United States Patent

[11] 3,617,946

[72] Inventor Brian Owen
Allentown, Pa.
[21] Appl. No. 7,872
[22] Filed Feb. 2, 1970
[45] Patented Nov. 2, 1971
[73] Assignee Bell Telephone Laboratories, Incorporated
Murray Hill, N.J.

[54] **JUNCTION CIRCULATOR WHEREIN A CONDUCTIVE CORE EXTENDS WITHIN GYROMAGNETIC MATERIAL**
6 Claims, 4 Drawing Figs.

[52] U.S. Cl. 333/1.1, 333/9
[51] Int. Cl. H01p 1/32, H01p 5/12
[50] Field of Search 333/1.1

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Primary Examiner—Herman Karl Saalbach
Assistant Examiner—Paul L. Gensler
Attorneys—R. J. Guenther and E. W. Adams, Jr.

ABSTRACT: A junction circulator in which the usual magnetically biased ferrite post is modified by being separated from one conductive boundary by a dielectric gap and by having a conductive core extending axially therein from the other boundary. These modifications induce wave fields which simulate those of the turnstile circulator and produce a comparable broadband circulation.

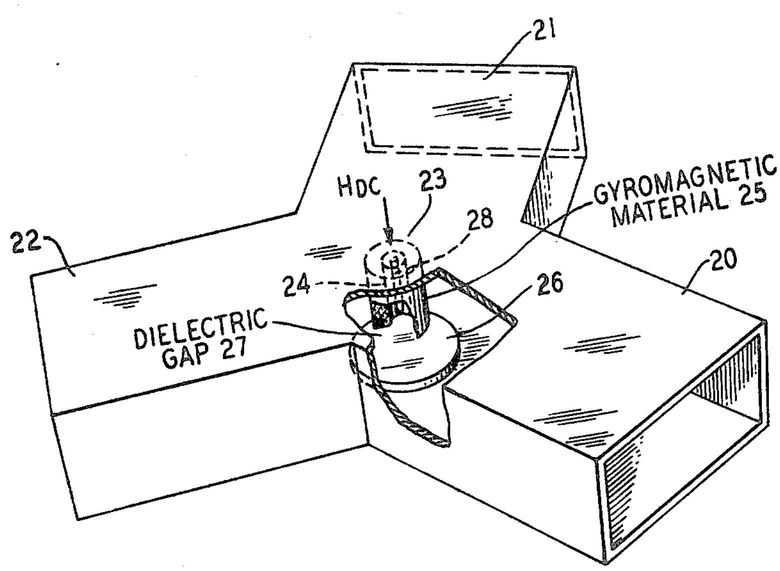


FIG. 1
(PRIOR ART)

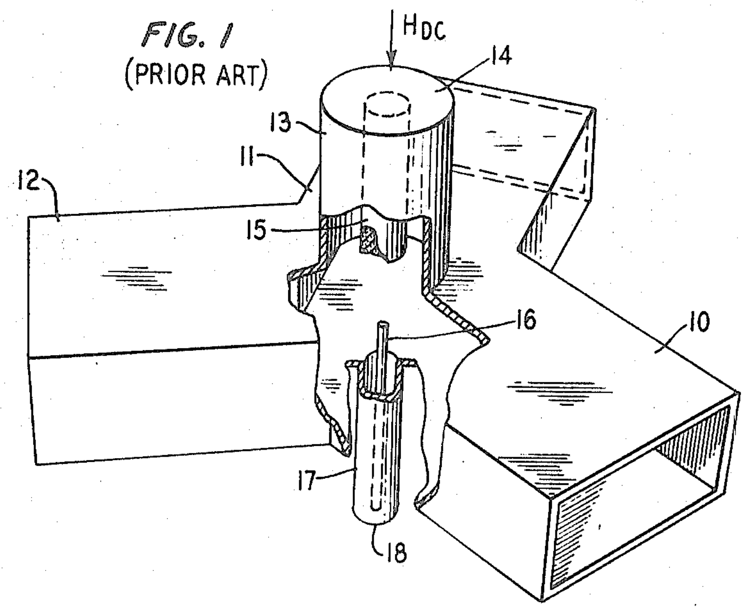


FIG. 2

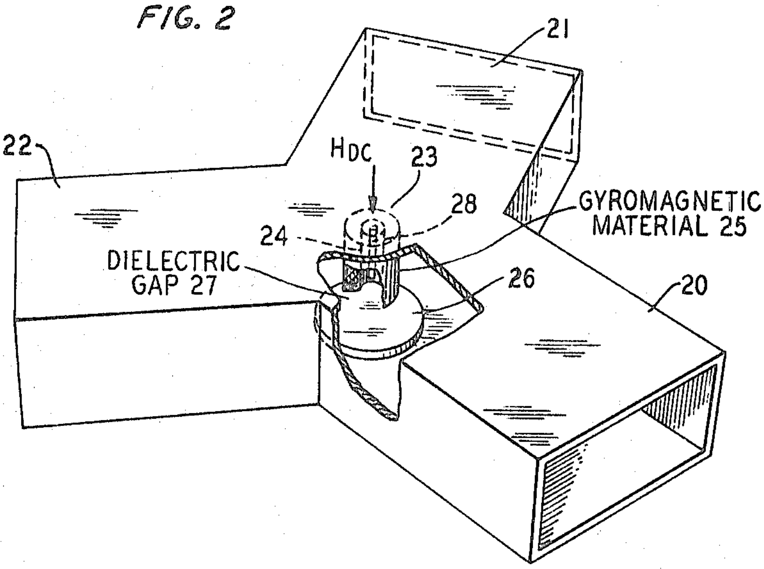
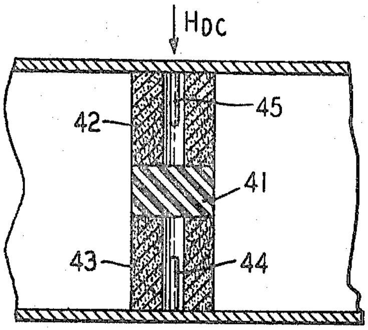


FIG. 4



INVENTOR
B. OWEN
BY Roy M. Porter, Jr.
ATTORNEY

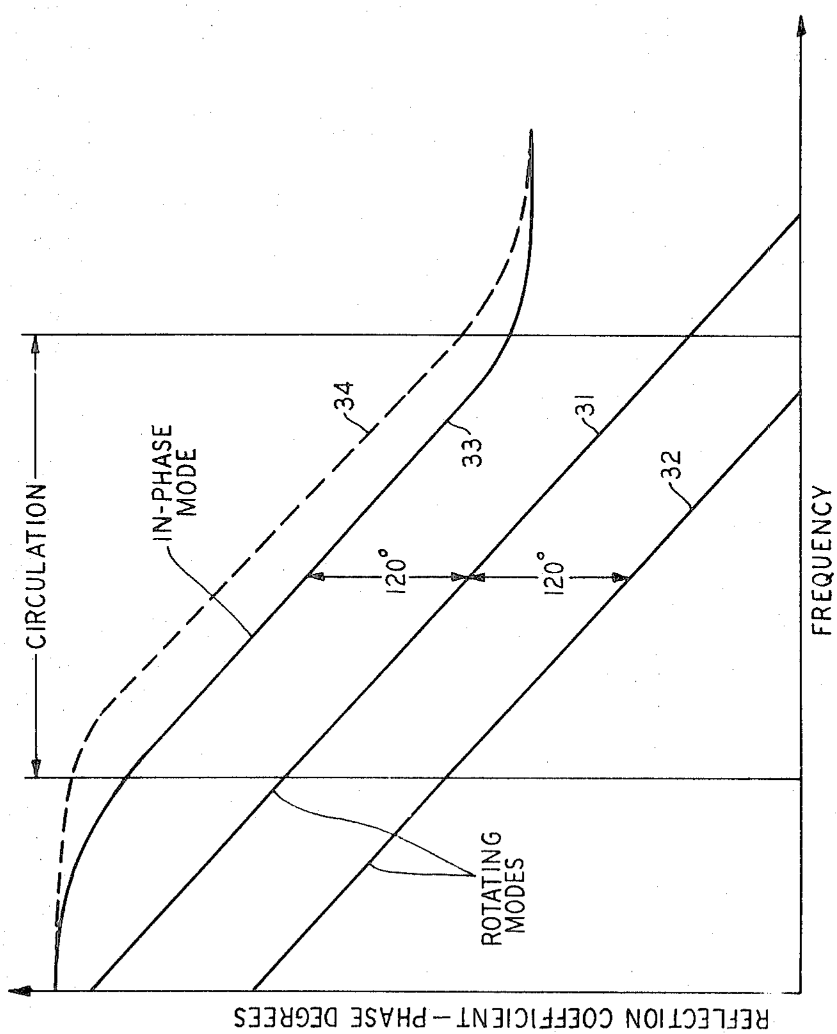

CIRCULATION
IN-PHASE MODE
34
33
31
32
120°
120°
ROTATING MODES
FREQUENCY
REFLECTION COEFFICIENT—PHASE DEGREES

FIG. 3

JUNCTION CIRCULATOR WHEREIN A CONDUCTIVE CORE EXTENDS WITHIN GYROMAGNETIC MATERIAL

BACKGROUND OF THE INVENTION

This invention relates to symmetrical coupling devices for electromagnetic wave energy and, more particularly, to very broadband waveguide Y-junction circulators.

The basic Y-junction circulator comprises a conductively bounded junction of three waveguides having a magnetically biased gyromagnetic body extending along the axis of symmetry of the junction. Numerous variations of this basic structure, principally having to do with the size and shape of the gyromagnetic body and with means for matching its impedance to the remainder of the structure, have been proposed to improve one or another of the operating characteristics of the circulator.

It is now clearly understood that circulator action depends upon the relationship between the responses of the junction to three modes supported in the junction, namely, an in-phase mode and two counterrotating modes, the reflection coefficients of which must be mutually displaced in phase by 120°. The differences in bandwidth of various forms of circulators depend upon the degree to which it is possible in a particular structure to maintain this phase relation as frequency is changed.

One particular form has been described by Haugen and Schaug-Pettersen, "A Microwave Symmetrical Y Circulator," *Intern Rapport* R–66, Norwegian Defense Research Establishment, Dec., 1958, which has a bandwidth limited only by the constancy of gyromagnetic effects with frequency and by the onset of higher order modes. This form has been referred to as a double-stub or double-tuned turnstile circulator, the name being descriptive of the two structural appendages which characterize its construction. Specifically, the usual waveguide junction is supplemented by a first shorted circular waveguide stub rising out of one side of the junction in which the axially biased gyromagnetic body is located and a second shorted coaxial stub extending from the opposite side of the junction. The structure derives its broadband width from its ability to couple the counterrotating modes in the circular guide stub and in the in-phase mode into the coaxial guide stub. These modes can thus be tuned independently in a way which results in their reflection coefficients being displaced by 120° over a broadband.

Despite its phenomenal bandwidth advantages, the turnstile circulator has remained a laboratory curiosity because of its unwieldy and relatively complex mechanical structure. At least one attempt to simplify the turnstile has been described by B. A. Auld in "The Synthesis of Symmetrical Waveguide Circulators," 7 *IRE Transactions on Microwave Theory and Techniques*, pg. 238, Apr., 1959. However, this particular simplification did not preserve the independence of all modes and therefore did not preserve the bandwidth capabilities.

SUMMARY OF THE INVENTION

In accordance with the present invention the superior electrical performance of a double-tuned turnstile circulator is duplicated with a structure that is little more mechanically complicated than a typical Y-junction circulator. More particularly, the usual magnetically biased, gyromagnetic, cylindrically shaped post extending along the axis of symmetry of the junction is foreshortened to create a dielectric discontinuity between one conductive boundary of the junction and one end of the post. At the same time a conductive core is extended from one conductive boundary of the junction part of the way along the axis of the post. In general, the dielectric gap causes counterrotating electric fields to be induced in the gyromagnetic body normal to the magnetic bias so that the gyromagnetic body acts as did the circular guide stub of the turnstile. The conductive core, on the other hand, tunes a mode functionally corresponding to the mode supported in the coaxial stub of the turnstile. However, all parts of the structure are fully contained within the junction.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cutaway perspective view of a typical prior art turnstile circulator;

FIG. 2 is a cutaway perspective view of a junction circulator in accordance with the present invention;

FIG. 3 shows typical reflection coefficient characteristics useful in understanding the operation of the invention; and

FIG. 4 shows in cross section an alternative arrangement of components within the junction of FIG. 2.

DETAILED DESCRIPTION

Referring more particularly to FIG. 1, the prior art double-tuned circulator according to Haugen and Schaug-Pettersen is shown since copies of its published description are not easily available for the purpose of comparison with the present invention. It comprises three rectangular waveguides 10, 11 and 12 intersecting in a Y at angles 120° in an H-plane junction (the plane of the guide broad dimension) to form a conductively bounded common region from which the waveguide branches symmetrically extend. Extending coaxially with the axis of symmetry of the Y from the upper boundary of the common region is a section of circular waveguide 13 that is coupled at its lower end by a circular aperture to the junction and that is closed at its upper end by a shorting boundary 14. A cylinder 15 of magnetically polarized gyromagnetic material, such as yttrium iron garnet or ferrite, is located axially within guide 13. Cylinder 15 is longitudinally biased along the axis of symmetry by being permanently magnetically polarized or polarized by the use of external magnets as schematically represented by the vector H_{DC}. Extending from the opposite conductive boundary of the junction and coaxial with the axis of symmetry, is a section of coaxial conductor having a center conductor 16 and an outer conductor 17 coupled to the common region by a probelike extension of center conductor 16. The lower end of coaxial 16–17 is shorted by conducting member 18.

Operation of such a circulator is usually explained by dividing the excitation of one port of the junction into three excitations each involving excitation of all three ports. The three excitations correspond to the eigenvectors for the scattering matrix for the junction. A first excitation excites all three ports equally and in phase while the remaining two excitations result in equal excitations with phases that result in counterrotating circular polarizations within the junction. The requirement for circulation in terms of these excitations is that their reflection coefficients corresponding to the eigenvalues for the scattering matrix be displaced in phase by 120°.

It is useful to examine the fields at the axis of symmetry due to each of these excitations. For the in-phase mode, the components of electric field parallel to the axis of symmetry due to the excitation of the three ports will be in phase and simply add to one another. The transverse components, while in phase, are space displaced by 120° and cancel vectorially. Therefore, the electric field at the axis of symmetry due to the in-phase mode lies only along the axis of symmetry. Similarly, for the counterrotating modes, the components of electric field along the axis of symmetry are phase displaced by 120° and sum to zero. The transverse components, while phase displaced by 120°, are spaced displaced by 120° resulting in circularly polarized fields. Similar arguments could be made about the magnetic fields with the conclusion that the counterrotating modes can, and the in-phase mode cannot, couple to waves travelling along the axis of symmetry in circular guide 13. Likewise, with proper choice of diameter for coaxial 16–17, the in-phase mode can, and the counterrotating modes cannot, couple to coaxial 16–17. This separation of mode provides the means for adjusting the reflection coefficients as required for circulation.

Thus in the prior art structure of FIG. 1 the counterrotating modes propagate up the circular loaded guide 13 with an electric field and a transverse magnetic field normal to the biasing field H_{DC} and are reflected back toward the junction by short 14. The net phase shifts for these modes with the gyromagnetic material unmagnetized are identical and are determined by the length of circular guide **13**. Magnetizing cylinder **15**, however, increases and decreases the path lengths of the counterrotating modes, respectively, and by adjusting H_{DC} and the length of guide **13** and cylinder **15**, these modes can be separated by 120° from each other as required for circulator action. This corresponds to Faraday rotation by cylinder **15** of 60°. The in-phase mode, on the other hand, cannot propagate into circular guide **13** but is coupled into coaxial section **16–17** where it is reflected back toward the junction by short **18**. If the electrical lengths to short **18** and to short **14** are comparable, both paths will have the same frequency dependence. Therefore, even as frequency changes over a very broad band, the modes will track each other with the required 120°-phase difference limited only by the constancy of the Faraday rotation of cylinder **15** with frequency until that frequency is reached at which higher order modes appear in guide **13**.

With this background in mind the principles of the present invention may be understood from FIG. **2**. In all cases in which the structure, materials, or principles of operation are the same as those described above, a detailed description thereof need not be repeated.

Referring then to FIG. **2** a waveguide junction like that of FIG. **1** is shown comprising guides **20**, **21** and **22** corresponding in every respect to guides **10**, **11** and **12**. No external appendages are required. Instead, gyromagnetic element **25** takes the form of an axially biased cylinder located within the common region of the junction on the axis of symmetry. Cylinder **25** has a small hole **24** drilled along its axis. The top end of cylinder **25** is contiguous to the top conductive boundary **23** of the common region and a gap **27** filled either by air, or by a suitable nonmagnetic dielectric material having dielectric constant close to that of air or at least substantially different from that of cylinder **25**, forms a space between the lower end of cylinder **25** and the lower conductive boundary of the junction. In accordance with a preferred embodiment of the invention a conductive platform **26** raises the lower conductive boundary, shortens gap **27** and acts as an impedance-matching transformer. However, it appears that by proper empirical adjustment the need for platform **26** can be eliminated in certain embodiments and some frequency sensitivity associated therewith avoided. A thin conductive pin **28** is located axially within hole **24** and is conductively connected to the top conductive boundary.

The significance of gap **27** can be understood when it is recalled that in an ordinary H-plane resonant junction, the electric fields are everywhere parallel to the axis of symmetry. The region formed by gap **27**, however, has a dielectric constant and permeability product that is different from that of the region occupied by the gyromagnetic material of cylinder **25** so that the phase constants of the two regions differ. This creates an electric field in the plane of the interface between the two regions. Thus, only the counterrotating excitations launch waves as dielectrically supported modes in cylinder **25**, travelling up cylinder **25** to be reflected at boundary **23** and to couple back into the junction at gap **27**. The similarities between these waves and those supported in guide **13** of FIG. **1** are quite apparent. Thus, the phase of the counterrotating modes are determined by the length of cylinder **25** and the degree of its magnetic polarization.

The in-phase mode sees cylinder **25** only as a dielectric resonator since this mode has no circularly polarized magnetic fields and does not excite any mode propagating along the axis of cylinder **25** and thus there is no gyromagnetic interaction with its material. This mode has, however, an electric field on the axis of symmetry such that the resonant frequency depends upon the penetration of pin **28**. As noted above, the counterrotating modes have only transverse electric fields at the axis of symmetry, and, therefore, are not affected by pin **28**. The effect of pin **28** together with cylinder **25**, therefore, simulates the effect of coaxial **16–17** of FIG. **1**.

The relationships can be seen from FIG. **3** which shows typical reflection coefficients in phase degrees of the three modes described above as they vary with frequency. Thus, the counterrotating modes as represented by curves **31** and **32** (considered as having linear delays) are phase separated by 120° by controlling the Faraday rotation parameters of cylinder **15** including its length, composition and magnetization. Pin **28** is then employed to position the in-phase mode curve as represented by curve **33** (considered as having a resonant delay) so that its most linear portion falls within the band of intended operation in a given junction with a phase 120° away from the phase of the nearest rotating mode of curve **31**. In particular, increasing the length of pin **28** causes the in-phase mode coefficient to shift from the position of dotted curve **34** in the direction of the required curve **33**. Circulation is then possible over the full range in which the curves generally parallel each other as indicated.

A typical embodiment according to these considerations would have the following illustrative proportions. Using waveguides with a 2:1 aspect ratio and operating within the standard recommended frequency range for dominant mode operation, the outer diameter of cylinder **25** when formed of ferrite should be approximately 1 wavelength in the ferrite medium at the lowest operating frequency. The ratio of the diameter of hole **24** to outer diameter of cylinder **25** should preferably be no greater than one-sixth. The pin **27** should have the minimum practical diameter with a penetration of the order of one-third the waveguide height. In practice it is convenient to determine the required pin length by means of a pin with penetration adjustable to approximately one-half the guide height. The gap **27** is typically of the order of one-fifth to one-fourth the guide height. The ferrite should be selected to avoid low field losses in accordance with standard practice for low field devices.

In principle, pin **28** may extend from either conductive boundary in the structure of FIG. **2** or a pair of pins may be employed. However, the structure as illustrated is obviously preferred from a fabrication standpoint. In certain cases for greater power-handling capability, it may be desirable to couple to the counterrotating modes by introducing two dielectric discontinuities as shown in FIG. **4**. In this structure counterrotating modes are generated at both of the two interfaces formed by a single gap **41** of nonmagnetic dielectric material centrally interposed between two gyromagnetic cylinders **42** and **43**, each having one end contiguous to one conductive boundary of the junction. Duplicate modes propagate in opposite directions in cylinders **42** and **43** and are reflected respectively by the upper and lower junction boundaries to couple back into the junction at the gap. Either one or both conductive pins **44** and **45** tune the in-phase mode as described.

The present invention provides an improvement upon circulators of the turnstile type. While particularly illustrated by way of the three-branch or Y-junction form, it should be noted that four-branch turnstile junction has been described by P. J. Allen in U.S. Pat. No. 2,867,772, granted June 6, 1959, and in the *IRE Transactions on Microwave Theory and Techniques*, Oct. 1956 on page 223. The principles of the invention are equally applicable to improving this four-branch form as will be obvious to one skilled in the art of the foregoing teachings.

What is claimed is:

1. A broadband circulator for electromagnetic wave energy comprising a conductively bounded structure having a plurality of branches symmetrically extending away from a conductively bounded common region having a pair of opposite conductive boundaries and adapted to support said wave energy with an electric field perpendicular to said boundaries and a magnetic field lying substantially in loops in planes parallel to said boundaries, a body of magnetically polarized gyromagnetic material symmetrically disposed with respect to said common region, said body being contiguous to one conductive boundary of said common region and being spaced from the opposite conductive boundary to leave a dielectric gap

therebetween, and a conductive core extending symmetrically within said body from said one boundary.

2. A broadband circulator for electromagnetic wave energy comprising a conductively bounded structure having a plurality of branches symmetrically extending away from a conductively bounded common region having a pair of opposite conductive boundaries and adapted to support said wave energy with an electric field perpendicular to said boundaries and a magnetic field lying substantially in loops in planes parallel to said boundaries, a body of magnetically polarized gyromagnetic material having a longitudinal axis symmetrically disposed in said common region, means for creating a conductive and reflecting discontinuity at one end of said body, means for creating a dielectric discontinuity at the other end of said body, and means for tuning the electric field that lies along the axis of said body.

3. The circulator of claim 2 wherein said conductively bounded structure comprises three rectangular waveguides forming a Y-junction.

4. The circulator of claim 2 wherein said means for tuning comprises a thin conductive pin extending along said axis from one conductive boundary to a point spaced from the other conductive boundary.

5. The circulator of claim 2 wherein said one end of said body is contiguous to one conductive boundary of the junction and the other end of said body is spaced from the other boundary of the junction.

6. The circulator of claim 5 including a raised conductive platform interposed between and filling a part only of the space between said other end and said other boundary.

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