The Turnstile Circulator*

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Summary—**Theory and performance of a narrow band circulator employing but a single junction and a 45-degree Faraday rotator are discussed. Factors affecting bandwidth are considered and pertinent curves are plotted. Isolation bandwidth curves permit prediction of performance. This compact circulator, although frequency sensitive, is tunable and provides high reverse and cross isolations making it especially suited to duplexing, isolating and switching applications.**

ONE OF THE most valuable fundamental applications of the microwave gyrator[1] is in the realization of the microwave circulator,[1-6] a nonreciprocal multiport network having unique properties. A number of forms of microwave gyrator are now known and have been incorporated in a variety of circulators differing in geometry and performance capability. This paper describes still another circulator form—one of the simplest—incorporating a 45° Faraday rotator and a single turnstile junction. Although the circulator to be described is frequency sensitive, it is capable of high isolation with low insertion loss, is compact, and has a convenient terminal arrangement.

THE TURNSTILE JUNCTION

Before discussing the principle of the turnstile circulator, the pertinent properties of the basic turnstile junction[7-9] will be briefly reviewed. As illustrated in Fig. 1, the turnstile is a 6-port junction consisting of a circular waveguide symmetrically joining two intersecting rectangular waveguides. A symmetrical matching structure is located at the center of the junction. When the junction is properly matched and all ports are terminated in matched loads the junction exhibits the coupling properties listed in Tables I and II.

From symmetry of the junction its other coupling properties can be inferred.

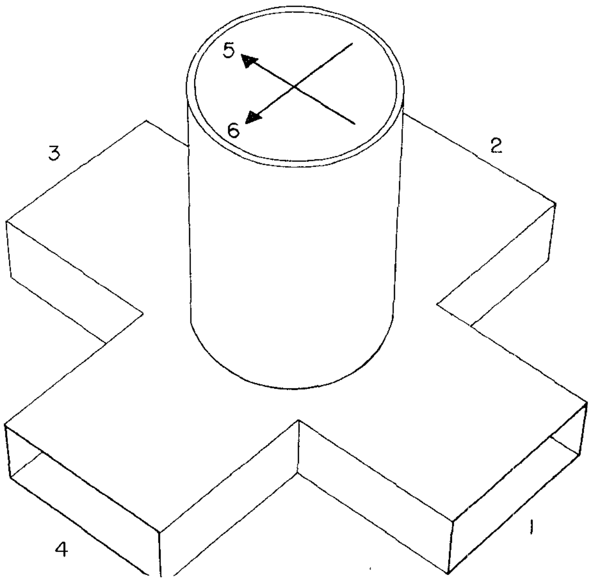

Fig. 1—The waveguide turnstile—a symmetrical 6-port junction.

TABLE I

UNIT POWER INPUT TO ARM 1

Arm	Coupled Power	Voltage*	Coupling
1	—	—	(No reflection)
2	1/4	0.5	−6 db.
3	0	0	(Isolated)
4	1/4	0.5	−6 db.
5	1/2	0.707	−3 db.
6	0	0	(Isolated)

TABLE II

UNIT POWER INPUT TO ARM 6

Arm	Coupled Power	Voltage*	Coupling
1	0	0	(Isolated)
2	1/2	−0.707	−3 db.
3	0	0	(Isolated)
4	1/2	0.707	−3 db.
5	0	0	(Isolated)
6	—	—	(No reflection)

* Voltage referred to Z_0 of rectangular waveguide arms.

THE TURNSTILE CIRCULATOR

The turnstile circulator consists simply of a turnstile junction containing a 45° Faraday rotator in the circular waveguide which is short-circuited at an appropriate point. Circulator action will be explained by referring to Fig. 2. Consider a conventional turnstile junction

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which is properly matched, with a signal entering arm 1, and the remaining three rectangular arms terminated in matched loads. The signal will divide at the junction and excite arms 2 and 4 equally and in phase, and will excite the circular arm with a linear TE_{11} mode polarized in the plane of arrow 5. Opposing arms of the junction are isolated from one another (Table I) and thus no power is coupled out arm 3.

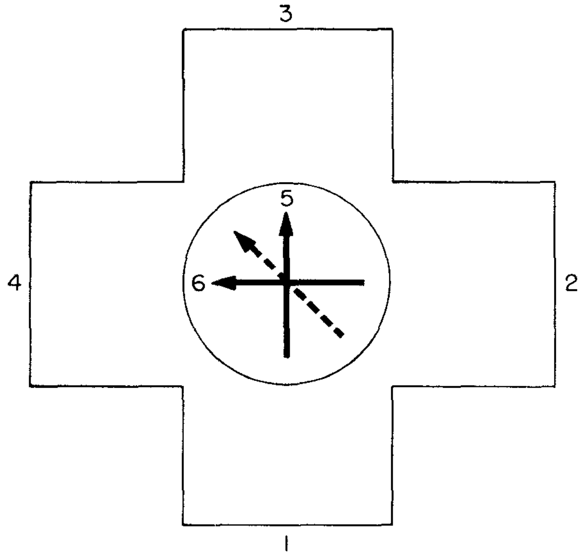

Fig. 2—In the turnstile circulator, polarization 5 is rotated 45 degrees, is reflected, then is rotated 45 degrees further to polarization 6.

After passing up through the 45° Faraday rotator, the component in the circular arm will be polarized at 45° as indicated by the dashed arrow. This component is then reflected by the short circuit back through the Faraday rotator causing an additional 45° rotation, so that the component is now polarized in the plane of arrow 6, at right angles to its original polarization. Ordinarily, on entering the junction, the power in such a component would divide equally but out of phase between arms 2 and 4 (Table II). However, assuming a lossless rotator, the voltage which this component excites in arms 2 and 4 is equal to exactly one-half the input voltage on arm 1. Since the polarization (in 5) has been rotated exactly 90° (to 6) there is no coupling of this component to arms 1 or 3.

By adjusting the position of the short circuit in the circular arm, vector 6 can be so phased at the junction that the *direct* and *reflected* components cancel at arm 4 and add in arm 2. The net result being that all of the power entering arm 1 leaves the junction by arm 2, while arms 3 and 4 are isolated from arm 1. Because of symmetry conditions and by similar reasoning, it should be apparent that a signal entering arm 2 couples only to arm 3, arm 3 couples only to arm 4, and arm 4 couples only to arm 1. This is the characteristic property of a circulator.

If the sense of Faraday rotation is reversed, as by reversing the applied magnetic field, or if the circular arm short circuit is moved a quarter of a wavelength, the order of the indicated coupling relationships will also be reversed. Arm 1 then would couple to arm 4, arm 4 to arm 3, etc.

Signal cancellation in the arm adjacent to the input arm is the result of cancellation between the *direct component* which couples directly from arm 1 to arm 2, and the *reflected component* which travels up and back the length of the shorted circular waveguide arm. It is this differential path length which makes the turnstile circulator frequency sensitive. Obviously, the shorter the circular arm the greater the bandwidth obtainable. In practice it is the physical length of the 45° Faraday rotator which limits the minimum length of the circular waveguide stub. A "turnstile circulator" with a *zero-length* Faraday rotator element need not be frequency sensitive.

CIRCULATOR PERFORMANCE—THEORETICAL

A number of factors affect performance of the turnstile circulator. These include junction imperfections, rotator loss and mismatch, phase error, and deviation from correct Faraday rotation angle. For simplicity in the discussion which follows, a perfect junction is assumed, the rotator element is reflectionless and lossless, round-trip rotation is exactly 90°, and arms 2, 3, and 4 are terminated in matched loads.

If all voltages are referenced to the point in the turnstile junction at which vector addition of the direct and reflected components takes place, then with an input signal, v, on arm 1 the voltage at the junction terminus of arms 2 and 4 is

$$E_0 = \frac{v}{2} \pm \frac{v}{2} \exp(-j\beta l). \qquad (1)$$

βl is the differential path length in radians, β being the effective phase constant, at the operating frequency, of the circular waveguide stub having a round-trip length l.

If l, the total path length in the circular guide is restricted to an integral number, n, of half guide wavelengths $(\lambda_{g0}/2)$ at the design frequency, and β is expressed in terms of guide wavelength λ_g at the operating frequency, then (1) can be written

$$E_0 = \frac{v}{2}\left[1 \pm \exp\left(\frac{-j2\pi}{\lambda_g} \cdot \frac{n\lambda_{g0}}{2}\right)\right]. \qquad (2)$$

Eq. (2) expresses the variation in outputs of arms 2 and 4 as a function of circular guide wavelength, λ_g. To make (2) more general, let $\lambda_{g0}/\lambda_g = \lambda_g'$, where λ_g' is what may be termed the "normalized guide wavelength." Then, substituting in (2) and expanding,

$$E_0 = \frac{v}{2}(1 \pm \cos n\pi\lambda_g' \mp j \sin n\pi\lambda_g'). \qquad (3)$$

Eq. (3) has been plotted in Figs. 3 and 4 for various integral values of n, against the normalized circular guide wavelength, λ_g'. Note that the functions are periodic. Ordinarily, the turnstile circulator is operated in the vicinity of $\lambda_g' = 1$. For a given direction of Faraday rotation, *even* integral values of n place the null in one adjacent arm, while *odd* integral values of n place the

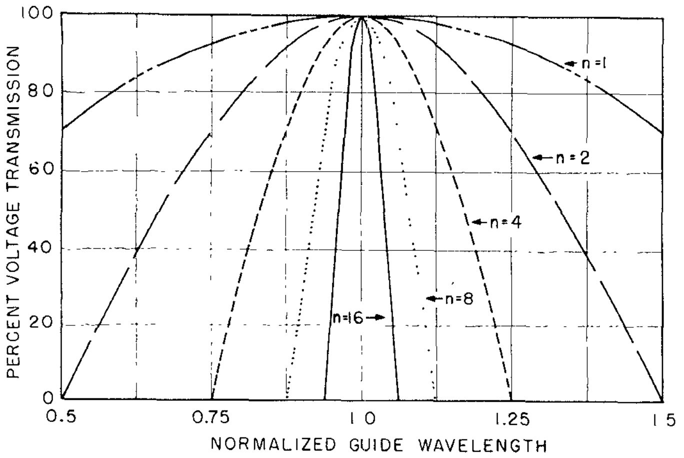

Fig. 3—Forward transmission characteristic of the turnstile circulator for various differential path lengths.

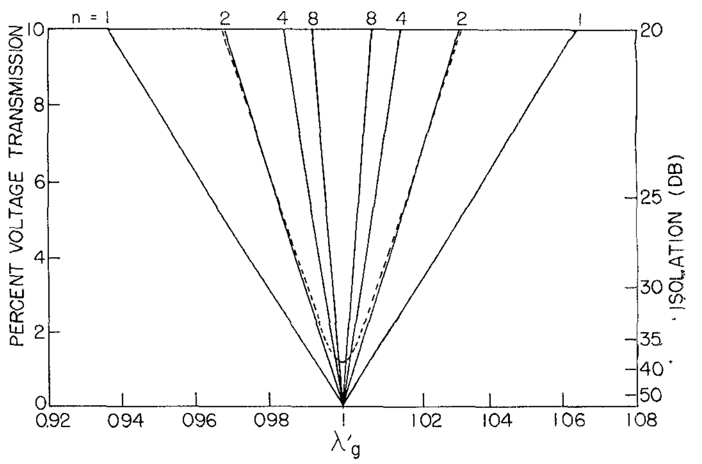

Fig. 5—Reverse isolation characteristic, and effect on isolation of a 0.2 db rotator loss.

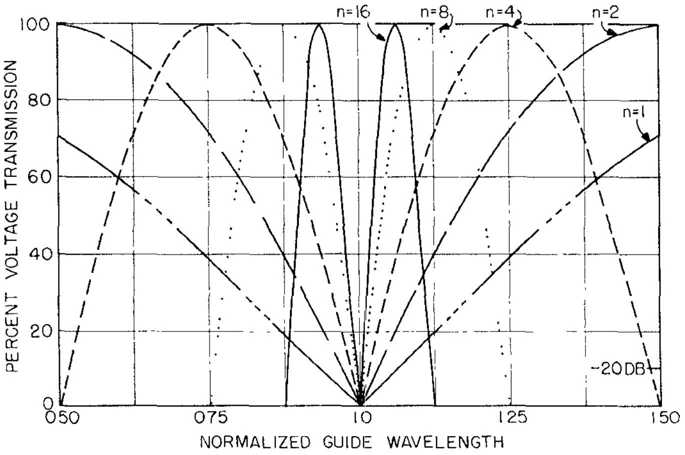

Fig. 4—Reverse transmission characteristic for various differential path lengths.

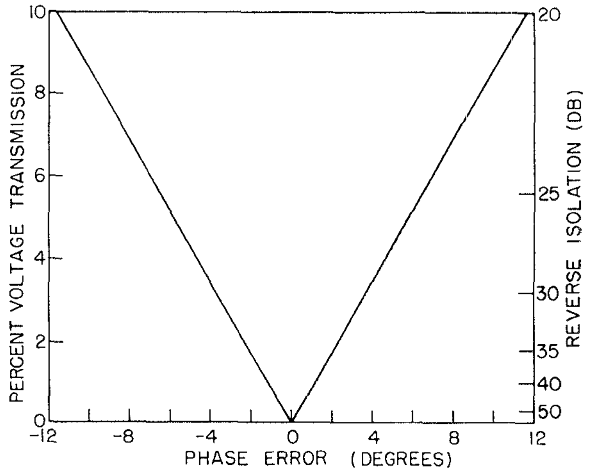

Fig. 6—Reverse isolation as a function of differential phase error.

null in the other adjacent arm. Reversing the direction of Faraday rotation also interchanges the isolated and transmission arms (*i.e.*, it reverses the direction of "circulation").

For small values of E_0 (less than $v/10$), (3) may be simplified and rearranged to

$$\left|\frac{E_0}{v}\right| \sim \frac{|\sin n\pi\lambda_g'|}{2}, \tag{4}$$

and the adjacent arm- or "reverse" isolation can be expressed directly in db.

$$\text{Reverse Isolation (db)} \sim 20 \log \frac{|\sin n\pi\lambda_g'}{2} \cdot \tag{5}$$

Eqs. (4) and (5) are illustrated in Fig. 5 where E_0 is expressed in per cent voltage transmission (*i.e.*, $100E_0/v$) and is plotted for various values of n against the normalized circular guide wavelength, λ_g'. The right-hand ordinate shows the reverse isolation in db.

The deterioration in reverse isolation (Fig. 5) as λ_g' deviates from unity is of course due to phase error between the direct and the reflected components. The effect of this phase error, ϕ, is expressed more explicitly in (6) and (7), plotted in Fig. 6.

$$\frac{E_0}{v} \sim \frac{\sin\phi}{2} \tag{6}$$

$$\text{Reverse Isolation (db)} \sim 20 \log \frac{\sin\phi}{2} \cdot \tag{7}$$

When there is no rotation error and loss is negligible, these equations are accurate for phase errors as large as ±12 degrees. Fig. 6 is convenient for determining the phase accuracy required for a desired reverse isolation, and of course applies regardless of n, frequency, or guide wavelength. (*Cross* isolation, on the other hand, is independent of phase error, but is affected by Faraday rotation error. This effect will be discussed later.)

The principal effect of a small amount of loss in the rotator is to reduce the maximum value of attainable reverse isolation. The dashed curve in Fig. 5 shows the effect of a rotator loss of 0.2 db for the case $n=2$. Incidentally, the insertion loss of the circulator is approximately one-half that of the rotator itself.

BANDWIDTH DETERMINATION

To obtain reverse isolation bandwidths of the turnstile circulator explicitly it is necessary to determine the frequencies which correspond to values of λ_g'. Upper and lower limiting values of λ_g' for various reverse isolations have been computed for $n=1$ and are given in Table III as λ_{g1}', and λ_{g2}'.

TABLE III

Reverse Isolation (db)	λ_{g1}'	λ_{g2}'
20	1.06407	0.93593
30	1.02024	0.97976
40	1.00641	0.99359
50	1.00202	0.99798

$$\left[\lambda_{g1} = \frac{\lambda_{g0}}{\lambda_{g1}'},\ \lambda_{g2} = \frac{\lambda_{g0}}{\lambda_{g2}'}\right].$$

Now, if λ_{g0}, the circular guide wavelength at the design frequency is known, λ_{g1} and λ_{g2} can be determined, and using (8), the upper and lower frequency limits can be found.

$$f = 30 \frac{\sqrt{\lambda_c^2 + \lambda_g^2}}{\lambda_c \lambda_g} \tag{8}$$

where f is in kmc, λ_c is cut-off wavelength in cm of the circular waveguide, and λ_g is the wavelength (λ_{g1} or λ_{g2}) in cm in the circular guide at the frequency in question.

For the bandwidths involved, the error is not serious if one considers the reverse isolation bandwidth to vary inversely with n. Thus, one might conveniently solve for bandwidth as above and divide by the value of n for the particular circulator in question.

The db bandwidths for a 15/16″ id circular waveguide have been computed for $n=1$ at a design center frequency of 9375 mc, and making the approximation that the bandwidth varies inversely with n, curves have been plotted in Fig. 7. It can be seen that if a turnstile circulator could be designed with a circular arm as short as $n=1$, then a 20 db bandwidth of 454 mc should be obtained. In practice, however, it may be difficult to realize such a short Faraday rotator. Usable bandwidths are readily obtainable, however, as shown in a later section which describes an experimental model.

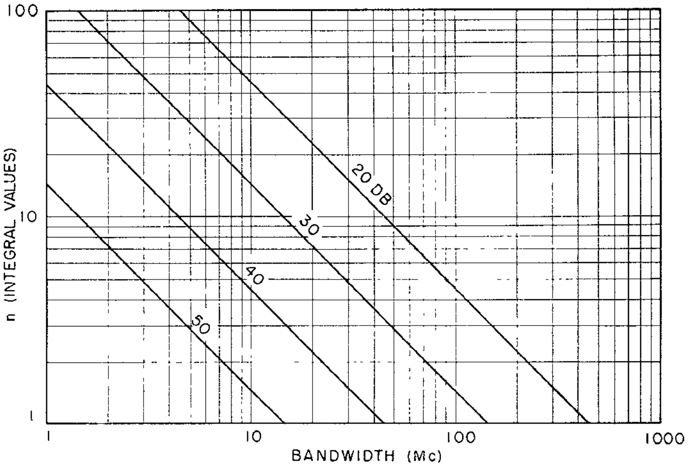

Fig. 7—Reverse isolation bandwidth curves as a function of differential path length.

Effect of Rotation Error

In the foregoing considerations it has been assumed that there was no Faraday rotation error. Now it will be assumed that there is no phase error, and the effect on isolation of rotation error will be considered. In the *ideal* turnstile circulator there is no coupling between opposing rectangular arms, that is, the *cross* isolation is infinite. Any departure from exact 90° total rotation, however, results in a field component in the plane of vector 5 (Fig. 2) which couples to arm 3 causing a deterioration in cross isolation, and to arm 1 causing input vswr to increase. Rotation error also causes a slight reduction in the amplitude of the component in the plane of vector 6 (Fig. 2) which has a secondary effect on the *reverse* isolation of the circulator.

It can be shown that with no other errors, the cross isolation in the turnstile circulator is determined by the Faraday rotation error (*i.e.*, the departure, ψ, from 90°) in accordance with the following expression.

$$\text{Cross Isolation (db)} = 20 \log \frac{\sin \psi}{2} \tag{9}$$

where ψ is rotation error, that is, departure from 90° rotation.

Reverse isolation is also affected by rotation error but to a lesser extent as indicated by

$$\text{Reverse Isolation (db)} = 20 \log \frac{1 - \cos \psi}{2}. \tag{10}$$

It is assumed in (10) that there is no phase or attenuation error.

Eqs. (9) and (10) have been plotted in Fig. 8 to graphically illustrate the relative effect of rotation error on the reverse isolation (curve A) and the cross isolation (curve B). For comparison, curve C indicates the effect of rotation error on reverse isolation in a conventional Faraday rotation circulator, where

$$\text{Reverse Isolation (db)} = 20 \log \sin \psi. \tag{11}$$

Ideally, *cross* isolation in the conventional rotation circulator is independent of rotation error.

In the turnstile circulator, if a change in rotation is introduced *after* the phase has been properly adjusted, a phase error may also be introduced which will result in a reverse isolation less than that indicated by (10). Correcting the phase will restore the isolation. This indicates that the proper way to adjust the turnstile circulator for maximum isolations is first to adjust Faraday rotation for best *cross* isolation, and then to adjust phase (circular arm length) for best *reverse* isolation, at the operating frequency.

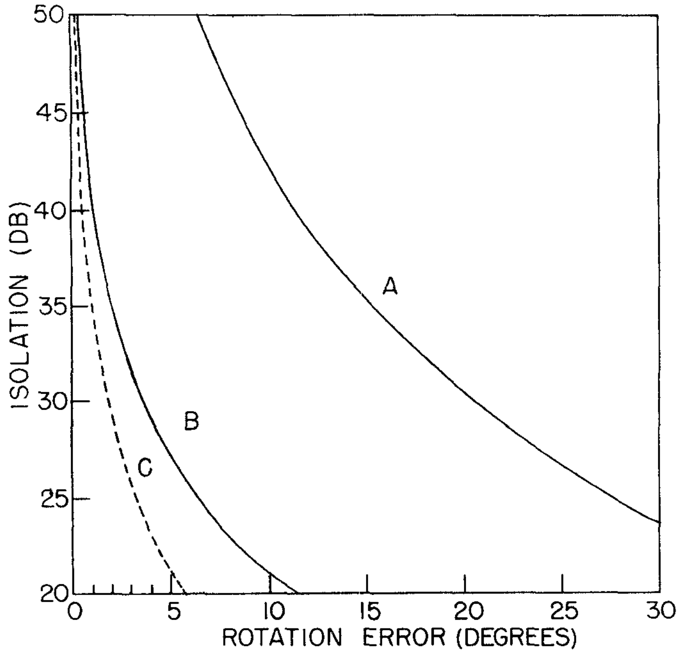

Fig. 8—Effect of rotation error on isolation. A) Reverse isolation. B) Cross isolation. C) Reverse isolation in a conventional rotation circulator.

Experimental Circulator Performance

An experimental turnstile circulator similar to the one pictured in Fig. 9 on the right, has been constructed and its performance measured. The circular waveguide arm had an inside diameter of 15/16 inch and, as determined from experimental measurements, a length of $n=8$. The Faraday rotator was a rod of Ferramic 1331 about one inch long and 7/32 inch in diameter. Polystyrene matching plugs on both ends of the ferrite rod made the unit about two inches long over-all. This was supported in a styrofoam cylinder which fitted the circular waveguide snugly. Magnetic field was applied by an external solenoid. A circular choke plunger was used as an adjustable short circuit.

Optimum adjustment of the circulator at 9375 mc resulted in a maximum cross isolation of 46 db, and a maximum reverse isolation of 46 db. Measured bandwidths were as follows: 20 db, 57 mc; 30 db, 18 mc; 40 db, 5 mc. Assuming n to be 8, these points fall exactly on the curves of Fig. 7, within an experimental measurement error of ±0.5 mc. In this particular model the circular arm was somewhat longer than that required to accommodate the rotator. Circulator insertion loss was measured as 0.15 db, and input vswr was under 1.05:1 at the design frequency.

Application

Being a frequency-sensitive device, the turnstile circulator is perhaps best adapted to fixed frequency applications where a high performance circulator is required, although it can be made tunable over a wide band. Its relatively economical construction, simplicity, compactness, and convenient terminal arrangement make it acceptable for many circulator applications. The high cross isolation obtainable suggests its value as a duplexer in cw radar applications, for example. The high reverse isolation is of particular value in switching applications such as antenna lobe switching or for signal chopping. It should be pointed out that in this application, as the Faraday rotation passes through zero the cross isolation goes to 6 db and the input vswr goes to 3:1. In pulse systems, these undesirable effects can be avoided simply by synchronizing the switching cycle. The turnstile circulator should be of value in numerous other circulator applications.

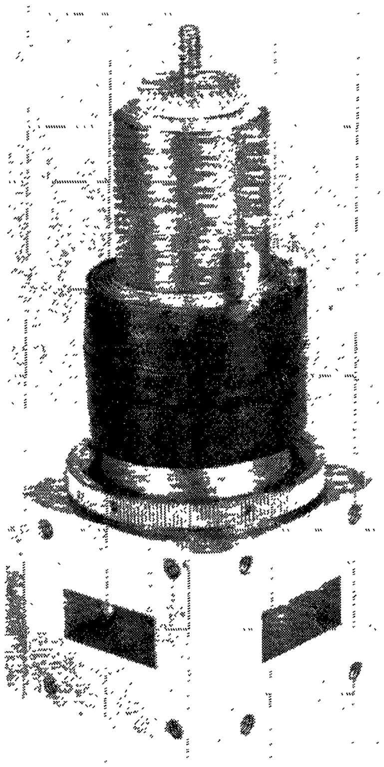

Fig. 9—Experimental X-band model of the turnstile circulator.

Conclusion

The turnstile circulator is a compact, narrow band, high-performance circulator, having convenient terminal arrangement, and since it employs but a single junction is relatively economical to construct. High values of cross and reverse isolation are obtainable in a circulator having very low forward loss. The device is especially well suited to fixed frequency duplexing, isolating, or switching. Although inherently "narrow band," the circulator can be designed to be tunable over a broad band. Average power handling capability is limited by ferrite heating, while peak power capability will be limited either by ferrite saturation effects or by voltage breakdown in the circular waveguide where standing waves occur. Turnstile circulators having low insertion loss and significant isolation bandwidths can be made with commercially available ferrite materials.

Acknowledgment

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