April 9, 1963 J. G. CLARK ETAL 3,085,212

TUNABLE CIRCULATOR

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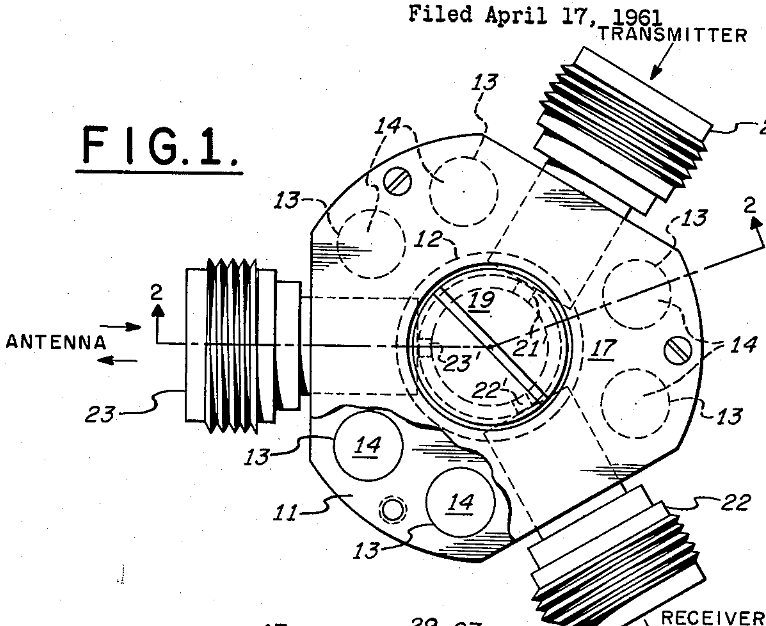
FIG. 1.



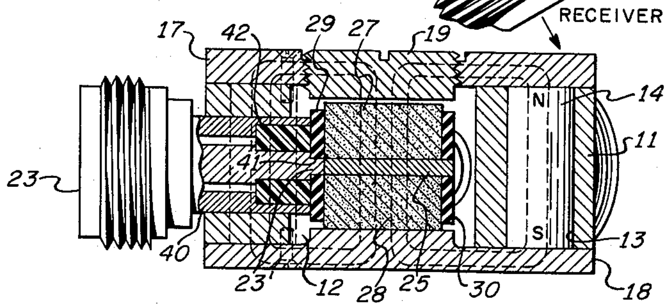


FIG. 2.

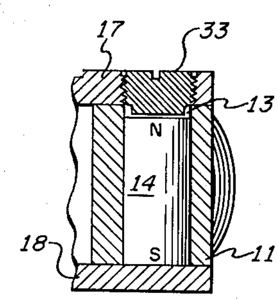


FIG. 3.

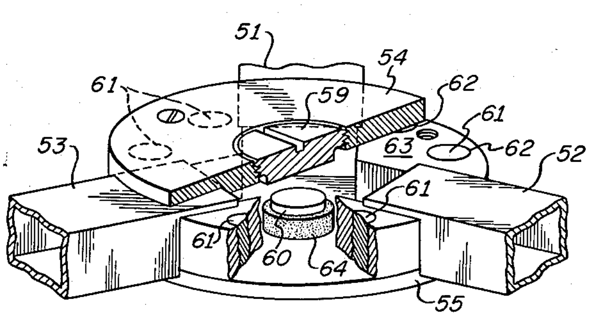


FIG. 4.

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TUNABLE CIRCULATOR

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This invention relates to improved nonreciprocal electromagnetic wave transmission line junctions and more particularly to a unique construction and arrangement of the junction which result in tunable, compact devices which possess excellent electrical qualities.

A particularly useful form of the invention is a tunable three-port junction for the nonreciprocal propagation of TEM mode electromagnetic waves. A theoretical investigation of nonreciprocal junctions including this type is presented by B. A. Auld on pages 238–246 of IRE Transactions on Microwave Theory and Techniques, April 1959, to which reference is hereby made. These devices are useful as duplexers, isolators, attenuators and switches. Known prior art nonreciprocal electromagnetic wave transmission line junctions of the type now under consideration are relatively large and bulky in size, and their optimum operating conditions are restricted to a relatively narrow and fixed frequency range. Both of these objectionable features are overcome by the present invention.

It therefore is an object of this invention to provide a small, compact nonreciprocal transmission line junction.

Another object of this invention is to provide a small, compact nonreciprocal transmission line circulator which is tunable to obtain optimum operation at any frequency within a relatively wide range of frequencies.

A further object of this invention is to provide a tunable nonreciprocal transmission line junction useful as a circulator for TEM mode electromagnetic waves.

The present invention will be described by referring to the accompanying drawings, wherein:

FIG. 1 is a top view of a device constructed in accordance with this invention and is used for nonreciprocal propagation of transverse electromagnetic (TEM) mode waves;

FIG. 2 is a sectional view taken along the section 2—2 of FIG. 1;

FIG. 3 is a partial sectional view similar to FIG. 2 but showing another embodiment of the invention; and

FIG. 4 is a perspective view, partially broken away, showing still another embodiment of this invention useful for nonreciprocal propagation of transverse electric (TE) mode waves.

Referring now more particularly to FIGS. 1 and 2, which illustrate a presently preferred embodiment of a tunable Y-junction circulator for the nonreciprocal propagation of TEM mode waves, the device is comprised of an outer housing member 11 of non-magnetic material such as aluminum. Housing member 11 has a central aperture 12 extending therethrough, and a plurality of axially extending bores 13 extending through the housing parallel to and disposed around said central aperture 12. A rod-shaped permanent magnet 14 is disposed in each of said bores 13 with the like poles of said magnets at the same ends of said housing 11. End plates, or cover plates, 17 and 18 of magnetic material are positioned over the opposite ends of housing member 11, and extend radially over the ends of permanent magnets 14. End plate 17 has a centrally-positioned threaded plug 19 of magnetic material which may be turned to vary its axial position.

Coaxial line connectors 21, 22 and 23 extend through the sides of outer housing member 11, FIG. 1, and the center conductors 21′, 22′ and 23′ of said connectors are connected to notches cut into the conductive disc 25 which

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is centrally positioned within aperture 12. A strip transmission line junction thus is formed wherein conductive disc 25 is the center conductor and the inner surfaces of end members 17 and 18 form the respective ground planes of said junction. Preferably, at least the inner surfaces of end members 17 and 18 are of a good conductive material to assure low attenuation of waves propagating through the junction.

Two discs, or posts, 27 and 28 of magnetically polarizable material which exhibits gyromagnetic properties at the frequency of waves propagating through the junction are axially disposed within the junction on opposite sides of central conductive disc 25. The material of discs 27 and 28 may be ferrite, garnet, or any other known material capable of exhibiting the desired properties for nonreciprocal operation. These materials are well known and are commercially available. A yttrium-iron garnet material having a gadalinium addition of approximately 60% has been used with success. Sleeves 29 and 30 of a low-loss dielectric material are positioned coaxially about discs 27 and 28 of gyromagnetic material, and preferably have a height less than the axial separation between center conductor 25 and the ground planes formed by end members 17 and 18. As will be explained in more detail below, these dielectric sleeves provide one means for tuning the Y-junction circulator for optimum operation in a given frequency range.

As may be seen by the dashed lines in FIG. 2, a magnetic circuit for biasing gyromagnetic elements 27 and 28 is established from the north poles of permanent magnets 14, centrally through the top end member 17 and plug 19, axially through the members 27 and 28 of gyromagnetic material, radially through bottom end member 18 to the south poles of permanent magnets 14. In the arrangement shown in FIG. 2, the magnetic circuit has extremely low reluctance, thus minimizing the size of the permanent magnets 14 required to properly magnetize gyromagnetic members 27 and 28. Although six permanent magnets are illustrated in FIG. 1, more or fewer magnets may be employed according to the requirements of the particular device. The reluctance of the magnetic circuit illustrated in FIG. 2 may be varied by turning threaded plug 19 to move it outwardly or inwardly and thus create a greater or smaller air gap between the post 27 of gyromagnetic material and end plug 19.

When the Y-junction circulator illustrated in FIGS. 1 and 2 is properly adjusted for operation as a duplexer, electromagnetic energy from a transmitter, not shown, is coupled into coaxial line connector 21 and propagates through the junction substantially exclusively to coaxial line connector 23, and thence to a radiating antenna, not shown. Electromagnetic waves received by the antenna are coupled into coaxial line connector 23, through the junction and substantially exclusively to coaxial line connector 22 which is connected to a receiver, not shown.

One advantageous feature of the Y-junction circulator illustrated in FIGS. 1 and 2 is its small size. In a device constructed as illustrated, the physical characteristics, exclusive of connectors, are as follows: 1.5 inches in diameter, .75 inch in height and approximately 3.75 ounces in weight. The features which permit this miniaturization may be seen in FIG. 2. The outer conductor 40 of coaxial connector 23 extends entirely through outer housing member 11 and abuts against dielectric sleeves 29 and 30, and the inner conductor 23′ of the connector is connected directly in a slot 41 milled in central conductive disc 25. This eliminates the need for a transitional section between the connector 23 and central conductive disc 25, thus reducing the diameter of the device. Additionally, the diameter of central conductive disc 25 is no greater than is necessary to support the posts 27 and 28 of gyromagnetic material and dielectric sleeves 29 and 30. The dielectric sleeves 29 and 30 abut against the outer conductors 40 of the connectors and help center the posts 27 and 28 of gyromagnetic material within the junction.

Electrical continuity is established from outer conductor 40, through the conductive housing 11 to the respective end members 17 and 18 which form the ground planes of the TEM mode junction. Outer conductor 40 is insulated from inner conductor 23' by means of a dielectric supporting washer 42.

Another extremely advantageous feature of the Y-junction circulator of this invention is its versatility of tuning in that it readily may be tuned for optimum operation at a given frequency within a relatively wide range of frequencies. This is a distinct advantage over known devices of this type because they are fixed-tuned and are inherently narrow-band devices.

The above-referenced theoretical development by Auld shows that the successful operation of a three-port circulator of this type requires a symmetrical phase relationship between three junction parameters, i.e., the three junction scattering matrix eigenvalues. These parameters can be considered as reflection coefficients which experience a phase variation as a function of frequency variation, and with any physical alteration that is made in the junction. However, to assure optimum operating conditions for circulation, such variations and alterations must conform to an additional condition of symmetry so as to preserve the symmetry group of the junction. Because the condition for optimum circulation involves a specific phase relationship between three quantities, it is necessary, in general, to effect a change in at least two of these quantities to satisfy the required condition for optimum operation. In a physical sense, this requires that at least two physical characteristics of the junction be altered. It has been found, for example, that to shift the frequency of operation of a Y-junction circulator from a frequency f_1 to a frequency f_2, it is not sufficient to change only the magnetic biasing field as is the case with nonreciprocal ferrite devices in a straight section of hollow waveguide, for example. It has been found to be necessary to change simultaneously the magnetic biasing field and some other characteristic of the junction. Prior efforts to change this other characteristic have involved changing the height and/or diameter of the posts 27 and 28 of gyromagnetic material. This material is difficult to machine, however, and this operation is costly and time consuming. The design of the device of this invention provides several means for changing this other characteristic of the junction to provide optimum operation at a selected frequency in a range of frequencies. As a first means, the height and diameter of dielectric sleeves 29 and 30, and the dielectric constant of the material of said sleeves readily may be changed to provide a significant change in the operating frequency of the junction. The dielectric materials employed have been Teflon, nylon and Stycast, manufactured by Emmerson and Cummings Co., Canton, Mass. All of these materials are easily machined, and these and other materials of differing dielectric constants may be employed. Additionally, the axial position in the junction of the dielectric sleeves 29 and 30 can be made to produce a significant tuning effect, and for this reason said sleeves 29 and 30 are shorter than the axial separation between center conductive disc 25 and end members 17 and 18, thus allowing some choice for positioning dielectric sleeves 29 and 30 to obtain optimum operation in a desired frequency range.

The axial positioning of threaded plug 19 in end member 17 is an additional tuning adjustment for finer tuning than provided by the dielectric sleeves, and in itself, provides two simultaneous adjustments in the junction. That is, the axial movement of said plug 19 varies the air gap in the magnetic circuit for biasing the gyromagnetic members 27 and 28, thus changing the magnetic field strength, and additionally varies the physical geometry of the junction in a symmetrical manner since the inner surface of plug 19 forms a portion of an outer ground plane of the strip transmission line junction.

During the assembling and initial testing of the device, the position of dielectric sleeves 29 and 30 may be chosen to achieve optimum operation within a selected frequency range, and to achieve operation at a given frequency within this range, the position of plug 19 may be varied for optimum results. It thus may be seen that the device of this invention is quite versatile because the one basic design and construction of the device may be made to operate over a relatively wide frequency range. This is to be contrasted with known prior art devices wherein appreciable technical and engineering efforts often are required to modify a basic design of a device to achieve optimum operation at various frequencies.

The posts 27 and 28 of gyromagnetic material, and the dielectric sleeves 29 and 30 may be secured to the central conductive disc 25 or to the inner surface of threaded plug 19 and end member 18. In the tuning of the device by axially positioning plug 19 with the post 27 of gyromagnetic material and dielectric sleeve 29 secured thereto, the movement of post 27 and sleeve 29 away from the center conductive disc 25 increases the frequency of optimum operation. Similarly, a reduction in the height and/or the diameter and/or dielectric constant of dielectric sleeves 29 and 30 also will raise the frequency of optimum operation. A second threaded plug similar to plug 19 also may be provided in the bottom end member 18, if desired.

In a Y-junction circulator constructed substantially as illustrated in FIGS. 1 and 2, and intended for operation in the C-band of microwave frequencies, it was found that with dielectric sleeves 29 and 30 made from Stycast K–20, the height of said sleeves could be varied to obtain optimum operation at any selected frequency in the range from 4.4 kmc. to beyond 10 kmc. When the height of the dielectric sleeves were changed, the strength of the magnetic biasing field for the gyromagnetic material also was varied by axially adjusting the position of plug 19. It was found that for a certain fixed position of the dielectric sleeves 29 and 30, the frequency of optimum operation could be varied between 5.4 kmc. and 5.9 kmc. by changing the magnetic field strength by means of threaded plug 19. At a frequency of operation of 5.56 kmc. the device had an insertion loss in the selected transmission path of 0.2 db, an isolation of 35 db in the non-selected transmission path and an input VSWR of 1.05.

An alternative embodiment of the device illustrated in FIGS. 1 and 2 is shown in the partial sectional view of FIG. 3, and provides additional adjusting means for varying the reluctance of the magnetic circuit. This additional adjusting means is comprised of threaded plugs 33 of magnetic material positioned in end member 17 directly above each of the permanent magnets 14. These additional threaded plugs 33 may be moved axially independently of the centrally positioned plug 19, thus providing an adjusting means in the magnetic circuit which does not also effect the physical characteristics of the junction, as does an axial adjustment of the centrally positioned plug 19. Except for the addition of the tuning plugs 33, the device of FIG. 3 would in all other respects be identical to the device illustrated in FIG. 2.

The description of this invention thus far has been confined to a junction having a central conductive member 25 and ground planes on opposite sides thereof, provided by end members 17 and 18, for the propagation of TEM mode waves. A hollow waveguide type of Y-junction also may be constructed according to the present invention in the manner illustrated in FIG. 4. In this figure, hollow rectangular waveguide sections 51, 52, and 63 are conductively connected in a common Y-junction. Circular end members 54 and 55 of magnetic material form the top and bottom conductive surfaces of said junction. A centrally-positioned threaded plug 59 of magnetic material corresponds to the plug 19 of FIG. 2, and may be rotated to various axial positions to vary the reluctance of the magnetic circuit of said device, and to change the physical geometry of the junction in a symmetrical manner. A post 60 of gyromagnetic material is symmetrically positioned on the bottom surface of the junction, and a sleeve of low-loss dielectric material 64 is disposed coaxially about said post. Rod-shaped permanent magnets 61 are positioned within bores 62 which extend through the portion 63 of the structure external to the wave propagating paths. The magnetic circuit, and the adjusting means therefor, of the device illustrated in FIG. 4 may be similar to those of either of the other embodiments previously described.

The present invention is not limited in its use to Y-junction nonreciprocal devices, but is equally applicable to other types of junctions such as a T-junction, for example.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than limitation and changes within the purview of the appended claims may be made without departing from the true scope and spirit of the invention in its broader aspects.

What is claimed is:

A nonreciprocal electromagnetic wave transmission line junction comprising

an outer housing member of non-magnetic material having a central aperture therethrough,

three TEM mode electromagnetic wave transmission lines having inner and outer conductors disposed around said housing with the inner conductors radially extending therethrough,

a thin disc of conductive material positioned within said aperture transversely to the central axis thereof, said disc being conductively connected to the center conductors of said transmission line,

first and second posts of magnetically polarizable material that exhibits gyromagnetic properties at the frequency of waves propagating through said junction centrally disposed within said aperture on opposite sides of said disc,

a plurality of bores extending through said housing parallel to and positioned around said central aperture,

a plurality of permanent magnets each positioned within one of said bores with their polar axes directed in the same direction parallel to the central axis of said aperture,

first and second end plates of magnetic material extending over the respective ends of said aperture and over the respective ends of said permanent magnets,

whereby a low reluctance magnetic circuit is established from one set of like poles of said magnets, centrally through one of said magnetic end plates, axially through said two posts of gyromagnetic material and radially through said second magnetic end plate to the other set of poles of said magnets,

the inner surfaces of said end plates being conductive to form ground planes on opposite sides of said thin conductive disc to support the propagation of TEM waves through said junction,

at least a portion of one of said end plates being axially moveable to vary the reluctance of said magnetic circuit and to vary the axial spacing between at least a portion of one ground plane formed by said movable end plate and said thin axial disc,

and first and second sleeves of low-loss dielectric material disposed within said junction and respectively surrounding each of said posts of gyromagnetic material,

at least one of said dielectric sleeves having an axial length less than the separation between said thin conductive disc and a ground plane and being secured to said axially movable end plate to permit adjustable positioning of said dielectric sleeve within said junction, thereby providing tuning means for said junction.

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