lend themselves.

Some of the applications discussed are:

1. Continuous-wave (cw) duplexing.
2. Generation of elliptical polarizations.
3. Transmitting linear and receiving cross-linear polarizations.
4. Transmitting and receiving linear polarization.
5. Transmitting and receiving circularly polarized waves.
6. Four-way symmetrical power division.
7. Measuring degree of ellipticity of circularly polarized waves.

THE TURNSTILE Junction, a microwave network element whose theory has been described in the literature,[1–3] seems to have received little attention in the field of microwave applications.

The junction has properties which lend themselves to some very important and unique applications in the microwave field.

It is the intent of this paper to describe the characteristics of this Junction under various conditions, with particular emphasis on some of the applications to which these characteristics lend themselves.

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1. Continuous-wave (cw) duplexing.
2. Generation of elliptical polarizations.
3. Transmitting linear and receiving cross-linear polarizations.
4. Transmitting linear and receiving linear polarizations.
5. Transmitting and receiving circularly polarized waves.
6. Measuring degree of ellipticity of a wave.
7. Four-way symmetrical power divider.

The Turnstile Junction, as can be seen in Fig. 1, consists of four coplanar, rectangular arms and one circular arm, orthogonal to the rectangular arms. The network is termed a six-terminal pair unit with two of the terminal pair being attributed to the two polarizations in the circular guide, being shown by vectors A and B with the other terminal pairs being the four rectangular arms. The matching of the Junction is accomplished by adjustments of concentric pins, A and B, both in diameter and in length. The necessary and sufficient condition for match of the Junction is that the impedance looking into any of the arms (including circular) shall be matched when matched loads are put on the other four arms. Under the condition of a matched Junction, the following condition of power split exists.

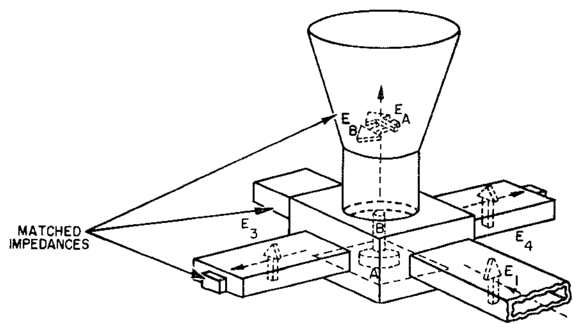

Fig. 1—Matching and power division relationships in turnstile.

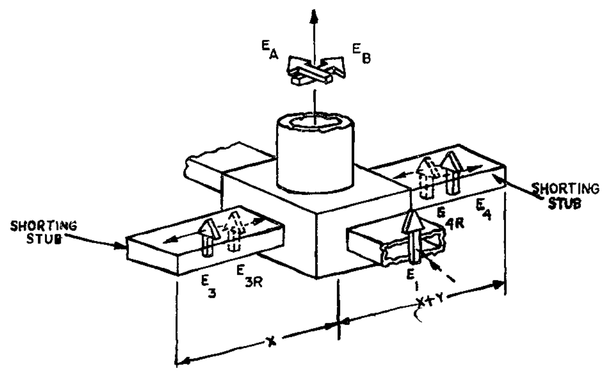

Fig. 2—Turnstile junction with shorts on two opposite rectangular arms.

If power is fed into any of the rectangular arms (we will assume arm 1), with arms 2, 3, 4, and the circular guides terminated in a match, one half of the incident power will be transmitted up the pipe with a polarization indicated by vector E_A in Fig. 1; the remaining fifty per cent of the incident power will divide equally between arms 3 and 4, with no power entering arm 2.

Using the above statement of power division, the proof of which is found in the literature,[1] we will show the applications to which this network can be put.

Referring to Fig. 2 we have terminated arms 3 and 4 in short circuits and impress our energy on arm 1, which divides according to the above relationships.

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[1] C. G. Montgomery, R. H. Dicke, and E. M. Purcell, "Principles of Microwave Circuits, Radiation Lab. Series, vol. 8, p. 459; 1948.

[2] G. L. Ragan, "Microwave Transmission Circuits," Radiation Lab. Series, vol. 9, p. 375; 1948.

[3] L. D. Smullin and C. G. Montgomery, "Microwave Duplexers," Radiation Lab. Series, vol. 14, p. 373; 1948.

Assuming the input to arm 1 to be of the form $E_1 = A \sin wt$, the initial division will be

$$E_3 = \frac{A}{2} \sin wt_0 \qquad E_4 = \frac{A}{2} \sin wt_0$$

$$E_A = \frac{A}{\sqrt{2}} \sin wt_0.$$

The reflected energy from the shorts on arms 3 and 4 will be:

$$E_{3R} = \frac{A}{2} \sin (wt_0 + 2x)$$

$$E_{4R} = \frac{A}{2} \sin [wt_0 + 2(x + y)],$$

where x and $x+y$ are the electrical lengths of arms 3 and 4, respectively. These reflected signals will tend to divide in the same manner as E_1. However, we wish to determine values of x and $x+y$ such that E_{3R} and E_{4R} will be propagated in the round guide with a polarization shown by vector E_B.

Before we can arrive at these values, we must consider the symmetry conditions of the Junction. From a study of the geometry of the Junction, it can be seen that there will be even symmetry between each rectangular arm and its two adjacent rectangular arms. In addition, there is odd symmetry between any two opposite rectangular arms and the circular arm.

From a consideration of these symmetry conditions, it can be seen that for E_{3R} and E_{4R} to add in the circular arm, there must be a 180° phase difference between the two signals, giving us

$$2(x + y) - 2x = \frac{\lambda g}{2},$$

or

$$y = \frac{\lambda g}{4},$$

where E_{3R} and E_{4R} add to form $E_B = A\sqrt{2}$ (sin $wt_0 + 2x$).

We now have propagating in the circular waveguide, two vectors of equal magnitude and 90° apart in space. The resulting field configuration of two equal orthogonal fields is an ellipse—the type of ellipse depending upon the relative time phase difference between the two orthogonal vectors. If the two vectors are in time phase, the resulting field will be a linear field oriented at 45° to vectors E_A and E_B. We will henceforth refer to this case as cross-linear polarization. If there is a 90° time phase difference between the two vectors, the resulting field will be a constant amplitude rotating vector which is referred to as circular polarization.

The time phase difference between the two vectors is accomplished by changing the absolute lengths of the shorts on arms 3 and 4, while still maintaining the $\lambda g/4$ difference in length between the two arms.

Since our condition for the cross-linear case was that E_A and E_B be in time phase,

$$E_B = \frac{A}{\sqrt{2}} \sin \left(wt_0 + 2n\frac{\lambda g}{2}\right),$$

giving the length for arm 3 as $n\ \lambda g/2$ and arm 4 as $(n\lambda g/2)+(\lambda g/4)$.

For the circular case we must obtain the 90° phase difference between E_A and E_B, giving

$$E_B = \frac{A}{\sqrt{2}} \sin \left[wt_0 + 2\left(\frac{\lambda g}{8} + \frac{n\lambda g}{2}\right),\right]$$

where arm 3 is now

$$\frac{\lambda g}{8}(1 + 4n),$$

and arm 4 is

$$\frac{\lambda g}{8}(3 + 4n),$$

where n is any positive integer.

The polarization can be changed from clockwise to counterclockwise rotation merely be interchanging the lengths of arms 3 and 4.

Microwave Duplexer

We now have sufficient information to describe the use of the turnstile as a cw duplexer. In this respect, we will discuss only the cases of circular and cross-linear polarization. However, the discussion can be extended to ellipses of any other major to minor axis ratio.

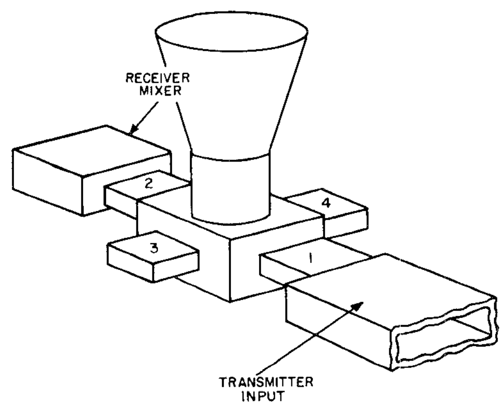

Fig. 3—Turnstile junction used as a cw duplexer.

Referring to Fig. 3, we have a microwave oscillator feeding into arm 1 of a Turnstile Junction, with the circular arm being terminated in a conical radiating horn. Arm 2, of the junction is terminated in a receiver mixer, which in this case can be a standard magic T, balanced mixer.

The radiating horn need not be limited to a circular cross section, but must have a form factor such that the horn is matched for fields propagating both in the E_A and E_B directions.

From the previous discussion we have shown that, when arms 3 and 4 are terminated in shorts which have a difference in length of $\lambda g/4$, all of the energy incident on arm 1 will be transmitted to the circular guide with no energy being coupled to arm 2 which is now our receiver mixer arm. From this consideration the junction acts as a duplexer between transmitter and receiver, for elliptical polarizations of any degree of ellipticity.

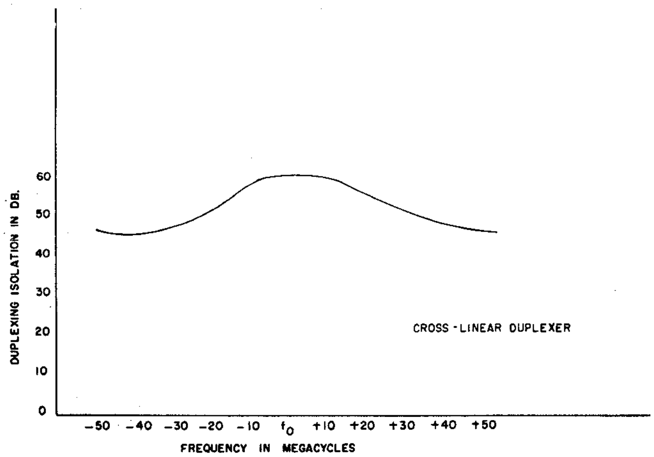

Fig. 4—Isolations vs frequency for cross-linear duplexer.

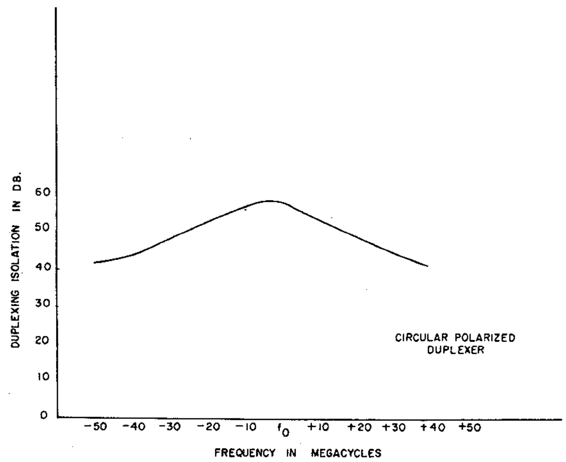

Fig. 5—Isolation vs frequency for circular duplexer.

Figs. 4 and 5 show curves of isolation between arms 1 and 2 versus frequency for the circular and cross-linear case. The unit on which this data was taken was designed for fixed frequency operation, and no attempt was made to broad-band the duplexing characteristics of the junction.

The reason for the difference in isolation characteristics between the circular and cross-linear cases will be explained in a following section.

Fig. 6 shows an actual Turnstile Junction combined with a magic T making up a complete duplexer, circular polarizer and balanced mixer assembly, at "x band."

Receiving Characteristics

Since the receiving characteristics of the cross-linear case differs from that of the circular case, we will discuss the two conditions separately.

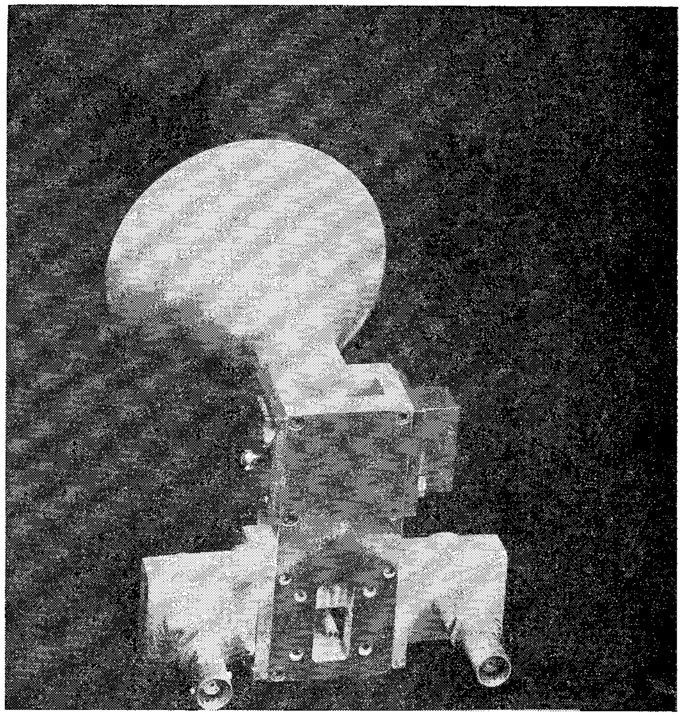

Fig. 6—Turnstile duplexer, circular polarizer, and receiver balanced mixer assembly.

Cross Linear

Fig. 7 shows the turnstile arranged for transmitting cross-linear polarization, with arm 1 the transmitter input. For this condition we have:

$$E_A = A \sin (wt_0)$$

$$E_B = A \sin (wt_0).$$

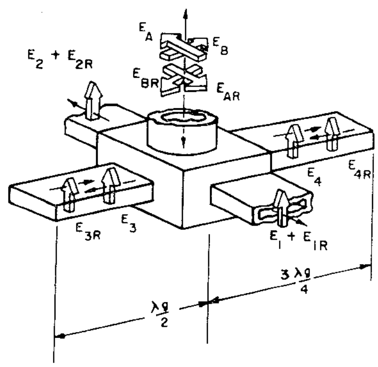

Fig. 7—Turnstile for transmitting linear and receiving cross-linear polarization.

Assuming that this signal is reflected from a plane target of infinite conductivity, oriented normal to the direction of travel of the wave, the boundary conditions necessary to satisfy the condition for zero tangential E field at the reflecting surface give us the two components of reflected field as

$$E_{AR} = A \sin (wt_0 + 180°)$$

$$E_{BR} = A \sin (wt_0 + 180°).$$

Considering the odd symmetry condition between the circular and rectangular arms E_{AR} tends to divide into arms 1 and 2, with

$$E_1 = \frac{A}{\sqrt{2}} \sin (wt + 180)$$

$$E_2 = \frac{A}{\sqrt{2}} \sin wt$$

E_{BR} divided into arms 3 and 4 with

$$E_3 = \frac{A}{\sqrt{2}} \sin (wt + 180)$$

$$E_4 = \frac{A}{\sqrt{2}} \sin wt.$$

The reflected signals from arms 3 and 4 arriving back at the junction will be of the form:

$$E_{3R} = \frac{A}{\sqrt{2}} \sin (wt + 180)$$

$$E_{4R} = \frac{A}{\sqrt{2}} \sin (wt + 180).$$

Due to odd symmetry, components of E_{3R} and E_{4R} that tend to propagate up circular guide cancel.

Thus, E_{3R} and E_{4R} divide equally between arms 1 and 2 with

$$E_{1R} = \frac{A}{\sqrt{2}} \sin (wt + 180)$$

$$E_{2R} = \frac{A}{\sqrt{2}} \sin (wt + 180).$$

However,

$$E_{2R} + E_2 = 0,$$

due to the out-of-phase relationship, and hence all of the reflected signal is returned to arm 1.

To summarize this condition, with turnstile adjusted for cross-linear polarization, a plane reflecting surface reflects all returned signal to transmitter arm.

From the standpoint of received signal, this means that a target which does not change the polarization (referred to a plane reflector) of the transmitted signal will appear in the transmitter arm of the turnstile.

In Fig. 8 we have a turnstile set up as in Fig. 7. We will now assume that the reflecting target is such that the returned signals are rotated 90° relative to the reflected signal in Fig. 7.

Our signal relationships for this case follow:

$$E_A = A \sin wt_0 \qquad E_{AR} = A \sin wt_0$$

$$E_B = A \sin wt_0 \qquad E_{BR} = -A \sin wt_0$$

E_{AR} divided into arms 3 and 4 with $E_3 = \frac{A}{\sqrt{2}} \sin wt_0$

$$E_4 = -\frac{A}{\sqrt{2}} \sin wt_0.$$

These signals reflected from the shorts and arriving back at the center of the junction become

$$E_{3R} = \frac{A}{\sqrt{2}} \sin wt_0 \qquad E_{4R} = \frac{A}{\sqrt{2}} \sin wt_0.$$

These signals divide further into arms 1 and 2 with

$$E_{1R} = \frac{A}{\sqrt{2}} \sin wt_0$$

$$E_{2R} = \frac{A}{\sqrt{2}} \sin wt_0.$$

The reflected signal E_{BR} divided into arms 1 and 2 with

$$E_1 = -\frac{A}{\sqrt{2}} \sin wt_0 \qquad E_2 = \frac{A}{\sqrt{2}} \sin wt_0.$$

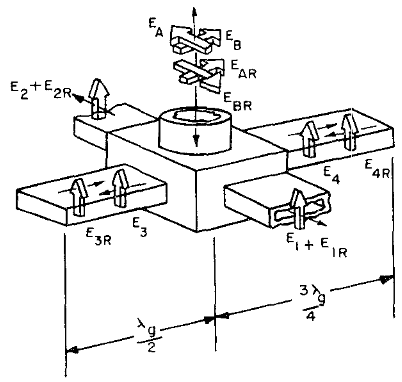

Fig. 8—Turnstile with 90° field rotation between transmitted and received signal.

Combining these two signals with E_{1R} and E_{2R}, we see that there is cancellation in arm 1 with all the reflected signal transmitted to arm 2. This result is opposite to that of the case of Fig. 7. To summarize this condition, if the reflected wave is shifted 90° with respect to that of a plane reflector, the reflected signal will enter arm 2, which is our receiver arm.

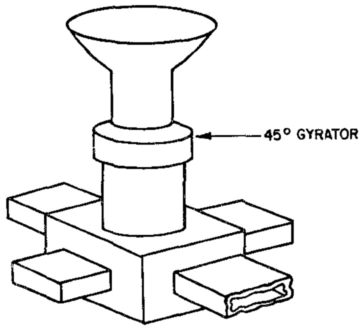

Fig. 9—Turnstile arrangement for transmitting and receiving linear polarization.

This shift can be achieved by inserting a 45° gyrator in series with the conical, radiating horn, so that the signal receives 45° rotation on being transmitted and an additional 45° on being received. This arrangement is shown in Fig. 9.

Circular Polarization

We will now discuss the condition of received signals when the turnstile is set up for circular polarization. Referring to Fig. 10, we have the junction set up for circular polarization which we will assume is clockwise with vector E the rotating vector being a resultant of components E_A and E_B, which are 90° out of phase and varying sinusoidally with time. With arm 1 the input, the components vectors are

$$E_B = A \cos wt_0$$
$$E_A = A \sin wt_0.$$

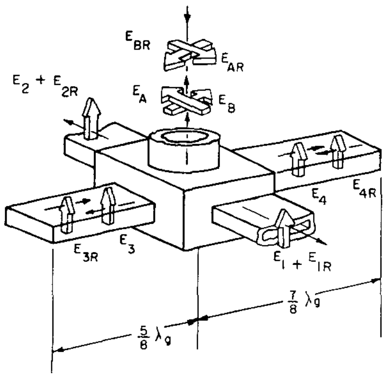

Fig. 10—Turnstile for transmitting and receiving circularly polarized waves.

The signals as reflected from a plane target become

$$E_{AR} = -A \sin wt_0$$
$$E_{BR} = -A \cos wt_0.$$

Vector E_{BR} will divide between arms 3 and 4 as follows:

$$E_3 = \frac{A}{\sqrt{2}} \cos wt \qquad E_4 = -\frac{A}{\sqrt{2}} \cos wt.$$

These are reflected by the shorts giving E_{3R} and E_{4R} at the junction.

$$E_{3R} = -\frac{A}{\sqrt{2}} \sin wt_0$$
$$E_{4R} = -\frac{A}{\sqrt{2}} \sin wt_0.$$

Vector E_{3R} divides into arms 1 and 2 where

$$E_1 = \frac{A}{\sqrt{2}} \sin wt_0$$
$$E_2 = -\frac{A}{\sqrt{2}} \sin wt_0.$$

E_{3R} and E_{4R} divide between arms 1 and 2 so that

$$E_{1R} = -\frac{A}{\sqrt{2}} \sin wt_0$$
$$E_{2R} = -\frac{A}{\sqrt{2}} \sin wt_0.$$

The fields in arm 1 cancel due to difference in sign, and therefore all energy will be sent into arm 2 which is our receiver arm.

We have therefore shown that the reflection from a target that does not depolarize the signal (referred to a plane conducting reflector) will be sent into the receiver arm.

In other words, if a turnstile is set up to generate clockwise polarization, it will receive counterclockwise polarization into the receiver arm. By the same reasoning, it can be shown that clockwise polarization will be sent into the transmitter arm.

In an earlier section of this paper, in which we discussed duplexing action, it was pointed out that there was a difference in duplexer characteristic between circular and cross-linear arrangements. This can be explained by the fact that the matched load on the circular guide varies in impedance with changes in frequency. In the circular case, these reflections are sent into the receiver arm, thus contributing to poorer isolation. In the cross-linear case these reflections are sent into the transmitter arm. They contribute to higher input vswr, but do not deteriorate the isolation characteristics.

Polarization Checker

It can be shown that any elliptically polarized wave can be broken down into two circularly polarized waves of different amplitudes, one clockwise and the other counterclockwise. This fact provides us with an excellent way to check the degree of ellipticity of a wave. If we adjust our turnstile shorts for circular polarization and put detectors on the other two rectangular arms, using the circular guide, flared into a pickup horn as the input, one of the rectangular arms will accept the clockwise polarization and the other arm, the counterclockwise component. The ratio between the powers in the two arms will then serve as a measure of the circularity of the incident wave.

Four-Way Power Divider

It was shown in reference to Fig. 7 that signals E_{BR} and E_{AR} on entering the junction divide initially, as follows:

$$E_1 = \frac{A}{\sqrt{2}} \sin wt$$
$$E_2 = \frac{A}{\sqrt{2}} \sin wt$$
$$E_3 = -\frac{A}{\sqrt{2}} \sin wt$$
$$E_4 = \frac{A}{\sqrt{2}} \sin wt.$$

Since E_{AR} and E_{BR} are in time phase, they can be considered as components of E_C, where

$$E_C = 2A \sin wt.$$

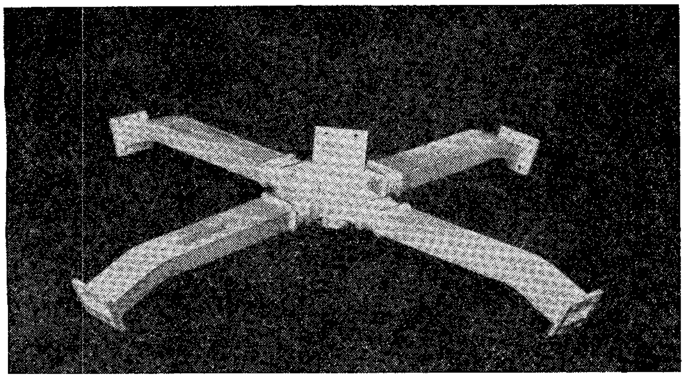

Fig. 11—Turnstile junction as a symmetrical 4-way power divider.

Thus, if a signal is impressed into the circular arm with its polarization along E_C, it will divide with equal amplitude in the four rectangular arms, giving us a symmetrical four-way power divider.

Fig. 11 shows a photograph of this arrangement. The equality of division is a function of the accuracy of orientation of the rectangular feed to the turnstile and the impedances on the rectangular arms.

An equal power split of 0.2 db is not difficult to achieve if care is taken to preserve symmetry in the construction of the junction. Fig. 12 shows a basic turnstile junction.

Three-Way Power Divider

In addition to the four-way power dividing properties of the Junction, it is also possible to modify the characteristics to a three-way power divider.

Referring to Fig. 7, if $E_1 = A \sin wt$, the initial signal division will be as follows:

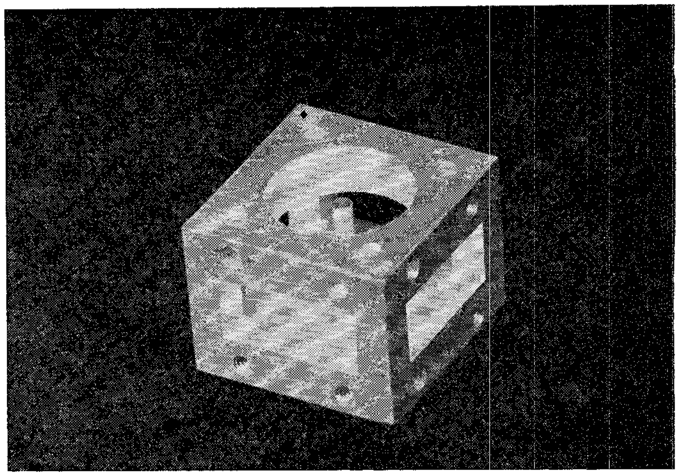

Fig. 12—Basic turnstile junction.

$$E_3 = \frac{A}{2} \sin wt \qquad E_4 = \frac{A}{2} \sin wt.$$

$$E_A = \frac{A}{\sqrt{2}} \sin wt$$

If the circular guide is now terminated in a short circuit, E_A will divide into arms 1 and 2 with

$$E_{1R} = \frac{A}{2} \sin (wt + 180°)$$

$$E_{2R} = \frac{A}{2} \sin wt.$$

If we now match the input to arm 1 with a simple post or iris we will have the incident power to arm 1 divided equally into arms 2, 3, and 4, thus affecting another useful application for the Junction.

The Ultra-Bandwidth Finline Coupler*

SLOAN D. ROBERTSON†

Summary—**The "finline coupler" is a recently developed microwave circuit element with which it has been possible to assemble hybrid junctions, directional couplers, and polarization-selective couplers capable of operating over bandwidths of at least three-to-one in frequency. Constructional details and experimental results are given.**

THE ACCELERATED development of modern communication technology in the past few years has been characterized by two readily discernible patterns; the progression to higher and higher frequencies in the spectrum, and the corollary demand for greater bandwidths. The requirements of the latter have been met in part by the development of traveling-wave amplifiers and backward-wave oscillators capable of operating over enormous bandwidths of the order of two-to-one in frequency. It would appear that a point has been reached where further development in the direction of increasing bandwidths is being inhibited by the lack of sufficiently wide-band microwave circuit components, such as directional couplers, hybrid junctions, and waveguide bends. It is the purpose of the present paper to describe the "finline coupler," a new microwave circuit element, in a form evolved jointly by H. T. Friis and the author, with which it has been possible to design hybrids, directional couplers, and polarization-selective couplers capable of operating over bandwidths of at least three-to-one in frequency.

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