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NONRECIPROCAL CIRCUIT ELEMENT

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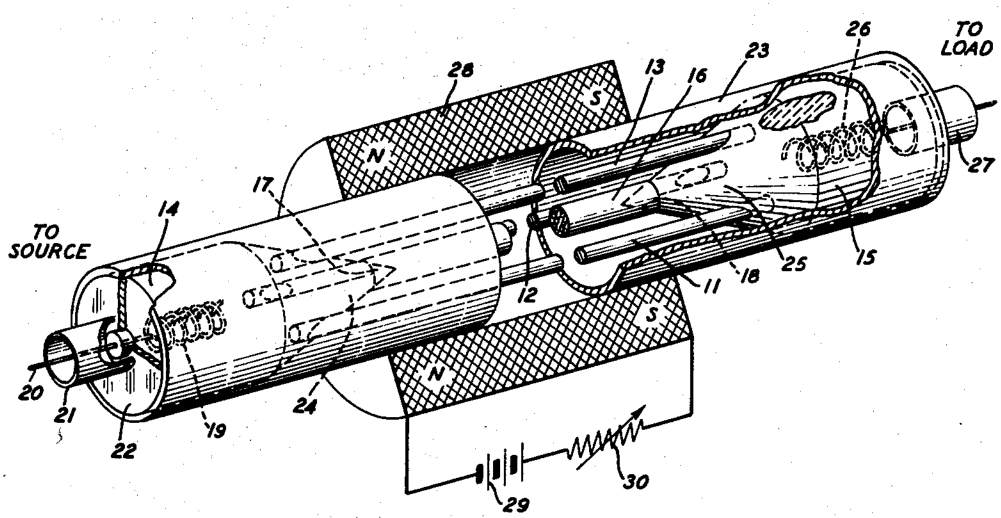

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NONRECIPROCAL CIRCUIT ELEMENT

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8 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 freqeuency 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 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, are 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.

In the copending application of A. M. Clogston, Serial No. 485,281, filed January 31, 1955, there is disclosed and claimed lower frequency isolators and nonreciprocal phase shifters that comprise a plurality of pairs of parallel wire transmission lines so arranged and excited that a circularly polarized component of radio frequency magnetic field is produced by the combination of the joint fields of energy carried separately by each pair. An element of polarized gyromagnetic material is located in the region of this circular polarization so that the circularly polarized component of radio frequency magnetic field 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 it 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 present invention is particularly directed to novel means of exciting and propagating a circularly polarized wave of low frequency.

It is an object of the present invention to increase the operating bandwidth of nonreciprocal transmission devices in frequency ranges below the microwave frequency

range by providing broad band means for producing and supporting a circularly polarized wave from wave energy conducted by coaxial type transmission lines.

It is a more specific object to simplify and improve the nonreciprocal devices of the types disclosed in said copending application of A. M. Clogston.

In accordance with the present invention a wave transmission structure comprising three parallel conductors is provided. When these conductors are excited 120 degrees out-of-phase, a circularly polarized magnetic field results from their combined fields in a center region common to each of the individual fields. Novel means is also provided for exciting this phase difference directly from a coaxial transmission line. This means comprises a helical radiating member matched by a dielectric transistion member to the extremities of the conductors.

These and other obpects 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 drawing and described in the following detailed description of this drawing which shows a perspective view of an illustrative embodiment of an isolator or directional phase shifter in accordance with the invention.

Referring more particularly to the figure, an illustrative embodiment of a broad band isolator or directional phase shifter is shown which may be interposed directly in a coaxial transmission system. This device comprises three similar, elongated conductors or wires **11**, **12** and **13** that extend parallel to each other longitudinally and are located transversely at equally spaced points around the circumference of a circle. Conductors **11** through **13** may be suitable supported in this relation in several ways, one of which comprises imbedding the longitudinal extremities of conductors **11** through **13** in dielectric members **14** and **15**, the shape and further purpose of which will be considered in more detail hereinafter. Support is also provided by a rigid, cylindrical shield **23** which may be made of conductive, nonconductive, or electrically dissipative material. Shield **23** protects conductors **11** through **13** from outside mechanical and electrical influences but otherwise plays no substantial part in the electrical operation of the invention.

Similarly disposed with respect to conductors **11** through **13** and extending longitudinally along the center of the circle defined by the transverse locations of conductors **11** through **13** is an elongated cylinder or pencil shaped element of gyromagnetic material **16**. Element **16** may be supported by allowing pointed ends of portions **24** and **25** of dielectric members **14** and **15** to extend within conical depressions **17** and **18** in the ends of element **16**. The material of element **16** 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 **16** 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 **16** is biased by a polarizing magnetic field applied parallel to the direction of propagation of the waves conducted along conductors **11** through **13**. This field may be supplied by a solenoid **28** mounted upon the outside of shield **23** 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 at the left-hand end of solenoid **28**. Therefore all reference to "clockwise" and "counterclockwise" hereinafter is taken as viewed in the positive direction of this field, i.e., as viewed from the right-hand extremities of conductors **11** through **13** looking toward their left-hand extremities. It should be noted, however, that element **16** 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 **16** 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 Patent No. 2,849,684.

One novel feature of the present invention resides in the means for exciting circularly polarized waves upon the transmission system comprising conductors **11** through **13**. In general this consists of exciting the three conductors 120 degrees out-of-phase in the fashion of a three-wire three-phase system. Such excitation will produce a circularly polarized magnetic field in the center region of the three conductors where the three separate fields occupy a common space. More particularly, conductors **11** through **13** are excited by a helical radiating element **19** which is imbedded in dielectric member **14** with the helical axis of element **19** parallel to conductors **11** through **13** and substantially coaxial with element **16**. Helix **19** comprises an extension of the inner conductor **20** of coaxial conductor **20—21**, the outside shield **21** of which is connected to a conductive end plate **22** of shield **23**. The helix continues for several turns and ends adjacent to the left-hand extremities of conductors **11** through **13**. The diameter of helix **19** is chosen so that its circumference is of the order of one wavelength of the energy to be conducted in the dielectric material of member **14**. Such a helix is known to radiate in what is designated the axial mode of radiation, the radiation pattern of which is maximum in the direction of the helix axis and is substantially circularly polarized. The sense of rotation of the radiated circularly polarized wave is the same as the spiral sense of the helix. Plate **22** performs the function of a "ground plane" necessary for this radiation and should be at least one half wavelength in diameter as measured in the dielectric as is more fully described in the chapter entitled "The Helical Antenna" in the textbook "Antennas" by J. D. Kraus, McGraw-Hill Book Company, 1950.

Helix **19** radiates a circularly polarized wave within dielectric member **14**, which is composed of material having a high dielectric constant such as steatite or polystyrene, acting as a very short dielectric guide. Taper portion **24** then provides an impedance match into the system comprising conductors **11** through **13**. Thus, a voltage is caused to build up between conductors **12** and **13**, 120 degrees later between conductors **13** and **11**, and 120 degrees later between conductors **11** and **12**. The resultant of the magnetic fields of these three waves at the position of element **16** appears to be circularly polarized. A similar arrangement of taper portion **25**, dielectric guide **15**, helix **26**, and coax **27** is provided adjacent to the right-hand extremity of conductors **11** through **13**. Helices **19** and **26** have the same sense of spiral as viewed in space.

In operation wave energy is supplied from a source by way of coax **20—21** to helix **19**. With a spiral sense of helix **19**, as shown in the drawing, this wave is circularly polarized in a counterclockwise sense as viewed in the above defined positive direction of the field. For this sense of rotation little or no attenuation is introduced to the wave by the gyromagnetic effect of element **16** when biased in the sense shown and by a field of sufficient strength to produce gyromagnetic resonance in the material of element **16**. The energy is guided by conductors **11** through **13** and is returned to coax **27** for delivery to a load.

In the reverse direction of propagation wave energy applied to coax **27** is converted by helix **26** into a wave having a circularly polarized field rotating in a clockwise sense as viewed in the defined positive direction. This wave therefore experiences substantial attenuation due to the gyromagnetic effect of element **16**. 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 **16** be kept small to reduce its dielectric loss in the direction of small attenuation and that its length parallel to conductors **11** through **13** be relatively long in terms of wavelength to introduce sufficient attenuation to absorb all or part as desired of the wave traversing in the direction of high attenuation. In a fundamental application, the embodiment of the figure 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 the figure becomes a directional phase shifter with maximum phase delay being introduced to the waves propagating from left to right through shield **23** which have counterclockwise rotating magnetic wave components at the position of element **16**. A minimum phase delay will be experienced by the waves propagating from right to left which have clockwise rotating components at the position of element **16**. 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**.

While the helical excitation thus described is believed to have several advantages which recommend its use as a preferred embodiment, it should be noted that other methods of exciting the required 120 degree phase related waves upon conductors **11** through **13** may be used. For example, they may be excited by a three-phase transformer or they might be tapped from points related by a 120 degree phase shift along a delay transmission path of any known type.

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 conductors conductively isolated from and extending parallel to each other along the entire lengths between their extremities, an element of magnetically polarized gyromagnetic material being similarly displaced with respect to each of said conductors, a two-conductor transmission line forming an input for said component, and a helical conductor comprising a helically formed extension of one of said input line conductors, said helical conductor having the helical axis thereof parallel to said elongated conductors and located adjacent to an extremity of said conductors for coupling wave energy supported by said line with a wave of electromagnetic energy transmitted along the length of said conductors.

2. The component of claim 1 wherein said element is elongated, extends parallel to said elongated conductors and is centrally located with respect to said conductors.

3. The component of claim 2 including means for producing an impedance match between the propagation path comprising said conductors and said helical conductor comprising a tapered member of dielectric material.

4. The component of claim 3 wherein said helix is imbedded in said dielectric member and is coaxial with said gyromagnetic element.

5. The component of claim 1 including a helical conductor located adjacent to both extremities of said elongated conductors, a pair of coaxial transmission lines having inner conductors, said helical conductors each being extensions of the inner conductor of one of said coaxial transmission lines.

6. A nonreciprocal electromagnetic wave component comprising three elongated conductors being equally spaced transversely around the circumference of a circle and extending longitudinally parallel to each other in conductive isolation from each other along a major portion of their lengths to form a plurality of two-conductor transmission lines when successive ones of said conductors are considered in pairs, means for exciting a voltage between successive ones of said conductors with a 120 degree phase difference, and an elongated element of magnetically polarized gyromagnetic material extending parallel to said conductors, said element being similarly displaced with respect to each of said conductors.

7. The component according to claim 6 including a steady magnetic field applied to said element parallel to the direction of extension of said conductors.

8. The component according to claim 7 wherein said element is disposed at substantially the center of said circle.

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