

[54] **DELTA CONNECTED LUMPED ELEMENT CIRCULATOR**

3,517,340 6/1970 Magalhaes.....333/1.1
3,614,675 10/1971 Konishi.....333/1.1 X

[75] Inventor: Reinhard Heinrich Knerr, Ore-field, Pa.

Primary Examiner—Paul L. Gensler
Attorney—R. J. Guenther et al.

[73] Assignee: Bell Telephone Laboratories, Incorporated, Murray Hill, Berkeley Heights, N.J.

[57] **ABSTRACT**

[22] Filed: Aug. 30, 1971

A junction strip line circulator of the lumped constant type in which the gyromagnetically coupled strip line members are delta connected in the common region and tuned by three capacitors effectively connected respectively from each vertex of the delta to a common point and by a further reactance from the common point to the strip line ground plane. Separate mode tuning is facilitated and the crossovers usually found in Y-connected circulators are eliminated.

[21] Appl. No.: 175,868

[52] U.S. Cl.333/1.1, 333/84 M

[51] Int. Cl.H01p 1/32, H01p 5/12

[58] Field of Search.....333/1.1

[56] **References Cited**

9 Claims, 8 Drawing Figures

UNITED STATES PATENTS

3,341,789 9/1967 Goodman et al.333/1.1
3,226,659 12/1965 Stracca.....333/1.1

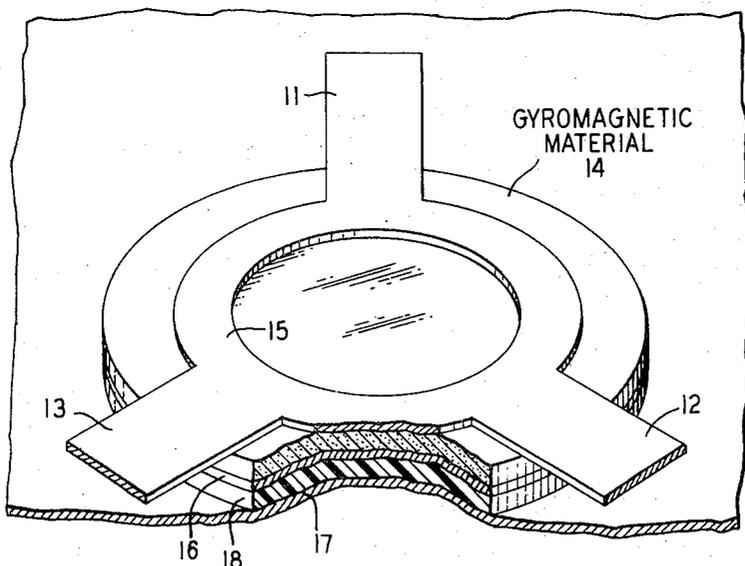


FIG. 1

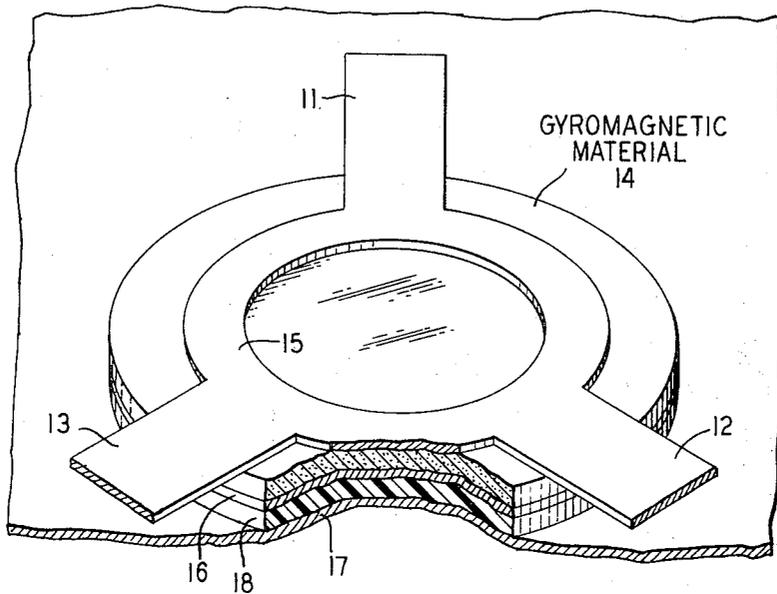


FIG. 2

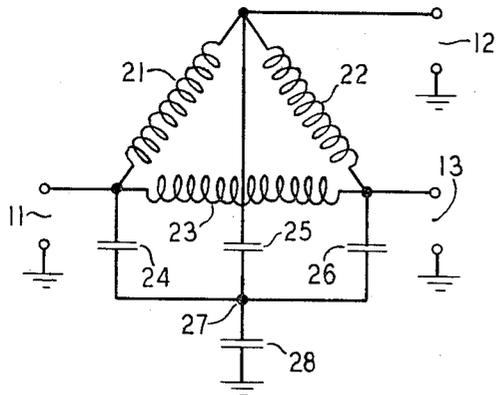


FIG. 3

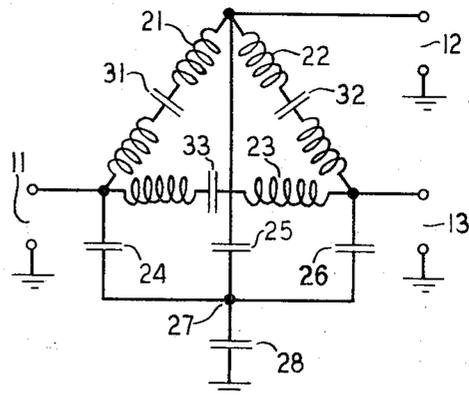


FIG. 4

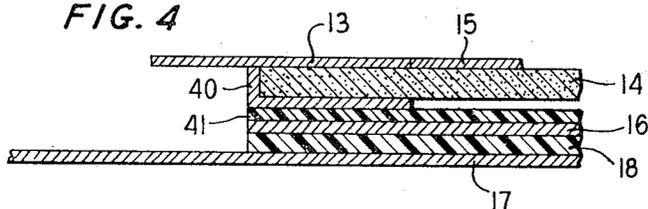


FIG. 5A

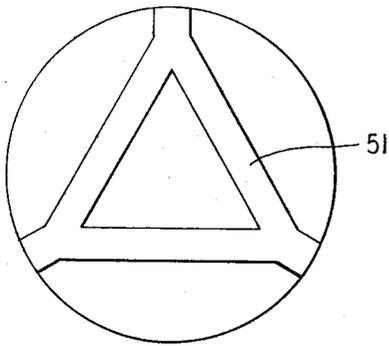


FIG. 5B

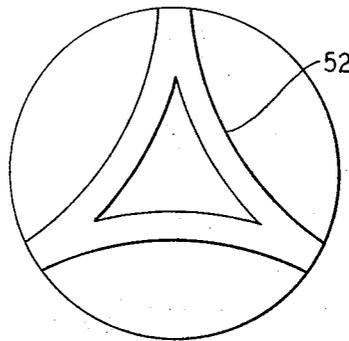


FIG. 5C

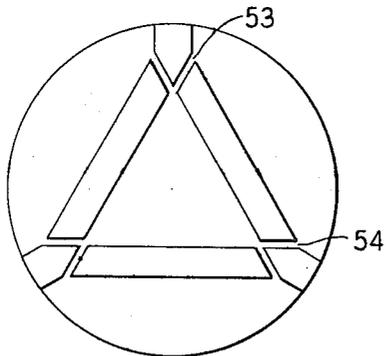
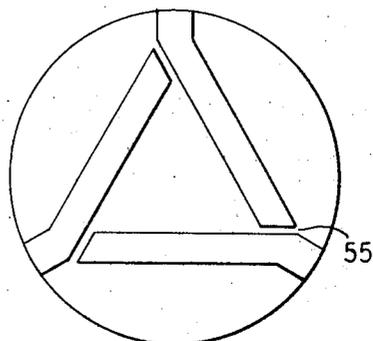


FIG. 5D



DELTA CONNECTED LUMPED ELEMENT CIRCULATOR

BACKGROUND OF THE INVENTION

This invention relates to strip line junction circulators of the lumped constant variety and, more particularly, to circulators of this type in which the lumped constant components are connected in a delta configuration.

The prior art form of lumped constant circulator has been treated analytically in articles by Deutsch and Wieser, *IEEE Transactions on Magnetics*, Vol. 2, No. 3, September 1966, pp. 278-282; Konishi, *IEEE Transactions on Microwave Theory and Techniques*, Vol. 13, November 1965, pp. 852-864; Davis and Cohen, *IEEE Transactions on Microwave Theory and Techniques*, Vol. 11, November 1963, pp. 506-512; and in Konishi U.S. Pat. No. 3,335,374; applicant's U.S. Pat. Nos. 3,538,459, Nov. 3, 1970, and 3,573,665, Apr. 6, 1971; and in applicant's copending application, Ser. No. 873,372, filed Nov. 3, 1969 now U.S. Pat. No. 3,605,040 granted Sept. 14, 1971.

In general, the circulator of this type includes a ferrite disk core and three branches or arms radially disposed with respect to the core with three-fold symmetry. Each arm further comprises a tuned circuit containing an inductive conductor and a discrete capacitive element intercoupled by the core in a common region. Circulator action depends upon the relationship between the responses of the tuned circuits to three modes supported therein; namely, an in-phase mode and two counter-rotating modes. The responses are typically analyzed by dividing the excitation at one port of the junction into three excitations involving excitation of all three ports. The three excitations correspond to the eigen vectors for the scattering matrix of the junction. A first excitation corresponds to the in-phase mode, while the remaining two excitations have phases that result in counter-rotating modes. The requirement for circulation in terms of these excitations is that the reflection coefficients corresponding to the eigen values for the scattering matrix be displaced in phase as nearly as possible by 120°. In terms of structure, each arm is formed by a strip line conductor disposed on the top surface of the core. When connected to sources of high frequency energy, these conductors exhibit the required inductive reactances, their fields intercouple through the core, and discrete capacitors are added to each arm to achieve the resonance necessary. In all of the foregoing prior art embodiments the inductive reactances are Y-connected, which in the preferred forms, structurally requires an insulated physical crossing of the conductors in the common region. It has, however, been recognized that every Y-connection theoretically has an equivalent delta-connection and this equivalence has been suggested for use in circulators by R. W. Roberts, Jr. in U.S. Pat. No. 3,286,201, granted Nov. 15, 1966. The delta-connection would avoid the physical crossings required for the Y-connection and would, therefore, produce a simpler device from a structural standpoint. However, the delta-connection as previously envisioned has not afforded sufficiently separate tuning for the in-phase and counter-rotating modes to enable satisfactory circulator action.

SUMMARY OF THE INVENTION

In accordance with the present invention it has been discovered that the delta-connection, when used in combination with a particular capacitive network, can provide separate tuning for the in-phase mode and the counter-rotating modes, thus making functional the simple delta-connection and avoiding the complication of crossovers.

More particularly, the strip line configuration takes the form of a simple ring in the common region to which the input-output arms are connected around the ring at equally spaced points which form the vertexes of the delta. Three capacitors, each effectively connected respectively from each vertex to a common point, and a further capacitor connected from the common point to the strip line ground plane completes the tuning network.

In a preferred embodiment these capacitors are formed by a single, thin, conductive plane member interposed between and spaced from both the strip line configuration and from the strip line ground plane. It will be shown that the capacitors thus formed between the strip line configuration and the intermediate plane are individual to each branch and influence all three modes but that the capacitor formed between the intermediate plane and the ground plane is common to all branches and influences only the in-phase mode since currents due to the rotating modes cancel each other in the common capacitor. Thus, the phase of the in-phase mode may be adjusted independently from the phases of the counter-rotating modes to obtain circulation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a broken out perspective view of one embodiment of this circulator in accordance with the present invention;

FIG. 2 is an equivalent circuit of the circulator of FIG. 1;

FIG. 3 illustrates a modification of the equivalent circuit of FIG. 2;

FIG. 4 illustrates by means of a partial cross sectional view a modification of the structure of FIG. 1; and

FIGS. 5A, B, C and D illustrate by means of top views alternative configurations of the configuration of FIG. 1.

DETAILED DESCRIPTION

Referring more particularly to FIG. 1, the circulator includes three strip line center conductors 11, 12 and 13, arranged in rotational symmetry on the upper face of substrate 14. Substrate 14 itself comprises a slab of magnetically polarized gyromagnetic material, commonly a ferrite or a substituted garnet. Each strip is conductively connected to or integrally formed with a ring 15 of conductive strip material at equally spaced points around the outer circumference of ring 15. The conductive material removed or omitted from the center of ring 15 may be such as to leave the strip width thereof equal to or different from the widths of the strips 11, 12 and 13 in order to control characteristic impedances, but this dimension does not appear to be critical. The wider the width of the ring as compared to the strip gives the ring a characteristic impedance that is lower than that of the strip as may be desirable in

some designs. In general, the outer diameter of ring 15 is in the order of one-half to one-eighth wavelength of the intended frequency of operation in the material of substrate 14. The entire conductive pattern may be formed upon substrate 14 by thin film, photolithographic processes well known in the art of printed circuits.

Intermediate conductive plane 16 is located next to the bottom face of ferrite substrate 14 and may be, for example, a conductive film applied as above to substrate 14. Plane 16 should be at least as large as ring 15 and may be larger so as to extend over the ends of strips 11, 12 and 13 in order to obtain additional capacity to the respective strips in the total amount as defined in the above-noted prior art. A conductive ground plane 17 is suitably spaced from intermediate plane 16 as by dielectric spacers 18. Plane 17 is continuous with or at least connects to the ground planes associated with the circuits connected to the free ends of conductors 11, 12 and 13 so that when any one of these is excited as an input by high frequency electromagnetic wave energy relative to ground plane 17, the two portions of ring 15 adjacent to the excited strips are simultaneously excited.

The equivalent circuit of the resulting circulator is shown in FIG. 2. The three segments of ring 15 between the ports are inductive at the operating frequency and may be represented by inductances 21, 22 and 23 connected in a delta configuration with the three vertexes of the delta connected to input terminals of ports 11, 12 and 13. The capacity from ring 15 (and the portion of strips 11, 12 and 13 contiguous to plane 16) to intermediate plane 16 is, of course, distributed. However, since the segments of ring 15 between the ports are inductive, the capacity nearest to an excited port has far more effect upon currents produced by that excitation than capacity further along the inductance. In other words the capacity can be transformed to an equivalent capacity such as capacities 24, 25 and 26 from each vertex to a common point 27. The capacity between intermediate plane 16 and ground plane 17 is represented by capacity 28.

The circuit of FIG. 2 serves to indicate that while the form of intermediate ground plane 16 is one having physical convenience, the required capacities may be provided at the locations indicated by lumped, fixed capacitors. Furthermore, while the strip line configuration of FIG. 1 is in the form of an unsymmetrical transmission line, it should be recognized that a second ground plane and/or a second intermediate plane either with or without a second body of ferrite can be located above the structure as shown to produce a symmetrical transmission line structure. The additional capacity between the second intermediate plane and the second ground plane would, in effect, be connected in parallel with the capacitors of FIG. 2.

The general parameters required for circulation are fully described in the above-mentioned prior art patents and publications and need not be repeated here. What should be understood in connection with the present invention is the nature of control made possible by the capacitor network 24, 25, 26 and 28.

Recall, therefore, that the in-phase mode may be represented by equal in-phase voltages applied simultaneously at ports 11, 12 and 13. Thus, each terminal is

at the same potential, no currents flow in inductors 21, 22 or 23 of FIG. 2. Currents flow instead from each terminal, through the appropriate individual capacitor 24, 25 or 26 and sum as they flow through capacitor 28 to the ground plane. All capacitors, therefore, have an influence on the in-phase mode. Either of the counter-rotating modes may be represented by equal voltages applied at the three ports that are displaced in phase from each other by 120° . Thus, currents now flow in inductors 21, 22 and 23 as well as capacitors 24, 25 and 26. In capacitor 28 they sum to zero because of their 120° degree phase spacing. Capacitor 28 has no effect upon the counter-rotating modes and, therefore, may be used to exclusively tune the in-phase mode.

FIG. 3 illustrates that since no currents flow through inductors 21, 22 and 23 for the in-phase mode as described above, capacitors 31, 32 and 33 may be introduced in series with inductors 21, 22 and 23, respectively, to have further exclusive control over the counter-rotating modes. Thus, these series capacitors are in effect the counterpart of shunt capacitor 28 for the rotating modes. Double tuning as known in the art for broadbanding the operation of the circulator may be obtained by adding an inductor in parallel or in series with capacitor 28 to resonate exclusively with the in-phase mode. Similarly, inductances may be added for the same purpose in parallel with capacitors 31, 32 and 33 to resonate exclusively with the counter-rotating modes.

The individual shunt capacitor, such as 24, 25 or 26 of FIG. 2, may be increased and/or separately adjusted by means of the modification shown in FIG. 4. In FIG. 4 reference numerals corresponding to FIG. 1 have been used to designate corresponding components. Modification will be seen to reside in the introduction of a conductive tab 40 which is conductively connected from strip 13 to extend vertically along the edge of core 14 and is then bent under to extend across the lower face of core 14 parallel to strip 13 on the top thereof. An additional spacer of dielectric material 41 is then provided between tab 40 and intermediate plane 16. Similar tabs are included on other arms 11 and 12. The capacity between intermediate plane 16 and individual arm 11, 12 or 13 is thus determined by the length of the tab and by the thickness and dielectric constant of separator 41. It should be noted that three such tabs may be extended over a wide area or the lower face of core 14 so long as they do not contact each other.

FIGS. 5A, B, C and D show alternative strip configurations which are generally similar electrically to the ring configuration of FIG. 1. Specifically, in FIG. 5A the strips, such as 51, are straight members between the delta vertexes. FIG. 5B shows that a strip, such as 52, may curve inwardly in the direction of the central axis of symmetry. FIG. 5C includes series capacitors (such as 31, 32, and 33 of FIG. 3) formed by strip gaps 53 and 54 which together electrically correspond to one of these series capacitors. A single capacitive gap could obviously be located in the center of any strip or the total capacity may be located at one end of the strip in the manner of gap 55 of FIG. 5D. Increased capacity at any of these locations may be obtained by creating an insulated overlap between ends of a given strip.

The principles of the present invention should not be confused with those of prior art devices known

generally as "ring circulators" which when shown in schematic form only bear a superficial similarity to the devices claimed here. These prior devices comprised three T-junctions connected in a ring by nonreciprocal phase shifters. They were large compared to a wavelength of the operating frequency and involved no lumped constant resonance.

What is claimed is:

1. A circulator for operation in a given band of high frequency electromagnetic wave energy comprising at least one ground plane and a strip line configuration above said ground plane, said configuration including three strip line ports arranged in rotational symmetry about a central axis, and a further conductive strip connecting the ports in succession one with the next, a core of magnetically biased gyromagnetic material located on said axis and intercoupling segments of said further strip when any of said ports is excited by high frequency wave energy relative to said ground plane, said segments each exhibiting an inductive reactance, means for introducing a capacitance having first and second portions between said configuration and said ground plane, said first portion being individually related to each one of said ports to a greater degree than to the other of said ports, said second portion being related symmetrically to all of said ports, said capacitance being of such value to interact with the inductive reactance of said segments to produce circulation within said given band.

2. The circulator according to claim 1 including capacitive gaps along the course of said further conductive strip.

3. The circulator according to claim 1 wherein said further conductive strip is in the form of a ring.

4. The circulator according to claim 1 wherein said capacitance is introduced by a conductive member interposed between said configuration and said ground plane so that said first portion is formed between said configuration and said member and so that said second portion is formed between said member and said ground plane.

5. The circulator according to claim 4 including additional conductive members connected to each of said ports and extending between said configuration and said conductive member to increase said first portion of said capacitance.

6. A circulator comprising at least one ground plane, a plurality of strip line ports arranged above said ground plane in rotational symmetry about a central axis, a plurality of further strips connecting said ports in

succession one with the next, a core of magnetically biased gyromagnetic material located on said axis and intercoupling said further strips when any of said ports is excited by high frequency wave energy relative to said ground plane, and an intermediate conductive layer separated by dielectric material from said conductive strips on one side and from said ground plane on the other.

7. A circulator comprising at least one ground plane, three strip line ports arranged above said ground plane, three further strips connecting each port in succession to the next port in a delta configuration, a core of magnetically biased gyromagnetic material intercoupling said further strips when any of said ports is excited by high frequency wave energy relative to said ground plane, and an intermediate conductive layer separated in space from said conductive strips and from said ground plane.

8. A circulator comprising at least one ground plane and a strip line configuration above said ground plane, said configuration including three strip line ports arranged in rotational symmetry about a central axis, and a further conductive strip connecting the ports in succession one with the next, a core of magnetically biased gyromagnetic material located on said axis and intercoupling segments of said further strip when any of said ports is excited by high frequency wave energy relative to said ground plane, means for introducing capacitance between said configuration and a point intermediate said configuration and said ground plane, and means for introducing capacitance between said intermediate point and said ground plane.

9. A circulator for operation in a given band of high frequency electromagnetic wave energy comprising at least one ground plane and a strip line configuration above said ground plane, said configuration including three strip line ports arranged in rotational symmetry about a central axis, and a further conductive strip connecting the ports in succession one with the next, a core of magnetically biased gyromagnetic material located on said axis and intercoupling segments of said further strip when any of said ports is excited by high frequency wave energy relative to said ground plane, said segments each exhibiting an inductive reactance, means including a conductive member for introducing capacitance between said configuration and said ground plane, said capacitance being of such value to interact with the inductive reactance of said segments to produce circulation within said given band.

* * * * *

55

60

65