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FOUR PORT FERRITE CIRCULATOR HAVING SLOT SYMMETRICALLY
LOCATED BETWEEN ADJACENT CONDUCTING ARMS

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2 Sheets-Sheet 1

FIG. 1

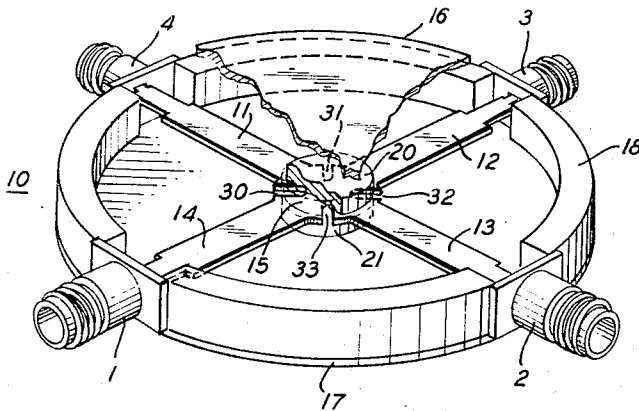


FIG. 2

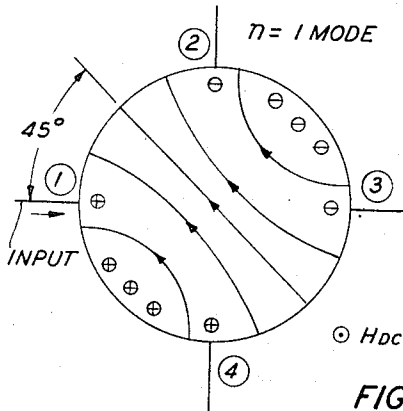


FIG. 3

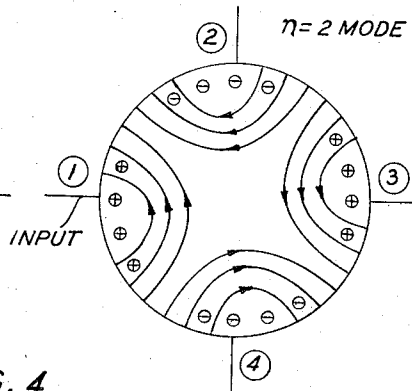
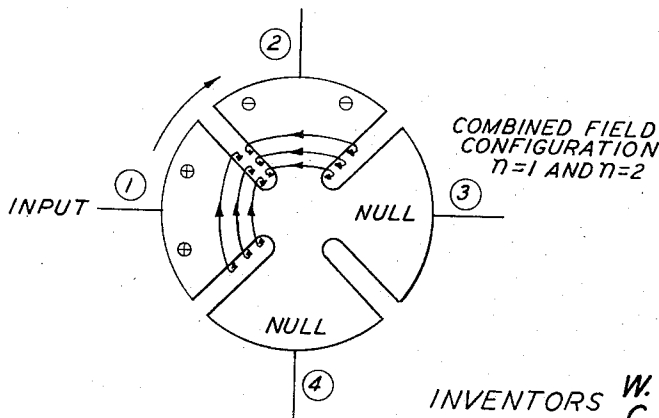


FIG. 4



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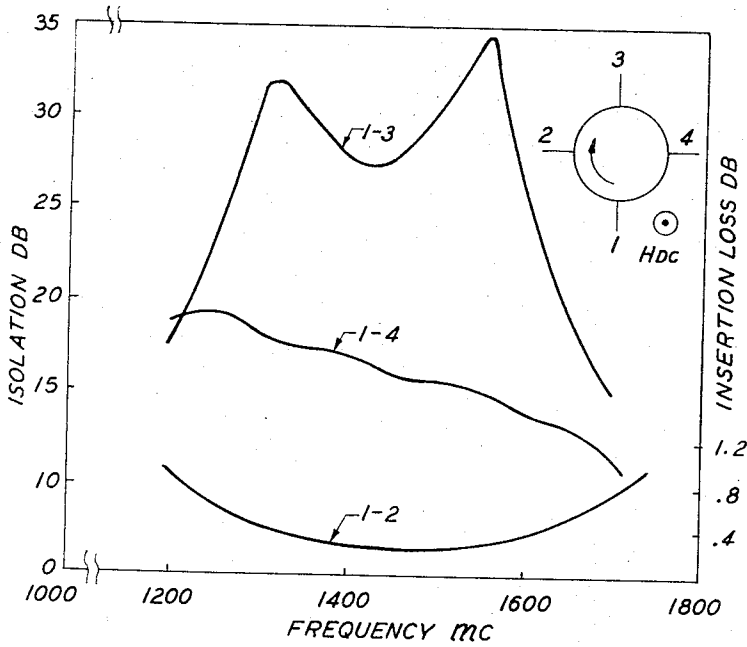
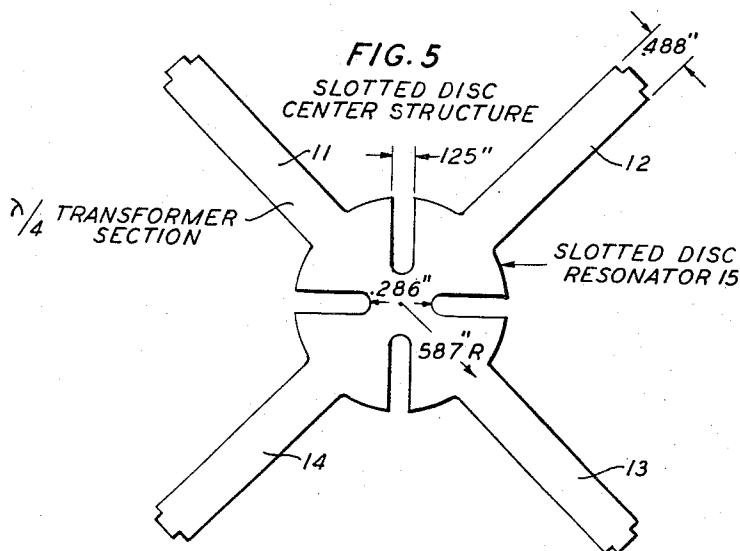
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FIG. 6



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FOUR PORT FERRITE CIRCULATOR HAVING SLOT SYMMETRICALLY LOCATED BETWEEN ADJACENT CONDUCTING ARMS

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This invention relates to single-junction, four-port coaxial circulators.

At present, coaxial four-port circulators are made up of two, tandem-connected three-port circulators. This is so since the operating characteristics of currently available single-junctions, four-port circulators are inadequate for many applications. Obviously, a single-junction, four-port circulator, having improved electrical characteristics, would be an attractive alternative in that it would be half the size of two three-ports and, correspondingly, less expensive.

Accordingly, it is the broad object of this invention to improve the operating characteristic of single-junction, four-port circulators.

In accordance with the present invention, improvements in the performance of single-junction, four-port strip transmission line circulators are realized by the particular configuration of the junction conductor. In particular, the junction conductor, which is a circular disc, is provided with radial slots for tuning the junction resonant modes. These slots are symmetrically disposed 90 degrees apart about the disc, equidistant between adjacent branches of the circulator.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is an illustrative embodiment of the invention;

FIG. 2, included for purposes of explanation, shows the field configuration of the $n=1$ mode of a simple disc resonator;

FIG. 3, included for purposes of explanation, shows the field configuration of the $n=2$ mode of a simple disc resonator;

FIG. 4, included for purposes of explanation, shows the combined field configuration of the $n=1$ and $n=2$ modes, where both are resonant at the same frequency;

FIG. 5 shows the dimensions of an L-band circulator in accordance with the invention; and

FIG. 6 shows the performance characteristic of the circulator of FIG. 5.

Referring to the drawings, FIG. 1 shows an illustrative embodiment of a single-junction, four-port strip transmission line circulator 10, in accordance with the invention. Basically, a circulator comprises a plurality of wavepaths emanating from a common junction. In the illustrative embodiment, the wavepaths are four balanced strip transmission lines whose inner conductors 11, 12, 13 and 14 radiate from a circular conductive disc 15. In particular, the conductors are spaced 90 degrees apart about the periphery of disc 15, and extend away from it in a radial direction.

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A pair of circular ground plane members 16 and 17, maintained in parallel spaced relationship by means of a cylindrical supporting member 18, are shared in common by the four transmission lines. The ground plane members 16 and 17, and the support member 18 are made of electrically conductive material, and are secured together by suitable means to form a conductively bounded junction cavity. While this particular embodiment has a circular cylindrical shape, and access to and from the four branches is by way of coaxial connectors 1, 2, 3 and 4, it is understood that these are merely structural details. Other arrangements and shapes can be used, as the situation demands, without departing from the teachings of the invention.

In accordance with usual practice, the width of the conductors 11, 12, 13 and 14, and the spacing between the conductors and the ground planes are such as to produce the desired characteristic impedance.

Located between ground plane 16 and disc 15 is a circular cylindrical element 20 of gyromagnetic material. Various nonconducting ferrimagnetic or ferromagnetic materials can be used for this purpose, of which yttrium-iron-garnet is illustrative. Element 20 preferably has a height that fills the space between disc 15 and conductor 16 and a diameter that is equal to, or less than, that of disc 15. These dimensions are matters of design and do not appear to be critical.

A second gyromagnetic element 21 is located between disc 15 and conductor 17, or, alternatively, a nongyromagnetic dielectric member can be used.

The gyromagnetic elements are magnetically biased normal to their broad surfaces by suitable means, not shown.

Circulator action is obtained when wave energy applied to one branch of a circulator is essentially coupled to one, and only one of the other branches of the circulator. As indicated by C. E. Fay and R. L. Comstock in their paper entitled "Operation of the Ferrite Junction Circulator," published in the January 1965 issue of the Institute of Electrical and Electronics Engineers Transactions on Microwave Theory and Techniques, vol. MTT-13, pages 15-27, this involves inducing two standing wave modes in the junction cavity such that, when taken together, they combine to produce a standing wave field configuration which includes null points at the non-coupled branches, and equal, high amplitude fields at the input and output branches. As noted by Fay and Comstock, however, a difficulty typically encountered is that a cavity normally does not resonate in more than one mode at a given frequency. That is, the cavity is generally supportive of the desired modes at different frequencies. Hence, means must be provided for tuning the cavity so as to bring these mode frequencies substantially into coincidence and, thereby, to establish the desired nulls and high amplitude fields at the various branches of the circulator at a single operating frequency. In this manner the cavity is rendered capable of supporting the two different resonant modes at nearly the same frequency.

In the above-identified article, a four-port circulator using the $n=1$ and $n=0$ modes is described. The circulator in accordance with the present invention utilizes the $n=1$ and $n=2$ modes. Normally, the $n=2$ mode is established at a higher frequency than the $n=1$ mode. Hence, means must be provided for tuning the cavity so as to lower its natural frequency for the $n=2$ mode. This is

done by the inclusion of four, substantially identical radial slots 30, 31, 32 and 33 in the junction disc 15. The slots, which are of uniform width, are spaced 90 degrees apart and extend radially inward from the disc periphery at a 45 degree angle to the adjacent conductors.

To illustrate the operation of the circulator more specifically, the standing wave pattern for the $n=1$ mode, rotated 45 degrees, is shown in FIG. 2. This is a dipolar mode in which the signal magnetic field lines extend parallel to the surface of disc 15, and in which the electric field lines are perpendicular to the surface of disc 15. These latter are designated $\oplus$ and $\ominus$, depending upon whether they extend into, or out of, the plane of the disc. The orientation of the field lines relative to the branches of the circulator is determined by the bias applied to the gyromagnetic material. In FIG. 2 the field pattern is rotated 45 degrees relative to the input branch, for reasons which will be explained hereinbelow. As can be seen, for this orientation the electric fields at branches 1 and 4 are equal, and since both are similarly designated $\oplus$, they are also in phase. Likewise, the electric fields at branches 2 and 3 are equal and in phase. However, as they are designated $\ominus$, they are out of phase with the electric fields at branches 1 and 4.

For the $n=2$ quadrupolar mode, shown in FIG. 3, the magnetic field lines are similarly parallel to the disc surface, and the electric field lines perpendicular to the disc surface. However, for this mode, the electric fields are in phase at branches 1 and 3, and at branches 2 and 4, with the latter pair being out of phase with the former. It is also observed that the $n=2$ mode is rotated, but to a lesser extent than the $n=1$ mode as the magnetic field intensity in the region of the gyromagnetic material is much less for the $n=2$ mode. In the slotted disc structure, substantially no rotation of the $n=2$ mode is observed.

The superposition of these modes in a slotted disc resonator, as illustrated in FIG. 4, results in a standing wave configuration which has field nulls at branches 3 and 4, and, hence, no energy is transmitted from the input branch 1 to either of these two branches. The fields at branches 1 and 2, however, are equal and, therefore, all the energy (less losses) coupled into the circulator through branch 1 is transmitted out of the circulator via branch 2.

As can be seen from the above discussion, the junction cavity is adjusted to support the $n=1$ mode at a specified orientation by adjusting the bias applied to the gyromagnetic material. Simultaneously, the cavity is tuned by means of the four, radial slots in disc 15, to support the $n=2$ mode at substantially the same frequency. While these two adjustments are not totally independent of each other, they are sufficiently independent to permit a high order of independent adjustment of the two modes. The following design procedure can be used to determine the size of disc 15 and of the tuning slots.

Designating the circulator bandwidth as BW, and the minimum isolation as S (and noting that in a good circulator, the isolation is practically identical to the return loss at the input port, in which case S can be expressed as a voltage standing wave ratio), the loaded Q of the cavity can be expressed approximately as

$$Q_L = \frac{1.4(S-1)^{1/2}}{BW} \quad (1)$$

To obtain 45 degree rotation of the $n=1$ mode, it is required that

$$\frac{\kappa}{\mu} \approx \frac{1.23}{Q_L} \quad (2)$$

where κ and μ are the two components of the Polder tensor.

Knowing κ/μ , the parameters p and σ are chosen from the curves given in FIG. 5 of the Fay-Comstock paper referred to above. It is advantageous to operate at the point where the gyromagnetic material is just satu-

rated ($\sigma=0$) since this point is out of the low-field loss region and still far from gyromagnetic resonance ($\sigma=1$).

Having selected p and σ , the effective scalar permeability of the gyromagnetic material, μ_{eff} , is found from the curves of FIG. 6 in the Fay-Comstock paper. Using μ_{eff} thus determined, the phase constant k of a wave propagating through the gyromagnetic material is calculated from

$$k = \frac{\omega}{c} \sqrt{\mu_{\text{eff}} \epsilon} \quad (3)$$

where

ω is the operating angular frequency;
 c the the velocity of light;

and

ϵ the relative permittivity of the gyromagnetic material.

Treating the segment of disc between slots as a radial transmission line, and assuming the diameter of the gyromagnetic element is equal to the disc diameter, the disc radius r_2 and the hub radius r_1 (the distance from the center of the disc to the bottom of the slots) are found from the relations

$$\psi = \tan^{-1} \left[\frac{J_1(kr_2)}{-N_1(kr_2)} \right] \quad (4)$$

and

$$\theta = \tan^{-1} \left[\frac{N_0(kr_1)}{J_0(kr_1)} \right] \quad (5)$$

where

$$\Psi - \theta = \frac{\pi}{2}$$

(See "Fields and Waves in Modern Radio," by S. Ramo and W. R. Whinnery, published by John Wiley and Sons, New York, Second Edition, 1953, for a discussion of radial transmission lines.)

From various experimental models of the invention, it has been found that ratios of r_2/r_1 of between 2.5 and 4.25 give good results. The lower ratios tend to improve the isolation between ports 1 and 4, while the higher ratios tend to improve the isolation between ports 1 and 3.

It has similarly been found that good results are obtained with slot widths that are approximately equal to, or slightly greater than, the distance between disc 15 and the ground planes 16 and 17. In general, the area of the four slots is a small fraction of the total disc area, being of the order of 30 percent or less.

FIG. 5 shows a slotted disc resonator for use at L-band. The disc is 0.050 inch thick and the ferrite cylinders (not shown) are 0.100 inch thick. Conductors 11, 12, 13 and 14 are a quarter wavelength long and function as transformers for matching the circulator to 50 ohm coaxial lines. Tuning screws (not shown) are advantageously incorporated into the structure to improve the impedance match. The overall diameter of the circulator is 6.25 inches and it is one inch thick, exclusive of biasing magnets.

FIG. 6 shows the performance characteristic of such a circulator using aluminum-substituted yttrium-iron-garnet ferrite members externally biased at 560 oe.

In all cases it is understood that the above described arrangement is illustrative of but one of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A single-junction, four-port circulator comprising: four lengths of strip transmission line each of which has an inner conductor which is spaced between and parallel to a common pair of outer conductors;

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said inner conductors lying in a common plane and terminating 90 degrees apart about the periphery of a conductive circular disc;
 said disc having no more than four radial slots of uniform width extending from its outer boundary inward towards its center;
 each slot being symmetrically located between pairs of adjacent conductors;
 an element of gyromagnetic material located between said disc and at least one of said outer conductors; and means for magnetically biasing said element.
 2. The circulator according to claim 1 wherein:
 the ratio of the radius of said disc to the distance from

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the center of said disc to said slots is of the order of 2.5 to 4.25.

3. The circulator according to claim 1 wherein:
 the width of said slots is approximately equal to the distance between said disc and said outer conductors.

References Cited

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