

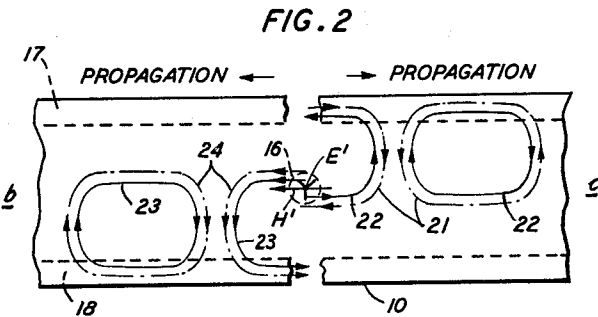
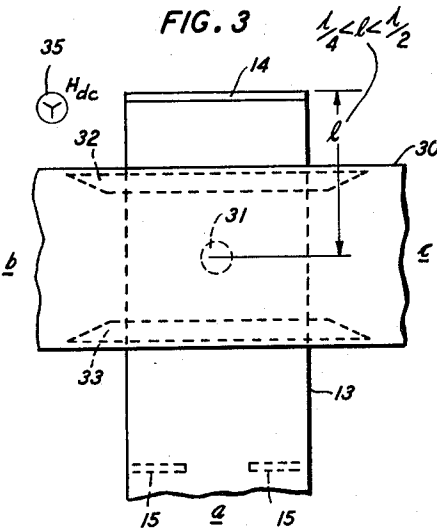
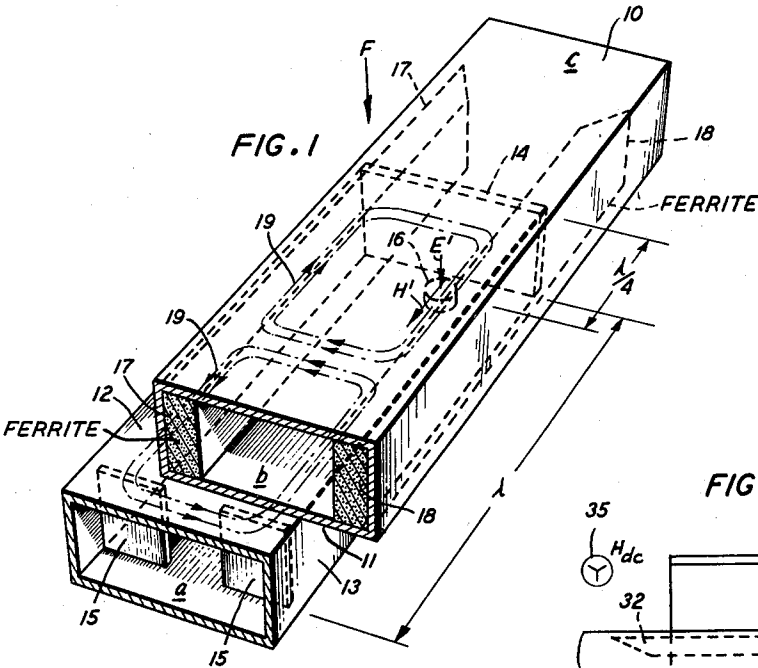
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NON-RECIPROCAL WAVE TRANSMISSION

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NON-RECIPROCAL WAVE TRANSMISSION

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4 Claims. (Cl. 333—10)

This invention relates to electrical transmission systems and, more particularly, to multibranch circuits having nonreciprocal transmission properties for use in said systems.

It is an object of the invention to establish nonreciprocal electrical connections between the branches of a three-branch network by new and simplified apparatus.

Recently, the electromagnetic transmission art has been substantially advanced by the development of a whole new group of nonreciprocal transmission components using one of the nonreciprocal properties of gyromagnetic materials such as ferrites. One of the more important of these components is a multibranch network known as a circulator circuit having the electrical property that energy is transmitted in circular fashion around the branches of the network so that energy appearing in one branch thereof is coupled to only one other branch for a given direction of transmission, but to another branch for the opposite direction of transmission. This affords a circuit component with an entirely new electrical property for which numerous applications have been proposed.

It is another object of the present invention to provide new and improved types of circulators.

It has been shown in the copending application of S. E. Miller Serial No. 371,437, filed July 31, 1953, now United States Patent No. 2,849,683, granted August 26, 1958, that the magnetic field of wave energy in a bounded transmission structure, such as a hollow conductive wave guide, is displaced transversely in the structure when a polarized element of gyromagnetic material is included within the structure. It has been recognized in accordance with the present invention that such displacement of a propagating wave produces along the center line of the guide transverse electric and longitudinal magnetic field components that have direction and phase coinciding with the direction and phase of the electric and magnetic fields, respectively, at a particular point in the field pattern of a standing wave. Since the field displacement of the propagating wave is different for opposite directions of propagation, this coincidence exists for a wave propagating in one direction only along the guide. Therefore, when a structure adapted to support a standing wave is coupled to the propagating guide with the coupling between the structures extending exclusively between the points in both structures representing this coincidence, wave energy applied to the standing wave structure is coupled and launched as a wave propagating in said one direction only in the guide, and energy applied to the guide for propagation in said one direction is coupled to said standing wave structure. However, wave energy initially excited in the propagating wave structure and traveling in a direction opposite to said one direction will not be coupled into the standing wave structure. This results in a three terminal circulator circuit.

In certain aspects the structure of the present invention may be considered as an improvement upon the structure disclosed in the above mentioned application of S. E. Miller. To this extent, a primary advantage of the

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present circulator stems from the elimination of reactive balancing elements of relatively critical adjustment employed by Miller.

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 an embodiment of the invention showing a propagating wave guide structure and a standing wave guide structure coupled by a gyromagnetic coupling element;

Fig. 2, given for explanatory purposes, shows the displaced field patterns of wave energy in the propagating wave guide structure of Fig. 1; and

Fig. 3 is a diagrammatic view of a modification of Fig. 1, showing the wave guide structure in an alternative physical orientation.

Referring more specifically to Fig. 1, a nonreciprocal three branch microwave network or three branch circulator circuit is shown as an illustrative embodiment of the present invention. This network comprises a section 10 of conductively bounded electrical transmission line for guiding a propagating wave of energy. Section 10 may be a rectangular wave guide of the metallic shield type having a wide internal cross section dimension of at least one half wavelength of the energy to be conducted thereby and a narrow dimension substantially one half of the wide dimension. A second rectangular guide 13, substantially identical to guide 10, is rendered a standing wave guide structure by terminating the back end thereof in a completely reflecting conductive piston 14 and locating a microwave iris 15 therein substantially one wavelength of the standing wave to be supported in front of piston 14.

Standing wave guide 13 and propagating wave guide 10 are electromagnetically coupled by locating the wide wall 12 of guide 13 contiguous and parallel to wide wall 11 of guide 10 and extending an aperture 16 through contiguous walls 11 and 12. This aperture is displaced to one side of the longitudinal center line of wall 12 of guide 13 by a distance to be defined more precisely hereinafter and is spaced from conductive piston 14 by substantially one quarter wavelength. Guide 10 is displaced on wall 12 so that the center line of the wall 11 of guide 10 is centered upon aperture 16. Aperture 16 has a diameter which is small compared to one wavelength, for example, in the order of three quarters of the narrow guide dimension.

Included within guide 10 is means for producing a nonreciprocal displacement of the magnetic field pattern of energy therein. In particular, guide 10 is partially filled in the region of coupling by a polarized gyromagnetic medium. As illustrated, by way of example, guide 10 includes a pair of slab-like elements 17 and 18 located adjacent to its respectively opposite internal narrow walls. The thickness of elements 17 and 18 may be on the order of at least one-tenth of the wide dimension of the guide. As a specific example of a gyromagnetic medium, elements 17 and 18 may be made of any of the several ferromagnetic materials combined in a spinel structure. For example, they may comprise iron oxide with a small quantity of one or more bivalent metals such as nickel, magnesium, zinc, manganese or other similar materials in which the other materials are combined with the iron oxide in a spinel structure. This material is known as a ferromagnetic spinel or a ferrite. As a specific example, elements 17 and 18 may be made of nickel-zinc ferrite prepared in the manner described in the publication of C. L. Hogan entitled "The Micro-

wave Gyrator" in the Bell System Technical Journal, January 1952, or in his Patent 2,748,353, granted May 29, 1956. The ends of elements 17 and 18 may be tapered in accordance with the usual practice to prevent undue reflections of wave energy therefrom.

Elements 17 and 18 are biased in the same direction by a steady magnetic field of a strength to be described, indicated schematically by the vector H_{dc} applied transversely, i.e., at right angles to the direction of propagation of wave energy in guides 10 and 13 and at right angles to wide walls 11 and 12. This field may be supplied by a solenoid structure comprising a C-shaped magnetic core having pole pieces bearing above and below guides 10 and 13 upon which turns of wire are wound and connected to a source of potential. This field may, however, be supplied by a solenoid with a metallic core of other suitable physical design, by a solenoid without a core, by a permanent magnet structure, or the ferromagnetic material of elements 17 and 18 may be permanently magnetized if desired.

The operation of the embodiment thus described may be understood by noting that when microwave energy is applied to guide 13 by way of the forward and labeled terminal *a*, a standing wave is set up between piston 14 and iris 15. This wave includes a magnetic field forming loops 19 that lie in planes parallel to the wide dimension of guide 13. Since the wave is a standing wave, the electric field has a maximum at the center of these magnetic loops. Therefore, at the location of aperture 16 there is no transverse magnetic field but rather there is a transverse electric field and a longitudinal magnetic field which may both be coupled by aperture 16 into guide 10. In guide 10 the coupled longitudinal magnetic field component may be represented by the symbol H' and the coupled electric field by the symbol E' .

The manner in which these two components may excite a propagating wave of energy in guide 10 depends upon the coincidence of phase and direction as defined by Maxwell's equations (or by the elementary "right-hand-rule") that E' and H' have with corresponding fields of the displaced wave energy that can be supported in guide 10. Referring therefore to Fig. 2, representative loops of a field pattern supportable by guide 10 in the presence of field displacing elements 17 and 18 is shown. In general, the effect of elements 17 and 18 upon this energy has been to concentrate the lines of magnetic field in a given side of guide 10 as viewed in the direction in which the wave is propagating, or from another viewpoint, to displace the field pattern of wave energy propagating along guide 10 oppositely in space for opposite directions of transmission. The reason for this is that a wave in a gyromagnetic medium which has a radio frequency magnetic field at right angles to the biasing magnetic field which rotates counterclockwise when viewed in the positive direction of the biasing field, has a permeability which increases as the intensity of the biasing field is increased. Conversely, a similar wave which has a clockwise rotating magnetic field is presented with a permeability which decreases as the intensity of the biasing field increases.

One physical explanation which has been advanced to explain this phenomenon involves the recognition that the gyromagnetic materials contain unpaired electron spins which tend to line up with the applied magnetic field. From this recognition stems the suitability of the term "gyromagnetic medium" to designate media having unpaired electron spins. These spins and their associated moments can be made to precess about the line of the biasing magnetic field, keeping an essentially constant component of the moment in the direction of the applied biasing field but providing a magnetic moment which may rotate in a plane normal to the field direction. These magnetic moments have a tendency to precess in one angular sense but to resist rotation in the opposite sense.

When the high frequency magnetic intensity of the wave energy is rotating in the same sense as the preferred direction for precession of the magnetic moment, the wave will encounter a permeability less than unity.

When the high frequency magnetic intensity is rotating in the opposite angular direction, however, the wave will encounter a permeability greater than unity. This results in a difference in permeability experienced for oppositely polarized components and is observed for low values of the polarizing magnetic field below that field intensity which produces ferromagnetic resonance in the material.

Thus, for a wave propagating to the right, a high permeability is presented on the left hand side of the wave as viewed in the direction of propagation and a low permeability to wave components on the right. This difference concentrates the lines of magnetic field in the upper side of the guide as shown in the drawing by loops 21 or 22. Thus along the center line of the guide, which normally has a zero longitudinal field intensity, a substantial component of longitudinal field is present representing the portion of the wave field pattern on the lower side of the guide. The converse is true for the wave represented by loops 23 or 24 propagating to the left.

Assuming that the wave is excited exclusively by a magnetic dipole having a direction represented by the vector H' , then the phase of the excited field propagating away from the dipole in either direction is such that the portion of the pattern at dipole H' , i.e., the lower portion of the wave propagating to the right and the upper portion of the wave propagating to the left, has the same direction as the exciting H' . This phase is shown by the phase indicating arrows on the dotted loops 21 and 24. On the other hand, if it is assumed that the excited wave is solely the result of an electric dipole represented by E' with a positive sense directed into the plane of the paper, then the phase of the waves propagating in each direction are represented by the phase indicating arrows on solid loops 22 and 23. When both dipoles exist simultaneously, the electrically excited wave is in a phase to cancel with the magnetically excited wave for propagation to the right but in a phase to combine with the magnetically excited wave for propagation to the left. A phase delay of 90 degrees which is inherent in any coupling through an aperture has been disregarded inasmuch as it would affect all components alike. Since the amplitude of the electrically excited wave in guide 10 depends upon the transverse position of aperture 16 on wall 12 and the amplitude of the magnetically excited wave depends primarily upon the strength of the magnetizing field, the strength of this field is selected with respect to the location of aperture 16 so that the component waves induced by E' and H' are equal.

Thus, microwave energy applied to guide 13 by way of terminal *a* will appear at the left end of guide 10 labeled terminal *b*. If, on the other hand, energy is applied to terminal *b*, it will at some instant of time have a displaced field pattern which may also be represented by loops 22 since it is a wave propagating to the right. An electric field will be coupled into guide 13 through aperture 16 with the same relative phase as E' since the field displacement does not change the sense of the electric field. The displaced longitudinal magnetic field component that appears at aperture 16, however, has a sense that is opposite to H' , and the component wave which this magnetic field is capable of exciting in guide 13 will cancel with that component wave which tends to be excited by the coupled electric field. In other words, the displaced wave propagating to the right in guide 10 has electric and magnetic field components at the position of aperture 16 in guide 10 that are incapable of combining at the position of aperture 16 in guide 13 to form a standing wave in guide 13. Thus, no energy will be coupled into guide 13 and all energy applied to terminal *b* of guide 10 will appear at the right hand

end thereof labeled terminal *c*. Energy, however, applied to terminal *c* for propagation to the left may be represented by loops 23. These loops represent energy having electric and magnetic field components consistent with E' and H' and may be coupled by aperture 16 to combine as a standing wave in guide 13. As may be shown by an analysis of thermal equilibrium in the structure, this coupled component will automatically comprise the entire energy in guide 10 when the dimension of iris 15 is adjusted for complete power transfer from terminal *a* to terminal *b*. The coupling characteristic typical of a circulator circuit is thereby obtained.

An alternative of the embodiment of the circulator of Fig. 1 is represented by Fig. 3 in which guide 10 of Fig. 1 is replaced by guide 30 oriented with its longitudinal axis perpendicular to the longitudinal axis of guide 13. Coupling aperture 31, in all other respects identical to aperture 16 of Fig. 1, is disposed on the center line of guide 13 at a point removed from piston 14 by more than one-quarter wave length but slightly less than one-half wave length. The center line of the wide dimension of guide 30 is centered upon aperture 31. Field displacing gyromagnetic elements 32 and 33, biased by polarizing magnetic field represented by the symbol F , and in all respects identical to elements 17 and 18 of Fig. 1, are located in guide 30.

While in Fig. 1 guide 10 was in part excited by a magnetic field component coupled to it through aperture 16 from a longitudinal magnetic field component in guide 13, the present embodiment depends for its operation upon coupling a transverse magnetic field component from guide 13 to the displaced longitudinal field in guide 30. In other respects, the operation of the circulator of Fig. 3 is substantially identical to that described for Fig. 1. To indicate this, the left and right ends of guide 30 are labeled *b* and *c*, respectively, and the open end of guide 13 is labeled *a*. Circulator action takes place between the terminals in the order *a*, *b* and *c* for an external polarizing field direction into the paper as represented by the symbol F .

In all cases it is understood that the above-described arrangements are simply 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 first conductively bounded structure adapted for supporting an electromagnetic wave propagating in respectively opposite longitudinal directions therein, a second conductively bounded structure adapted for supporting a standing electromagnetic wave therein, a common wall between said structures having an aperture positioned therein at a point of electric field intensity in both said structures for exciting an electric field in said first structure from the electric field in said second structure to produce a first wave in said first

structure capable of propagating in said opposite directions, said aperture being at a point of magnetic field intensity of one sense in said second structure and normally zero field intensity parallel to said one sense in said first structure, and means comprising magnetically polarized gyromagnetic material for displacing said normal magnetic field in said first structure to couple the magnetic field in said first structure with the magnetic field in said second structure to produce a second wave in said first structure that is equal in amplitude and opposite in phase to said first wave for one of said directions of propagation.

2. In combination, a pair of conductively bounded wave guide structures of rectangular transverse cross section for electromagnetic wave energy, said guides being disposed with their broad walls in contiguous relationship, at least one element of magnetically polarizable gyromagnetic material extending longitudinally within one of said guides, means for applying a magnetic field to said element, a short circuit terminating the other of said guides and a microwave iris spaced from said short circuit in said other guide, and means for coupling said guides comprising an aperture extending through said contiguous walls at a point in said other guide at which the electromagnetic wave energy therein has an electric field intensity and a longitudinal magnetic field of predominately one polarization and at a point on the longitudinal center line of said one guide.

3. The combination according to claim 2 wherein the longitudinal axes of said guides are parallel and wherein said aperture is located upon the longitudinal center line in said one guide and is displaced from the longitudinal center line in said other guide substantially one-quarter wavelength from said short circuit.

4. The combination according to claim 2 wherein the longitudinal axes of said guides are perpendicular and wherein said aperture is located upon the intersection of the longitudinal axes of both said guides.

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