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NONRECIPROCAL CIRCUIT ELEMENT

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2 Sheets-Sheet 1

FIG. 1

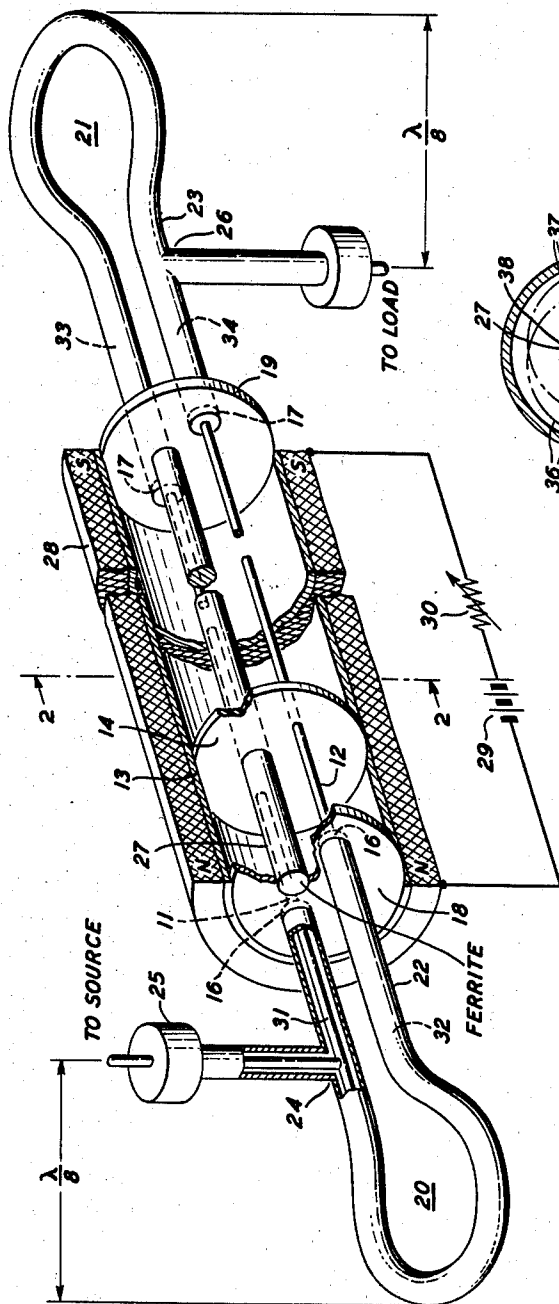
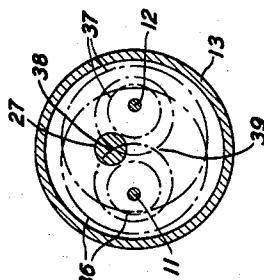


FIG. 2



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2,892,161

NONRECIPROCAL CIRCUIT ELEMENT

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19 Claims. (Cl. 333—26)

This invention relates to nonreciprocal transmission circuits for electromagnetic wave energy and, more particularly, to directional or nonreciprocal attenuators and phase shifters for said wave energy in the frequency ranges below a few thousands megacycles.

Recently the electromagnetic wave transmission art has been substantially advanced by the development of a group of nonreciprocal transmission components utilizing one or more of the several nonreciprocal effects produced by polarized elements of gyromagnetic materials, often designated ferromagnetic materials or ferrites. Included within this group of components are devices that act as nonreciprocal attenuators, which have been designated isolators; and nonreciprocal phase shifters, one class of which has been designated gyrators. A recent and complete survey of these devices, their principles of operation, and their uses is to be found in an article entitled "Behavior and Applications of Ferrite in the Microwave Range," by A. G. Fox, S. E. Miller and M. T. Weiss, Bell System Technical Journal, January 1955, pages 5 through 103.

In the great majority of cases these devices have employed wave guide components and are limited in their operation to the microwave frequency range and above. The need for nonreciprocal circuit elements, however, is at least as great in the lower frequency ranges in which coaxial and balanced transmission line components are used. These lower frequency ranges include the ranges designated very high frequency and ultra high frequency.

It is therefore an object of the present invention to produce nonreciprocal transmission effects for electromagnetic wave energy in frequency ranges below the microwave wavelength range.

It is a further object to produce nonreciprocal attenuation and nonreciprocal phase shifts for electromagnetic wave energy conducted by coaxial and balanced transmission line types of circuits.

Like the counterparts for microwave energy of the above mentioned prior art, the lower frequency isolators and nonreciprocal phase shifters in accordance with the present invention operate by exciting in an element of polarized gyromagnetic material, a circularly polarized component of radio frequency magnetic field that rotates in one sense relative to the steady polarizing field when the radio frequency wave is propagated in one direction but in the opposite sense when the wave is propagated in the opposite direction. When the polarizing field is adjusted to the strength necessary to produce ferromagnetic resonance in the gyromagnetic material, a substantial part of the energy is absorbed for one direction of rotation and direction of propagation, but is substantially unaffected for the other rotation and direction of propagation. When the polarizing field is adjusted to a strength substantially below that necessary to produce ferromagnetic resonance, a nonreciprocal phase shift is produced. The particularly novel features of the present invention reside in the means for exciting and supporting the necessary circular polarization in the

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gyromagnetic material. In one embodiment to be described, a coaxial-like structure is provided having two off-center inner conductors that are excited with respect to their common shield ninety degrees out-of-phase with each other. This circuit may be connected directly into a system using coaxial conductors. In another embodiment a pair of balanced wire lines are excited ninety degrees out-of-phase with each other. The latter circuit may be connected directly into a balanced transmission system.

These and other objects and features, the nature of the present invention and its various advantages, will appear more fully upon consideration of the various specific illustrative embodiments shown in the accompanying drawings and described in the following detailed description of these drawings.

In the drawings:

Fig. 1 is a perspective view of a coaxial type isolator or directional phase shifter in accordance with the present invention;

Fig. 2 is a cross-sectional view of the embodiment of Fig. 1 showing the lines of magnetic field pattern as they are excited in the embodiment of Fig. 1; and

Fig. 3 is a perspective view of a second embodiment of the invention employing the techniques of balanced wire line transmission systems.

Referring more particularly to Fig. 1, an illustrative embodiment of a coaxial type isolator or directional phase shifter is shown comprising a pair of similar, elongated conductive elements or wires 11 and 12 that extend parallel to each other in similar off-center transverse positions within an elongated conductive cylinder or shield 13. Conductors 11 and 12 may be suitably supported within cylinder 13 by a plurality of spacers, such as 14, made of material having a dielectric constant close to that of air. Conductors 31 and 33 constitute continuations of conductor 11 and conductors 32 and 34 constitute continuations of conductor 12. These continuations pass through washers 16 and 17, of ceramic or other insulating material, in the conductive end plates 18 and 19 of cylinder 13. Continuations 31 and 32 are joined together to form the center conductor of a conventional coaxial loop 20 the outside shield 22 of which is connected to plate 18. A similar loop 21 comprises the inner conductors 33 and 34 and their shield 23, the latter being connected to plate 19. The diameter of shield 13 is a small fraction, substantially less than one half wavelength of the energy to be conducted so that it will not act as a circular wave guide for this energy, and is more particularly chosen relative to the dimensions of coaxial loops 20 and 21 and the diameters of shields 22 and 23 in accordance with well known practice so that an impedance match is maintained between the two ends of loops 20 and 21 and the transmission system comprising conductors 11 and 12 and shield 13.

A coaxial type T connection 24 is provided in loop 20 with the point of connection being positioned to make conductor 32 an odd multiple of electrical quarter wavelengths of the energy to be transmitted longer as measured from the end of conductor 12 than conductor 31 as measured from the end of conductor 11. A similar connection 26 is provided for loop 21 spaced an odd multiple of quarter wavelengths nearer to conductor 12 than to conductor 11. Connections 24 and 26 may be standard coaxial T connectors of any suitable type.

Extending parallel to conductors 11 and 12 and located at a point similarly displaced with respect thereto as will be more particularly defined hereinafter, is an elongated cylinder or pencil-shaped element of gyromagnetic material 27. Element 27 may be supported by extending it through apertures in spacer 14 and plates

18 and 19. The material of element 27 is of the type having electrical and magnetic properties of the type described by the mathematical analysis of D. Polder in *Philosophical Magazine*, January 1949, vol. 40, pages 99 through 115. More specifically, element 27 may be made of any of the several ferromagnetic materials combined in a spinel structure. For example, it may comprise iron oxide with a small quantity of one or more bivalent metals such as nickel, magnesium, zinc, manganese, aluminum, or other similar material in which the other metals combine with the iron oxide in a spinel structure. This material is known as a ferromagnetic spinel or as ferrite. Frequently these materials are first powdered and then molded with a small percentage of plastic material according to the process described in the publication of C. L. Hogan, "The Microwave Gyrotator" in the *Bell System Technical Journal*, January 1952. One specific material which is particularly suitable at the lower frequencies contemplated by the present invention is magnesium-manganese-aluminum ferrite which has been found to exhibit a ferromagnetic resonance effect at a lower frequency range than prior considered ferrites with values of biasing magnetic field that are obtainable in practice. These frequencies have been observed to include the frequency range from below 170 megacycles per second to 2,000 megacycles per second at field strengths ranging from less than approximately 200 to 850 oersteds, respectively.

Element 27 is biased by a polarizing magnetic field applied parallel to the direction of propagation of the waves conducted along conductors 11 and 12. This field may be supplied by a solenoid 28 mounted upon the outside of shield 13 and supplied by energizing current from a source 29 through rheostat 30. To facilitate the explanation that follows, specific polarities are assigned to this field as indicated on the drawing, with the north pole thereof on the end toward loop 20. Therefore all reference to "clockwise" and "counterclockwise" hereinafter is taken as viewed in the positive direction of this field, i.e., as viewed from loop 21 looking toward loop 20. It should be noted, however, that element 27 may be magnetized in the opposite polarity and by a solenoid of other suitable physical design, by a permanent magnet structure, or the ferromagnetic material of element 27 may be permanently magnetized if desired.

It has been determined that when an element of gyromagnetic material located in the path of an electromagnetic wave in a region in which the magnetic field pattern of the wave has a substantially circularly polarized component as the wave propagates, and when the element is polarized by a magnetic field transverse to the plane of wave polarization rotation of intensity sufficient to produce ferromagnetic resonance in the material, the element will introduce substantial attenuation due to ferromagnetic resonance absorption to a wave having a component that rotates clockwise when viewed in the positive direction of the magnetic field, but will introduce little attenuation to a wave having field components that rotate in a counterclockwise sense. Similarly, if the magnetic field is decreased to an intensity substantially below that which produces ferromagnetic resonance, the components having the counterclockwise rotation will encounter a permeability which increases and becomes greater than unity as the field intensity is increased, while the wave having clockwise rotation will encounter a permeability which decreases and becomes less than unity as the field intensity is increased. This produces a different phase constant and a different delay for the oppositely rotating components. These phenomena and related aspects of them are disclosed in the copending applications of W. H. Hewitt, Jr., Serial No. 362,191 filed June 17, 1953; H. Suhl-L. R. Walker, Serial No. 362,176 filed June 17, 1953; S. E. Miller, Serial No. 362,193 filed June 17, 1953; and S. E.

Miller, Serial No. 371,594 filed July 31, 1953, now United States Patent 2,849,684 granted August 26, 1958.

In operation of the embodiment of Fig. 1, wave energy is applied to terminal 25 of connector 24 and divides in equal portions in the dominant coaxial mode, one half appearing as a voltage between shield 22 and conductor 31 with a magnetic field concentric with conductor 31, and the other half appearing as a voltage between shield 22 and conductor 32 with a field concentric with conductor 32. At plate 18 the energy surrounding conductor 31 excites a voltage between shield 13 and conductor 11 and is launched as a mode having a magnetic field distribution surrounding conductor 11 as represented by lines 36 on Fig. 2. Similarly, the energy surrounding conductor 32 excites a voltage between shield 13 and conductor 12 and launches a mode having a magnetic field distribution surrounding conductor 12 as represented by lines 37 on Fig. 2. A portion of field 36 occupies space common with field 37 within the common shield 13. Now there are two points, shown on Fig. 2 as 38 and 39, in this common space and on the plane of symmetry between conductors 11 and 12 at which the respective lines of magnetic field 36 and 37 are normal to each other. Because of the quarter wave longer length of conductor 32, the field 37 lags the field 36 by ninety degrees, and the resultant magnetic field at points 38 and 39 appears to be circularly polarized and to rotate in a counterclockwise sense as viewed in the above defined positive direction of the field. Either of these points is the one referred to above in defining the location of element 27.

Therefore, waves initially applied to terminal 25 and propagating from left to right in shield 13 experience little or no attenuation due to the gyromagnetic effect of element 27 when polarized by a field having the polarity shown on the drawing of sufficient strength to produce gyromagnetic resonance in the material of element 27. At the right-hand end of the structure, the energy within shield 13 is again separated as fields surrounding conductors 33 and 34, the portion surrounding conductor 33 being given an extra quarter wavelength delay so that the two parts are brought together in phase at connector 26. For the reverse direction of propagation, i.e., from right to left, the field 36 surrounding conductor 11 lags the field 37 surrounding conductor 12 by ninety degrees so that the resultant field presented at the position of element 27 appears to rotate in a clockwise sense as viewed in the defined positive direction of the biasing field. This wave therefore experiences substantial attenuation due to the gyromagnetic effect of element 27.

The result is a directional attenuator that introduces substantial loss to wave energy propagating in one direction, and little loss to wave energy propagating in the opposite direction. The degree of ferromagnetic attenuation is principally a function of the length of the gyromagnetic material extending in the direction experiencing ferromagnetic resonance, while certain reciprocal dielectric losses are associated with its over-all volume. It is therefore preferable that the diameter of element 27 be kept small to reduce its dielectric loss in the direction of small attenuation, and that its length parallel to conductors 11 and 12 be several wavelengths to introduce sufficient attenuation to absorb all or part, as desired, of the wave transversing in the direction of high attenuation.

In a fundamental application, the embodiment of Fig. 1 may be inserted directly in the coaxial lead between a source and a load. Energy from the source is delivered efficiently to the load, but possible reflections from the load are unable to reach and interfere with the source. It should be apparent that the relative directions of ferromagnetic attenuation depend upon the sense of the applied magnetic field so that reversing the sense thereof will reverse the direction of maximum attenuation.

If the biasing magnetic field is substantially decreased by reducing the magnetizing current with rheostat 30 to a value substantially below that which produces ferromagnetic resonance, the device of Fig. 1 becomes a directional phase shifter with maximum phase delay being introduced to waves propagating from left to right through shield 13 which have counterclockwise rotating magnetic wave components at the position of element 27. A minimum phase delay will be experienced by waves propagating from right to left which have clockwise rotating components at the position of element 27. The relative amplitudes of the phase shifts are a function of the strength of the magnetizing field and may be varied by adjusting rheostat 30.

An embodiment suitable for use in a two-wire balanced transmission system is shown in Fig. 3. As illustrated, this embodiment comprises two pairs of parallel, elongated conductors 41, 42, 43 and 44 equally spaced and symmetrically disposed relative to each other. Thin, transversely extending dielectric spacers 45 through 48 are longitudinally spaced along the length of the conductors to support them relative to each other in this relationship. Support is also provided by a rigid, cylindrical shield 49 which may be made of conductive, non-conductive or electrically dissipative material. Shield 49 protects conductors 41 through 44 from outside mechanical and electrical influences but otherwise plays no substantial part in the electrical operation of this embodiment. For reference purposes, the longitudinal portions of conductors 41 through 44 between spacers 46 and 47 will be referred to as the center portions thereof, while the portions between spacers 45 and 46, and 47 and 48 will be referred to as the left and right-hand extensions thereof, respectively.

Centrally disposed with respect to conductors 41 through 44, and therefore coaxial with shield 49, is an elongated element 51 of gyromagnetic material similar to element 27 of Fig. 1. Element 51 is longitudinally co-extensive with the center portion of conductors 41 through 44 and may be supported in this position by extending it through centrally located apertures in spacers 46 and 47. A longitudinal polarizing magnetic field for element 51 is supplied by the combination of solenoid 52, source 53 and rheostat 54. This field is assumed to have the same polarity as assigned in the embodiment of Fig. 1.

The center portion of the pair comprising the diametrically opposite conductors 42 and 43 is excited by a voltage wave that is ninety degrees out-of-phase with a voltage excited on the center portion of the pair comprising conductors 41 and 44 so that a circularly polarized wave is presented to element 51. One particularly novel manner of obtaining this excitation is illustrated on Fig. 3 which consists in general of loading one pair of conductors relative to the other. More particularly, the left-hand extension of conductors 41 and 44 is loaded by vane 55 of material having a high dielectric constant that extends diametrically between conductors 41 and 44 in the plane thereof and extends longitudinally therealong for a distance sufficient to produce a ninety degree delay in a voltage between conductors 41 and 44. A similar vane 56 is provided between the right-hand extensions of conductors 42 and 43. The left-hand ends of adjacent conductors 41 and 42 are connected together by bridge 57 to form one terminal of the balanced input to the device while conductors 43 and 44 are connected by bridge 58 to form the other terminal. A similar connection to the right-hand ends of the conductors is made by bridge 59 between conductors 41 and 42 and bridge 60 between conductors 43 and 44.

In operation of the embodiment of Fig. 3 as an isolator, the strength of the magnetic field supplied by solenoid 52 is adjusted to produce a ferromagnetic resonance condition in element 51. A voltage, balanced with respect to ground, is applied from a source between bridges

57 and 58. As the wave travels to the right the voltage between conductors 41 and 44 is successively delayed by vane 55 with respect to the voltage between conductors 42 and 43 until at the right end of vane 55, a circularly polarized wave is supported by the balanced four-wire system. In the embodiment as illustrated, such a circularly polarized wave will rotate in a counterclockwise sense viewed in the positive direction of the biasing magnetic field. Such a counterclockwise rotating wave is little affected by the ferromagnetic resonance condition of element 51. Vane 56 supplies a compensating ninety degree delay to the voltage between conductors 42 and 43 with respect to the voltage between conductors 41 and 44 so that between bridges 59 and 60 the two components will be in-phase and a resultant voltage is delivered to the desired load.

A reflection from the load, however, will be converted into a clockwise rotating wave in the four-wire system by vane 56 which delays the voltage between conductors 42 and 43 ninety degrees with respect to the voltage between conductors 41 and 44. This clockwise rotating wave is substantially dissipated or attenuated in the material of element 51 and little or none of it reaches the left-hand extensions of conductors 41 through 44.

Operation as a differential phase shifter is obtained by decreasing the biasing field substantially below that which produces ferromagnetic resonance in element 51. The counterclockwise rotating wave produced by excitation between bridges 57 and 58 is presented with a substantially different permeability and therefore experiences a substantially different delay from the clockwise rotating wave produced by excitation between bridges 59 and 60.

While the particular method illustrated for exciting the diametrically opposite pairs of conductors with voltages having a ninety degree phase difference is particularly adapted to the present invention, it should be noted that alternative means may also be used. For example, the electrical length of one pair of conductors could be made ninety degrees longer than the other pair of conductors by other methods of loading or by an actual difference in their physical lengths. In addition, a novel method of exciting the desired voltage waves which has the advantage of being broad band is disclosed and claimed in the copending application of J. H. Rowen, Serial No. 485,280 filed January 31, 1955.

In all cases it is understood that the above described arrangements are illustrative of a small number 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 nonreciprocal electromagnetic wave component comprising a plurality of elongated conductive elements, one portion of said elements comprising at least two wire-like elements extending parallel to and conductively isolated from each other along a major portion of their lengths, the remaining portion of said elements extending parallel to and conductively isolated from said wire-like elements and forming therewith a plurality of two-conductor transmission structures each adapted to support and propagate independent waves of electromagnetic wave energy, said transmission structures being coextensive with a relative physical orientation for which components of the magnetic field of the wave supported by each structure are substantially normal to components of the field supported by the other structures in a common region, an element of magnetically polarizable material exhibiting the gyromagnetic effect at the frequency of said wave energy supported in said common region, and means for applying steady magnetizing field to said element.

2. The component according to claim 1 wherein said remaining portion element of each transmission structure comprises a conductive shield common to all said transmission structures and surrounding the other conductive element of each structure.

3. The component according to claim 1 wherein each of said transmission structures comprises a pair of conductive wires diametrically disposed about a common axis extending longitudinally parallel to each other.

4. The component according to claim 1 including means for exciting said transmission structures from a common source and including means for delaying the wave exciting at least one of said structures ninety degrees with respect to the wave exciting the other of said structures.

5. The component according to claim 4 including means for delaying the wave upon said other of said structures ninety degrees with respect to the wave on said one structure and including means for delivering said waves to a common load.

6. The component according to claim 5 wherein the strength of said magnetic field produces ferromagnetic resonance in said gyromagnetic material.

7. A nonreciprocal electromagnetic wave component comprising a pair of elongated conductors spaced from and coextending parallel to each other, at least one other elongated conductor like disposed with respect to both conductors of said pair and forming transmission lines therewith, an elongated element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of wave energy supportable upon said conductors coextending parallel to said conductors on substantially the plane of symmetry between said pair of conductors, and means including a common source of wave energy for exciting a first voltage upon a transmission line including one conductor of said pair and for exciting a second voltage in phase quadrature with said first voltage upon a transmission line including the other conductor of said pair.

8. The component according to claim 7 including means for applying a steady magnetic field to said element parallel to the direction of the extension of said conductors.

9. The component according to claim 8 wherein said one other conductor comprises a conductive shield surrounding said pair of conductors.

10. The component according to claim 9 including means for exciting a voltage between each of said pair of conductors and said shield.

11. The component according to claim 10 including means for delaying the voltage between one conductor of said pair and said shield ninety degrees with respect to the voltage between the other conductor and said shield.

12. The component according to claim 8 wherein there are four elongated conductors arranged in diametrically opposite pairs with respect to the axis of said gyromagnetic element.

13. The component according to claim 12 including means for exciting a voltage between the conductors of 60 each pair.

14. The component according to claim 13 including means for delaying the voltage between one pair of conductors ninety degrees with respect to the voltage between the other pair of conductors.

15. A nonreciprocal electromagnetic wave component comprising an elongated conductive shield, a pair of elongated conductive elements extending parallel to each other within said shield in similar off-center transverse positions therein, an element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of said wave energy disposed on substantially the plane of symmetry between said conductors, and means for exciting each of said conductors by a voltage with respect to said shield ninety degrees out-of-phase with each other.

16. The component according to claim 15 wherein said means for exciting comprises a branching circuit having a branch connected to one of said conductors that is longer than a branch connected to the other of said conductors.

17. A nonreciprocal electromagnetic wave component comprising a first and a second pair of elongated conductive elements extending parallel to each other, said first pair lying in a plane making a perpendicular intersection with the plane of said second pair, an element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of said wave energy disposed along the line of the said intersection, means for exciting said first pair with electromagnetic wave energy, and means for exciting said second pair with electromagnetic wave energy ninety degrees out-of-phase with the excitation of said first pair.

18. A component according to claim 17 wherein said means for exciting said second pair includes a thin member of dielectric material lying in the plane of said second pair to delay a voltage wave conducted between said second pair.

19. A nonreciprocal electromagnetic wave component comprising first and second pairs of elongated conductors extending parallel to and conductively isolated from each other along a major portion of their lengths so that each pair forms a two-conductor transmission structure adapted to support and propagate independent waves of electromagnetic wave energy, said first pair lying in a plane making a perpendicular intersection with the plane of said second pair so that components of the magnetic field of the wave supported between said first pair are substantially normal to components of the field supported between said second pair along the line of said intersection, and an element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of said wave energy disposed along the line of said intersection.

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