

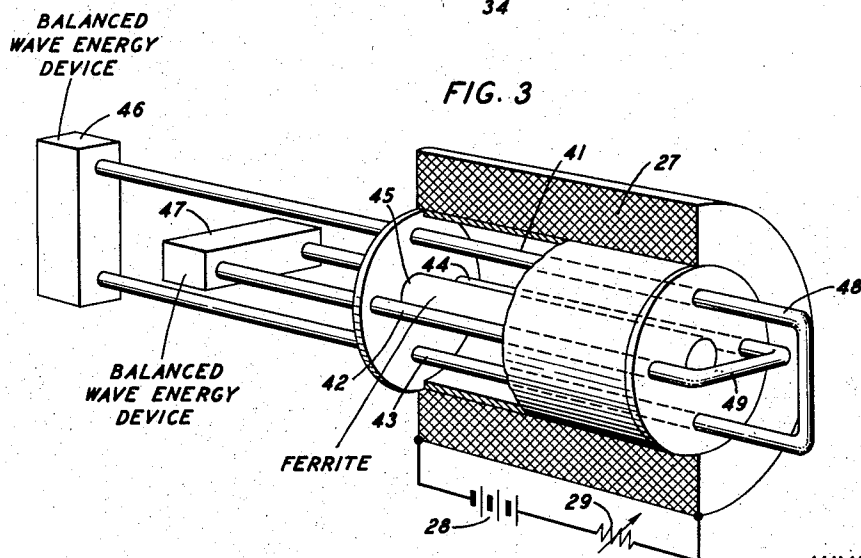
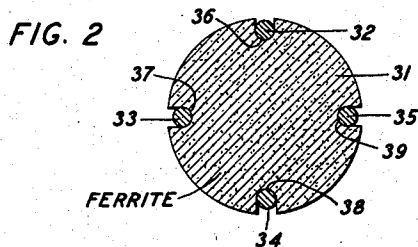
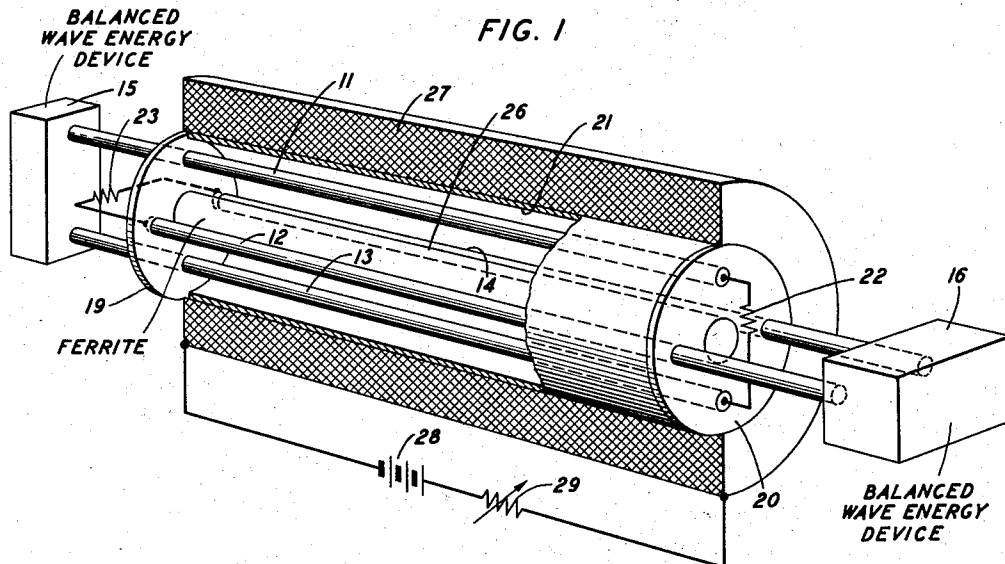
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NONRECIPROCAL CIRCUIT ELEMENT

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NONRECIPROCAL CIRCUIT ELEMENT

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This invention relates to nonreciprocal transmission circuits for electromagnetic wave energy and, more particularly, to multibranch networks known as gyrators for said wave energy in the frequency ranges below a few thousand 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 material, often designated ferromagnetic materials, or ferrites. Included within this group of components are devices known as "gyrators" which introduce a nonreciprocal phase inversion to electrical energy passing through them, i.e., introduce a 180 degree phase shift to wave energy passing in one direction through them relative to the phase shift introduced to energy passing in the opposite direction. A recent and complete survey of these devices, their principles of operation and their uses, is to be found in an article "Behavior and Applications of Ferrites 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 wave energy in the frequency ranges below the microwave wavelength range.

It is a further object to establish a nonreciprocal phase inversion between a pair of branches of a balanced transmission line type circuit.

In a particular embodiment, four conductors are arranged in diametrically opposite pairs with a longitudinally biased gyromagnetic element centrally disposed with respect to said conductors. Wave energy components applied from a connected electromagnetic wave device to a first of the pairs will be transferred to the second of the pairs of the precessing electrons within the gyromagnetic material. A resultant of the original and the transferred waves appears to rotate in space as the energy propagates along the structure and will eventually be rotated 90 degrees into the plane of the second pair at its other end. The rotation is antireciprocal like that of the Faraday rotation so that energy applied to the other end of the second pair will be transferred to the first pair in a phase that represents a 180 degree phase shift difference from the previously defined transfer from the first to the second pair. Such a nonreciprocal phase inversion is characteristic of the gyrator circuit for which uses and applications as a component are well known in the art.

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In a second embodiment, both pairs of conductors are terminated in a completely reflecting passive terminating means at the point where the resultant of the original and the transferred wave appears to have been rotated through 45 degrees. The resultant is thereby reflected back toward the first end of the device to receive a second and antireciprocal 45 degree rotation which brings the resultant into the plane of the second pair at the same end of the device as the input end. When energy is applied originally to the second pair, it will appear at the first pair with the phase relationship that is characteristic of a gyrator circuit.

These and other objects, the nature of the present invention and its various advantages and features 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 gyrator, in accordance with the invention, interposed schematically between two balanced wave energy devices;

Fig. 2 is a cross-sectional view showing an alternative physical arrangement for the components of a gyrator according to Fig. 1; and

Fig. 3 is a perspective view of another embodiment in accordance with the invention connected schematically at the same end thereof to two balanced wave energy devices.

Referring more particularly to Fig. 1, an illustrative embodiment of a gyrator circuit is shown. This circuit comprises four similar elongated conductors, or wires, 11 through 14 that extend parallel to each other longitudinally and are located transversely at equally spaced points around the circumference of a circle. The radius of each conductor should be small compared to the distance between the nearest conductor centers. Thin, transversely extending dielectric spacers 19 and 20 are longitudinally spaced to support the conductors relative to each other in this relationship. Support is also provided by a rigid cylindrical shield 21 which may be made of conductive, nonconductive or electrically dissipative material. Shield 21 protects conductors 11 through 14 from outside mechanical and electrical influences but otherwise plays no substantial part in the electrical operation of this embodiment.

The extremities of the two diametrically opposed conductors comprising one pair are connected to a balanced electromagnetic wave device at one end of the gyrator. This device may be a source of wave energy, a load circuit or other wave energy utilizing device, or a coupling transducer which in turn couples to a source or load depending upon the particular application. The other end of this pair is terminated at the other end of the gyrator by a passive terminating connection consisting of a dissipative impedance equal to the characteristic impedance between that pair. The other pair of conductors is connected to a similar impedance and device at the respectively opposite ends of the gyrator. More specifically, as shown in Fig. 1, a device 15 is connected to the left hand end of the diametrically opposite conductors 11 and 13. The right hand end of this pair is terminated in impedance 22 equal to the characteristic impedance of the pair. The right hand ends of conductors 12 and 14 are connected to device 16 with the left hand ends thereof being terminated in impedance 23.

A nonreciprocal coupling is provided between the pairs thus arranged by an elongated cylinder or pencil-shaped element 26 of gyromagnetic material similarly disposed with respect to conductors 11 through 14 and extending longitudinally along the center of the circle defined by the transverse locations of the conductors. Element 26

may be supported in this position by extending it through centrally located apertures in spacers 19 and 20.

The material of element 26 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, volume 40, pages 99 through 115. More specifically, element 26 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 Gyrator" 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 26 is biased by a polarizing magnetic field applied parallel to conductors 11 through 14. This field may be supplied by a solenoid 27 mounted upon the outside of shield 21 and supplied by an energizing current from source 28 through rheostat 29. It should be noted, however, that element 26 may be magnetized by a solenoid of other suitable physical design, by a permanent magnet structure, or the material of element 26 may be permanently magnetized.

The coupling produced by element 26 can be explained by the recognition that the gyromagnetic material of element 26 contains unpaired electron spins which tend to line up with the applied field. These spins have an associated magnetic moment which can be made to precess about the line of the biasing magnetic field, keeping an essentially constant moment component in the direction of the applied biasing field and at the same time providing a moment component which may rotate in a plane normal to the field direction. Thus when a reciprocating high frequency magnetic field of electromagnetic wave energy is impressed upon the moment, the moment will commence to precess in one angular sense and to resist rotation in the opposite sense.

The combined effect of many such electrons and their associated moments produces in the gyromagnetic material not only a flux representing the impressed magnetic field but also a flux representing a reciprocating field at right angles in space to the applied field and displaced in time from the applied field by a phase determined by the direction of precession of the electrons and independent of the direction of propagation of a wave along the lines. The amplitude of the coupled wave depends upon the parameters of the ferrite and may also be controlled by the strength of the biasing magnetic field.

Thus when a voltage wave is applied from device 15 to pair 11—13 for propagation to the right, an induced field will be set up between pairs 12—14. The excited and the induced fields will combine to form a resultant voltage propagating to the right that is polarized at some angle to the plane of excited pair 11—13. Initially this angle will be small but as the distance from the excited end is increased, the angle becomes increasingly larger. In other words, the resultant appears to rotate in space as the wave propagates in a sense that is clockwise as viewed in the positive direction of the biasing field, like the rotation produced by a Faraday-effect element. At

an appropriate electrical distance to the right, depending in a given structure upon its physical length and the biasing field strength, the resultant will have rotated 90 degrees, which places it in the plane of pair 12—14. If pair 11—13 is terminated in its characteristic impedance at this point, all energy may be abstracted upon pair 12—14 for application to device 16. The physical distance at which this occurs may be adjusted by adjusting the strength of the biasing field. Similarly, if energy is applied from device 16 to pair 12—14 in the same phase as the energy delivered to device 16, for example, as the reflection obtained if device 16 were a completely reflecting termination, the resultant of the excited and induced fields will appear to rotate anti-reciprocally, that is, in the same clockwise direction as viewed in the positive direction of the biasing field, until the resultant is brought into the plane of 11—13 for delivery to device 15 in a phase that is 180 degrees different from that of the energy originally applied from device 15. Thus if a given phase of energy applied at the left hand end of pair 11—13 is defined as being in phase with the energy leaving the right hand ends of pair 12—14, the apparatus of Fig. 1 introduces no phase shift to wave energy propagating from left to right therethrough but introduces a 180 degree phase shift or a phase inversion to wave energy propagating from right to left therethrough. This is the classical property of a gyrator and the property which makes the gyrator useful as a component in numerous nonreciprocal circuit arrangements now familiar to the art.

Referring to Fig. 2, an alternative cross section for a gyrator operating in accordance with the principles of the embodiment of Fig. 1 is shown. It will be noted that in Fig. 1 element 26 is illustrated as having a diameter that is small compared to the distance between the nearest conductor centers. However, at the expense of a certain increase in the dielectric loss introduced by the gyromagnetic element, its cross section may be substantially increased with the advantage of a much shorter length for the component and a somewhat simplified physical construction. Thus in Fig. 2 the gyromagnetic element 31 has a transverse diameter that is slightly larger than the diametrical distance between conductors 32 through 35. Element 31 is provided with longitudinal grooves 36 and 39 into which conductors 32 through 35 are received, respectively. Thus element 31 also provides the physical support for the conductors. When an axial longitudinal magnetic field is supplied to element 31 by means not shown, it operates in substantially the same manner as that of the embodiment of Fig. 1.

In Fig. 3 another embodiment of a gyrator in accordance with the invention is shown having physical advantages over the embodiment of Fig. 1 in that its length is substantially decreased by one half and that both branches appear at the same end of the component. Thus conductors 41 and 43 comprise one diametrically opposite pair of conductors and conductors 42 and 44 comprise the second pair, symmetrically arranged around gyromagnetic element 34. A first balanced wave energy device 46 is connected across the left hand ends of conductors 41 and 43 and a second balanced wave energy device 47 is connected across the left hand ends of conductors 42 and 44. The right hand ends of conductors 41 and 43 are connected together by a passive terminating connection comprising a highly conductive short circuiting element 48 and the right hand ends of conductors 42 and 44 are similarly terminated by conductive element 49.

In operation the longitudinal biasing field supplied by solenoid 27 is adjusted by means of rheostat 29 and potential source 28 relative to the length and composition of element 45 to produce a 45 degree rotation of the resultant wave described above in connection with Fig. 1. Thus a voltage wave applied to pair 41—43 from device 46 will appear to undergo a Faraday rotation of 45 degrees as it propagates to the right with components thereof being supported by both pairs of conductors. A substantially

complete reflection of these components is produced by short circuit connections 48 and 49 so that these components are reflected back along the pairs. The resultant again undergoes a 45 degree rotation in an antireciprocal direction to bring its polarization into the plane of pairs 42—43 for delivery to device 47. Correspondingly, energy applied from device 47 to pair 42—44 will eventually be delivered to device 46 but in a phase which is typical of the gyrator action of the combination.

For the purposes of its use in the present specification and in the appended claims, the term "wave energy device" is taken to include a source of wave energy or a load circuit in the form of a utilizing device for this energy or a circuit which serves both as a source and a load for respectively opposite directions of propagation. The term also includes coupling components or transducers such as transformers, directional couplers or hybrids which appear as a source and/or a load to the nonreciprocal component connected to them even though they are included between the nonreciprocal component and the ultimate source or load. The term does not include strictly "passive terminating connections" such as a short circuit termination of low impedance the function of which is to reflect wave energy without either absorbing or utilizing it. Neither does the term include a passive terminating connection such as a matched dissipative impedance the principal function of which is to convert electrical energy into heat energy. The terms "wave energy device" and "passive terminating connection" are therefore considered as mutually exclusive.

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. In combination, a pair of electromagnetic wave devices, a pair of parallel transmission lines each comprising two elongated spaced and parallel conductive elements, each of said transmission lines being located in a plane perpendicular to the plane of the other of said transmission lines intersecting in a line extending parallel to said elements, each of said pairs of transmission lines having one of said devices connected to an end thereof for launching on said transmission line a propagating wave traveling toward the other end thereof, and means for coupling said lines with a nonreciprocal coupling comprising a magnetically polarized element of material exhibiting the gyromagnetic effect at the frequency of wave energy supportable by said transmission lines extending in a space occupied in common by the magnetic field patterns of waves conducted by said lines.

2. The combination according to claim 1 wherein said devices are connected to adjacent ends of said pair of transmission lines.

3. The combination according to claim 1 wherein said devices are connected to adjacent ends of said pair of transmission lines.

4. The combination according to claim 1 wherein the other end of each pair from that to which said device is connected is terminated in a dissipative impedance.

5. The combination according to claim 2 wherein the other end of each pair from that to which said device is connected is terminated in a short circuit.

6. A nonreciprocal electromagnetic wave component comprising a plurality of elongated conductors spaced from and extending parallel to each other between their extremities, an element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of wave energy supportable by said spaced conductors being similarly displaced with respect to each of said conductors said conductors being surrounded by conductively insulat-

ing material, over such portion of their longitudinal dimension coextensive with said element, means for coupling to and from a voltage wave of given linear polarization supported between said conductors at one extremity thereof, and means for coupling to and from a voltage wave polarized at an angle to said given polarization at the other extremity of said conductors.

7. The component of claim 6 wherein said element is elongated, extends parallel to said conductors and is centrally located with respect to said conductors.

8. The component of claim 7 wherein said element is ferrite and is polarized parallel to said conductors.

9. The component of claim 6 wherein one extremity of every other conductor is connected to the extremity of an opposite conductor through a dissipative impedance and wherein the other extremity of every remaining conductor is connected to an opposite conductor through a dissipative impedance.

10. The component of claim 9 wherein said means for coupling comprises the remaining extremity of every conductor connected to the extremity of an opposite conductor through an electromagnetic wave device.

11. A nonreciprocal electromagnetic wave component comprising four elongated conducting elements spaced from and extending parallel to each other from one end of said component to the other end of said component, an elongated element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of wave energy supportable by said spaced conductors extending parallel to said conducting elements, a source of electromagnetic wave energy connected between two of said conductors at one end of said component, a load circuit for said wave energy connected between the other two of said conductors at said one end of said component, and a highly conductive connection between two of said conductors at the other end of said component.

12. In combination, a plurality of elongated conductors being equally spaced transversely around the circumference of a circle and extending longitudinally parallel to each other, an elongated element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of wave energy supportable by said spaced conductors extending parallel to said conductors through the center of said circle said conductors being conductively insulated from each other over such portion of their longitudinal dimension coextensive with said element, means for exciting a voltage wave between the ends of two of said conductors, a passive terminating connection connecting together the other ends of said two conductors, means for utilizing a voltage wave connected between the ends of two other of said conductors, and a passive terminating connection connecting together the other ends of said other conductors.

13. A nonreciprocal electromagnetic wave component comprising a plurality of pairs of elongated conductors spaced from and extending parallel to each other, an elongated element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of wave energy supportable by said spaced conductors extending parallel to said conductors, means for connecting one end of alternate ones of said pairs and the other end of the remaining ones of said pairs to respective electromagnetic wave devices, and means for terminating the remaining end of each pair in the characteristic impedance of that pair.

14. In combination in a nonreciprocal electromagnetic wave transmission system, a plurality of elongated conductors being disposed symmetrically relative to each other in diametrically opposite pairs, an elongated element of magnetically polarized ferromagnetic material centrally disposed with respect to said conductors, said conductors and said element being all parallel to each other between their longitudinal ends, means for coupling to and from electromagnetic wave energy of maximum intensity between the conductors of at least one of said pairs at one end, and

a highly conductive connection between the conductors of said one pair at the other end.

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