

July 18, 1961

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2,993,180

NON-RECIPROCAL WAVE TRANSMISSION

Filed Dec. 31, 1953

2 Sheets-Sheet 1

FIG. 1

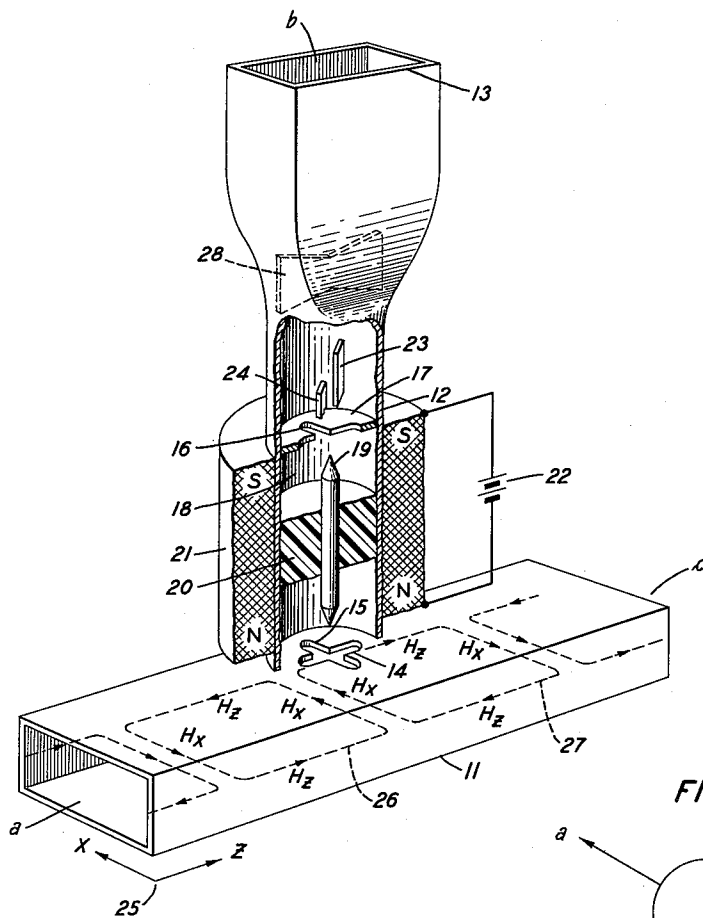


FIG. 3

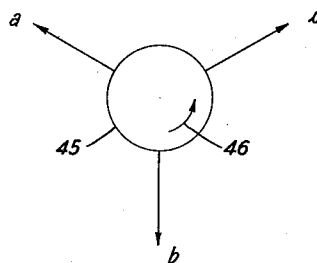
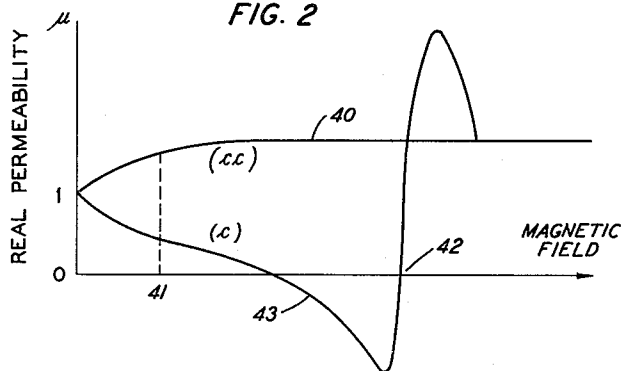


FIG. 2



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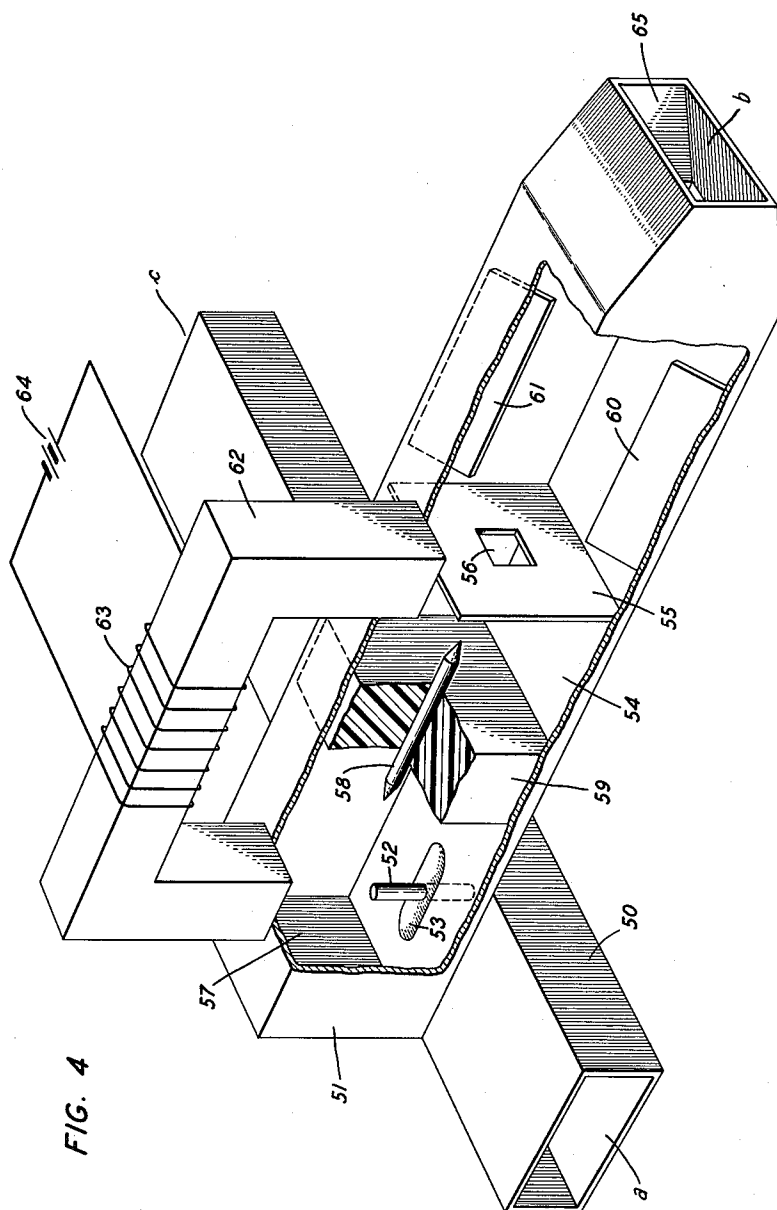


FIG. 4

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NON-RECIPROCAL WAVE TRANSMISSION

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9 Claims. (Cl. 333—9)

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

It is an object of the invention to establish non-reciprocal electrical connections between a plurality of branches of a multibranch network by new and simplified apparatus.

Recently, the electromagnetic wave transmission art has been substantially advanced by the development of a whole new group of non-reciprocal transmission components. A large number of these have utilized one of the non-reciprocal properties of gyromagnetic materials, most often designated ferromagnetic materials or ferrites. One of the more important of these components is a multibranch network known as a "circulator" circuit. While the several circulators heretofore invented have had different physical appearances and structural arrangements, each having its own specific advantage and usefulness, each has had 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.

Numerous applications of the circulator as a circuit element have been devised. It has been included in modulator circuits and in compressing and expanding circuits. It has been used as a TR-box type coupling between an antenna, transmitter and receiver circuits, as a channel dropping or branching circuit in multichannel microwave systems, and in many other applications.

It is another object of the present invention to provide a new type of circulator having an increased stability and a high reverse transmission loss.

It has been previously demonstrated that an element of gyromagnetic material polarized by a magnetic field will exhibit a different permeability to oppositely rotating circularly polarized waves propagated parallel to the direction of the applied field. In accordance with the present invention, a first wave-guide structure is coupled to a second wave-guide structure through a chamber which is excited with a counterclockwise rotating circularly polarized wave by wave energy propagating in one direction within the first structure and with a clockwise rotating circularly polarized wave by wave energy propagated in the opposite direction within the first structure. The gyromagnetic element is included within the chamber so that it is resonant for said counterclockwise rotating wave and far from resonance for said clockwise rotating wave. Thus, only wave energy traveling in said one direction in the first structure is coupled into said second structure. Simultaneously, energy in said second structure is coupled into the first structure by the chamber and launched in the first structure only for said opposite direction of propagation. This results in a three-terminal circulator circuit.

While the present invention provides an entirely new circulator configuration which is difficult to compare in all respects with the prior art devices, certain primary advantages of it may be pointed out. First, operation of the present invention is relatively non-critical to the exact strength of the magnetic field and to the condition of the ferromagnetic element. This then provides a stability and

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ease of adjustment not found in the prior circulators which depend upon rather precise effects of the ferromagnetic material which, in turn, depend jointly upon the physical size of the element and the value of the magnetizing field. Further, the discrimination obtained in the present invention between the energy coupled and the energy blocked in any given passage through the circuit is broad. This not only provides a high reverse transmission loss for a given passage through the circuit, but also provides a large latitude of control over the effects of frequency and temperature variation in the device and its associated circuit.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a perspective view of an embodiment of the present invention showing a junction of wave-guide structures coupled by a chamber containing a ferromagnetic element;

FIG. 2, given by way of illustration, is the characteristic of the real permeability of a ferromagnetic element versus the applied magnetic field for oppositely rotating circularly polarized waves;

FIG. 3 is a schematic representation of the circulator coupling characteristic for the embodiment of FIG. 1; and

FIG. 4 is a perspective view of a modification of FIG. 1 showing a junction of wave-guide structures in an alternative physical orientation.

Referring more specifically to FIG. 1, a non-reciprocal three branch microwave network or three branch circulator circuit is shown as an illustrative embodiment of the present invention. This network comprises a first section 11 of a conductively bounded electrical transmission line for guiding wave energy which may be a rectangular wave guide having a wide internal cross-sectional 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. Located perpendicular to guide 11 is a second section 12 of wave guide of a type capable of supporting circularly polarized waves, i.e., plane waves for which the electric polarization rotates in space as the wave propagates. As illustrated, section 12 may be a wave guide of circular cross section having a diameter slightly less than the wide dimension of guide 11, but it may be a guide of square cross section. Guide 12 abuts guide 11 with its transverse end connected as will be described hereinafter to a wide wall of guide 11.

The other end of guide 12 tapers smoothly and gradually into a guide of rectangular cross section 13 which will accept and support only linearly polarized waves having the electric vector parallel to the short side of the rectangular wave guide 13. Suitable means for producing a conversion between the circularly polarized waves in guide 12 and the linearly polarized waves in guide 13 is located in the end of guide 12 adjacent guide 13. As illustrated, this means may be a 90 degree differential phase shift section of any of the types disclosed, for example, in "Principles and Applications of Wave Guide Transmission," by G. C. Southworth, 1950, pages 327 through 331. By way of specific illustration, the phase shift section shown in FIG. 1 comprises two oppositely positioned metal fins 23 and 24, each extending perhaps one fourth of the way across guide 12 and lying in a plane which is inclined at 45 degrees to the polarization of wave energy in guide 13. Fins 23 and 24 produce a kind of capacitive loading and, accordingly, reduce the velocity of propagation of wave energy polarized parallel to the plane of the fins. As is well known, when the lengths of fins 23 and 24 are such that a 90 degree phase shift is introduced to this wave energy relative to the wave energy polarized perpendicular to the plane of the fins,

a circularly polarized wave in guide 12 is converted to and from a linearly polarized wave having a polarization which will be accepted and supported by guide 13. Also illustrated is means for dissipating spurious mode energy that may result from degeneration of some wave energy during the above described conversion. This means is illustrated as a vane 28 of resistive material extending perpendicular to the polarization in guide 13 and located adjacent to the tapered portion between guides 12 and 13.

The heart of the present invention consists of a gyro-magnetically tuned resonator comprising a conductive cavity that is resonant to circularly polarized waves rotating in one sense and far from resonance for waves rotating in the other sense. Thus a cavity 18 is formed in the lower portion of guide 12 between the top wall of guide 11 and a reactive iris 17. Iris 17 is spaced above guide 11 at a distance of a multiple of one half of the guide wavelength of the waves rotating in said one sense under the conditions to be defined in detail hereinafter. An aperture 14-15, the nature of which will be considered hereinafter, couples wave energy in guide 11 to and from cavity 18 while an aperture 16 in iris 17 couples wave energy between cavity 18 and the upper portion of guide 12.

Cavity 18 is tuned by a slender cylindrical element 19 of gyromagnetic material which is supported axially in cavity 18 by a support 20. Support 20 may be made in any desirable shape of a material of low dielectric constant, such as polyfoam. As a specific example of a gyromagnetic material, element 19 may be made of any of the several ferromagnetic materials combined in a spinel structure. For example, element 19 may comprise an iron oxide with a small quantity of one or more bivalent metals such as nickel, magnesium, zinc, manganese or other similar material, in which the other materials combined with the iron oxide in a spinel structure. This material is known as a ferromagnetic spinel or a ferrite. Frequently, these materials are first powdered and then molded with a small percentage of plastic material, such as Teflon or polystyrene. As a specific example, element 19 may be made of nickel-zinc ferrite prepared in the manner described in the publication of C. L. Hogan, "The Microwave Gyrotator," in the Bell System Technical Journal, January 1952, and in his copending application Serial No. 252,432, filed October 22, 1951, now Patent No. 2,748,353.

Element 19 is biased by a steady polarizing magnetic field of a strength to be described. As illustrated in FIG. 1, this field is applied parallel to the direction of propagation of the waves in guide 12 and may be supplied by a solenoid 21 mounted upon the outside of guide 12 and supplied by a source 22 of energizing current. To facilitate the explanation that follows, specific polarities are assigned to this field as indicated on the drawing with the north pole thereof adjacent aperture 14-15. Therefore, all reference to "clockwise" and "counterclockwise" hereinafter is taken as viewed in the positive direction of this field, i.e., as looking down upon aperture 14-15. It should be noted, however, that element 19 may be magnetized in the opposite polarity and by a solenoid of other suitable physical design, by a permanent magnetic structure, or the ferromagnetic material of element 19 may be permanently magnetized if desired.

The effect of element 19 upon circularly polarized waves in cavity portion 18 of guide 12 may now be considered. This consideration may most readily be made in connection with the explanatory diagram of FIG. 2 which shows the now familiar characteristic of the variation of the real permeability of a ferromagnetic element as the applied magnetic field is changed. This characteristic is disclosed and various other aspects of it discussed in connection with FIG. 2 of the copending application of S. E. Miller, Serial No. 362,193, filed June 17, 1953, now Patent No. 2,951,220, or FIG. 1 of "The Ferromagnetic Faraday Effect at Microwave Frequencies and Its Appli-

cations," by C. L. Hogan, published in the Reviews of Modern Physics, January 1953.

It will be seen from curve 40 of FIG. 2 that the permeability for a circularly polarized wave rotating counterclockwise as viewed in the positive direction of the applied magnetic field increases from unity as the magnetic field is increased to the saturation point 41, and then levels off to a substantially constant value. A clockwise rotating wave as represented by curve 43, however, decreases from unity, through zero and further decreases to a negative value. At the magnetic field strength 42 producing ferro-magnetic resonance in the material the permeability suddenly changes to a positive value. Cavity 18 may therefore be made resonant for circularly polarized waves of one rotation and at the same time be far from resonance for waves of the opposite rotation. It is noted that curve 40 for the counterclockwise rotating wave is substantially flat above saturation point 41. Therefore if the strength of the magnetic field produced by solenoid 21 is adjusted between saturation and resonance, and the spacing between iris 17 and guide 11 is selected to equal a multiple of one-half wavelengths of the counterclockwise rotating wave, chamber 18 will be resonant for this wave over a reasonably broad variation of the magnetic field strength. Furthermore, since the difference between the permeability for the clockwise wave and the counterclockwise wave is substantial over this range, the cavity may be very broadly or narrowly tuned, allowing a latitude of control over the band of operation without being near resonance for the clockwise rotating wave.

Having thus examined the properties of cavity 18 for counterclockwise and clockwise rotating circularly polarized waves, the manner in which these waves are excited in cavity 18 may now be examined. For this purpose it will be convenient to locate guides 11 and 12 in a coordinate system as represented by the divergent vectors 25 labeled x and z . The vector x indicates a positive sense along the transverse wide dimension of guide 40 11 and z indicates a positive sense along the longitudinal direction of propagation in guide 11. Therefore the predominantly transverse magnetic field components of a dominant mode wave in guide 11 at a particular instant of time are shown in Fig. 1 and labeled H_x , while the predominant longitudinal components are labeled H_z . These components form loops which lie in planes parallel to the wide dimension of guide 11. The arrows on the individual loops 26 and 27 indicate their polarity at a given instant of time and their sense is arbitrarily defined by the coordinates 25.

Aperture 14-15 is located in the top wall of guide 11 at a point off the center line thereof which places the aperture at a point having both H_x and H_z components. Slot 14 of aperture 14-15 is parallel to and therefore effective for coupling the H_z components into cavity 18 of guide 12, while slot 15 thereof is parallel to and therefore effective for coupling the H_x components. The amplitudes of these two components in guide 12 should be equal and this is obtained if slots 14 and 15 are of identical sizes and their intersection is located at the point in the top wall of guide 11 at which the H_z and H_x components are of equal amplitude. The point may be moved toward the center of the wall (stopping short of the precise center) if the size of slot 14 is correspondingly increased and slot 15 decreased. If the aperture is located at the exact point of equal H_z and H_x components in guide 11, the aperture may be simply one of circular or square shape. The abutting end of guide 12 may be centered above aperture 14-15. The shape of aperture 16 in iris 17 may be identical to aperture 14-15 if desired and if it comprises a crossed slot as shown, the slots may be aligned respectively with slots 14 and 15.

The relative phases of the components coupled from guide 11 into cavity 18 depend upon the direction of

propagation of the wave energy in guide 11. When the wave in guide 11 is propagating in the positive direction the component H_z of loop 26 is increasing to its maximum negative value while the component H_x is decreasing from its maximum positive value. In other words, the component H_z is in a phase 90 degrees ahead in time from the component H_x and this produces in cavity 18 a counterclockwise rotating circularly polarized wave. Now, when the wave in guide 11 is propagating in the negative direction the component H_z of loop 27 is increasing to its maximum positive value while the component H_x is decreasing from its maximum positive value. H_z is therefore 90 degrees behind in time from the component H_x and this produces in cavity 18 a clockwise rotating circularly polarized wave.

It is realized, of course, that the specific reference to "positive" and "negative" values and to "ahead" and "behind" in time are completely arbitrary and apply only to the illustrative senses shown on FIG. 1. Also, a phase delay of 90 degrees which is inherent in any coupling through an aperture has been disregarded inasmuch as it affects all components alike. This explanation does, however, serve to demonstrate that for one direction of propagation past the aperture 14—15, the wave induced in cavity 18 will rotate in one sense, while for the opposite direction of propagation the induced wave will rotate in the opposite sense.

It has been necessary to describe the invention in terms of its several components and to examine separately the function of each. It is now possible to describe the over-all mode of operation of the invention by following the path of microwave wave energy applied respectively at each of the output terminals a , b and c and to represent the coupling characteristic thus obtained schematically on FIG. 3. Thus wave energy applied to the right-hand end of guide 11 by way of terminal c will tend to produce a clockwise rotating wave which would not be resonant in chamber 18. Therefore no energy will be coupled into chamber 18 and all energy applied at terminal c will appear at the left-hand terminal a of guide 11. This condition is indicated schematically on FIG. 3 by the arrows labeled c and a , respectively, associated with a ring 45 and arrow 46 diagrammatically indicating progression in the sense from c to a .

A wave applied to terminal a of guide 11 will produce a counterclockwise rotating wave which is resonant in chamber 18 and will pass on through aperture 16. The energy passing through aperture 16 is converted back into a linearly polarized wave by fins 23 and 24 to appear at terminal b of guide 13.

A wave applied at terminal b will be converted into a counterclockwise rotating wave by fins 23 and 24, pass through aperture 16, will be resonant in cavity 18, and will be coupled through aperture 14—15 into guide 11 as a z -direction component followed 90 degrees later in time by an x -direction component. As noted above, it is the wave transmitted in the positive z -direction in guide 11 that has this phase relationship. Conversely, this phase relationship between the exciting components will produce a wave propagated only in the positive direction in guide 11 toward terminal c . The necessary amplitude relationships between the exciting x and z components for excitation of such a wave at the position of aperture 14—15 is inherently obtained by the location of the aperture and the relative dimensions of slots 14 and 15 as defined above. Thus a portion of the wave in cavity 18 which is coupled into guide 11 will appear at terminal c only. The magnitude of this coupled energy is determined by the sizes and impedances of aperture 14—15 and aperture 16, and energy, if any, that is not coupled into guide 11 will be reflected back to terminal b .

However, it is easily possible to match the impedance of terminal b for a wave applied thereto to that of terminal c through the coupling of aperture 16, cavity 18 and aperture 14—15. Therefore, the sizes of aperture 16 and

aperture 14—15 are selected by applying a signal at terminal b and enlarging the apertures until no wave energy is reflected back at terminal b . This adjustment is readily made with the aid of a conventional standing wave detector. Because of thermal equilibrium requirements in the structure, this adjustment simultaneously serves the function of matching terminal a to terminal b so that a wave applied at terminal a appears in its entirety at terminal b . The resulting terminal connections are indicated schematically on FIG. 3 which shows that all energy applied to terminal a will be coupled to terminal b and all energy applied to terminal b will be coupled to terminal c . The coupling characteristic thus represented is a characteristic of a group of networks heretofore designated circulator circuits because they have electrical properties such that energy appearing in one branch thereof is coupled only to one other branch for a given direction of transmission but to another branch for opposite transmission.

In FIG. 4 a second embodiment of the invention is shown in which physically modified components perform respectively similar functions to the corresponding components of the embodiment of FIG. 1. Thus, linearly polarized waves in guide 50 of rectangular cross section are coupled as circularly polarized waves into a guide 51 of square cross section. The coupling means comprises a probe 52 supported perpendicular to the plane of the wide wall of guide 50 in a dielectrically filled elongated aperture 53 in said wide wall. Probe 52 couples from the electric field in guide 50 to the field of a vertically polarized wave in guide 51. Aperture 53 is elongated transversely as viewed with respect to guide 50 and longitudinally with respect to guide 51 so that it couples transverse magnetic field components in guide 50 to the longitudinal magnetic field components of a horizontally polarized wave in guide 51. Since the horizontally and vertically polarized waves are 90 degrees out of phase in guide 51, a circularly polarized wave is produced. Since the sense of this phase difference depends upon the direction of propagation in guide 50, the circularly polarized wave in guide 51 is rotating clockwise or counterclockwise depending upon the direction of propagation of wave energy in guide 50.

A cavity 54 is formed between the closed end 57 of guide 51 and a conductive iris 55 shown as having a square aperture 56. An element 58 of gyromagnetic material is axially held in cavity 51 by support 59. Element 58 is magnetized by a field supplied by a C-shaped core 62 wound with turns 63 which are energized from source 64. Core 62 has pole pieces which bear against displaced locations on the wall of guide 51 so that the lines of magnetic flux pass through element 58 substantially parallel to the direction of propagation of the wave energy in guide 51.

The strength and polarity of the field produced by solenoid 62—63 are chosen so that cavity 54 is resonant for the circularly polarized wave induced therein by a wave propagated from terminal a to terminal c in guide 50. This energy passes from cavity 54 through iris 56 where it is reconverted into a linearly polarized wave by 90 degree phase shifting vanes 60 and 61 which are located in a plane inclined at 45 degrees to the polarity of the wave accepted by rectangular wave guide 65. Thus, a connection from terminal a to terminal b as shown on FIG. 3 is established. Likewise, a connection from terminal b to terminal c and from terminal c to terminal a is established in a fashion substantially similar to the connections between corresponding terminals of FIG. 1.

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 an electromagnetic wave transmission system, a resonator comprising a cavity for said wave energy, said cavity having a longitudinal axis, an element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of wave energy resonant in said cavity axially located in said cavity, means located at one end of said cavity for coupling circularly polarized wave energy into said cavity, means located at the opposite end of said cavity for coupling circularly polarized wave energy out of said cavity, said cavity being resonant when said waves are rotating in one sense as viewed relative to said polarized element and non-resonant when said waves are rotating in a sense opposite said one sense.

2. A non-reciprocal multibranch network for electromagnetic wave energy comprising first and second wave transmission structures interconnected through a resonant cavity, means responsive to wave energy propagating in said first structure for exciting said cavity with waves having a field pattern rotating in space in a first sense as said waves propagate when said wave energy in said first structure is propagating in a first direction and for exciting said cavity with waves having a field pattern rotating in space in a second sense as said waves propagate when said wave energy in said first structure is propagating in a second direction, and means included within said cavity having a real permeability of one value for said waves rotating in said first sense and a different value for said waves rotating in said second sense.

3. The combination according to claim 2 wherein said last named means is a magnetically polarized element of gyromagnetic material.

4. The combination according to claim 2, wherein said first structure is a wave guide of rectangular cross section having a narrow and a wide conductive wall, and wherein said exciting means comprises an aperture located in said wide wall and disposed to one side of the longitudinal center line of said wall.

5. The combination according to claim 2, wherein said first structure is a wave guide of rectangular cross section having a narrow and a wide conductive wall, and wherein said exciting means comprises a transversely extending aperture in said wide wall and a conductive probe supported in said aperture perpendicular to the plane of said wall.

6. The combination according to claim 2, wherein said second structure is a wave guide of rectangular cross section, and including means for converting and passing said wave energy of rotating field pattern in said cavity to and from a linearly polarized wave in said rectangular guide.

7. The combination according to claim 6, wherein said last named means for converting and passing polarized waves comprises an aperture in a conductive wall of said cavity and a 90 degree differential phase shift element having the planes of phase shift thereof inclined at 45

degrees to the plane of polarization of said linearly polarized wave.

8. A non-reciprocal multibranch network for electromagnetic wave energy comprising main and auxiliary sections of shielded transmission line for guiding said energy, means for coupling an end of said auxiliary line to a center portion of said main line, said means including means for exciting circularly polarized wave energy in said auxiliary line, a reactive iris located in said auxiliary line, an element of ferromagnetic material included in said auxiliary line between said end and said iris, means for magnetizing said element to the point at which said auxiliary line between said end and said iris becomes resonant for said circularly polarized wave, and means located in said auxiliary line on the other side of said iris from said element for coupling said circularly polarized wave to a linearly polarized wave.

9. In an electromagnetic wave transmission system, a resonator comprising a cavity for said wave energy, said cavity having a longitudinal axis, an element of magnetically polarized material exhibiting the gyromagnetic effect at the frequency of wave energy resonant in said cavity axially located in said cavity, means located at one end of said cavity for converting linearly polarized wave energy exclusively into circularly polarized wave energy rotating in a given single sense relative to a single direction of propagation of said linearly polarized energy and for exciting said cavity with said circularly polarized wave energy of said single sense, means located at the opposite end of said cavity for passing said circularly polarized wave energy out of said cavity, said cavity being resonant for said waves rotating in said given sense as viewed relative to said magnetically polarized element and non-resonant for waves rotating in a sense opposite to said given sense.

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