

Sept. 27, 1960

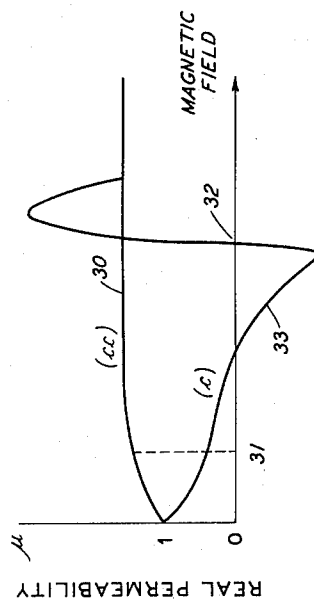
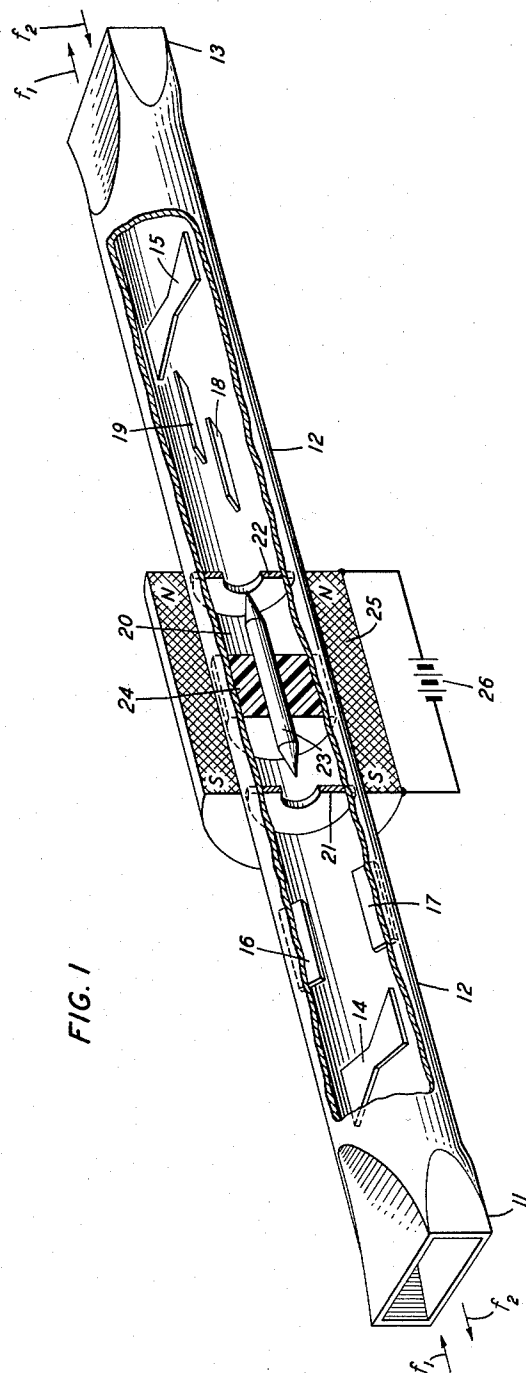
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2,954,535

NON-RECIPROCAL WAVE TRANSMISSION

Filed March 9, 1954

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

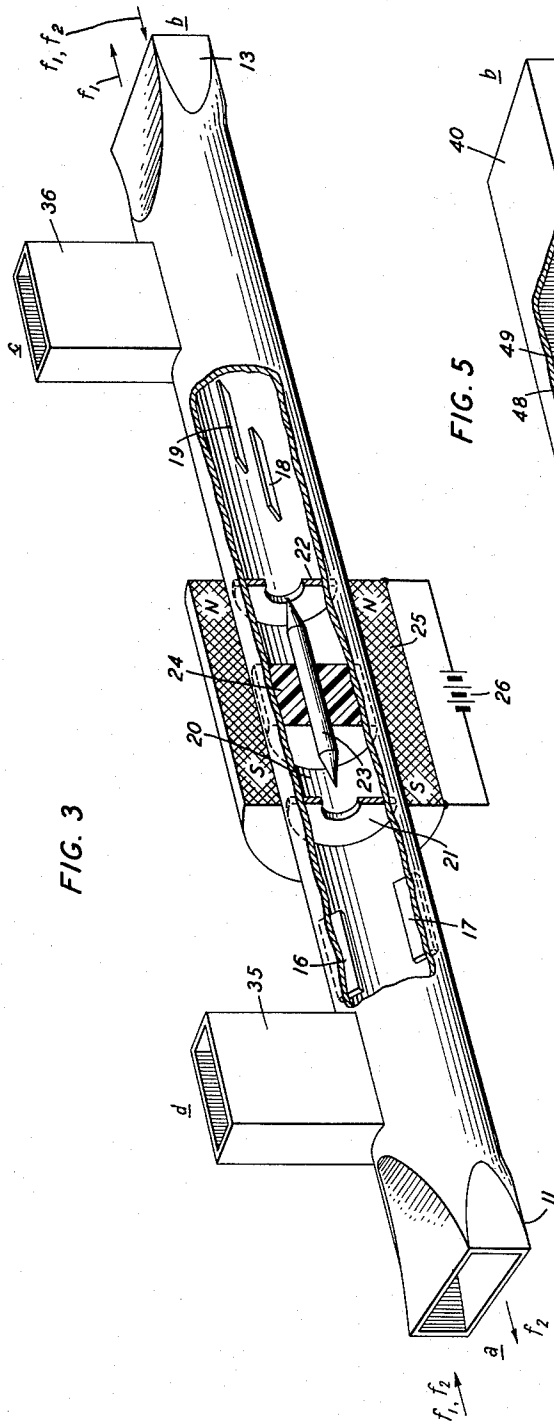


FIG. 3

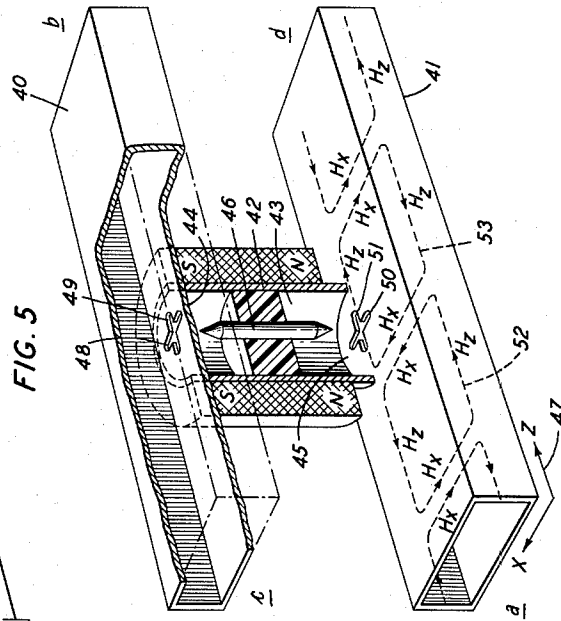


FIG. 5

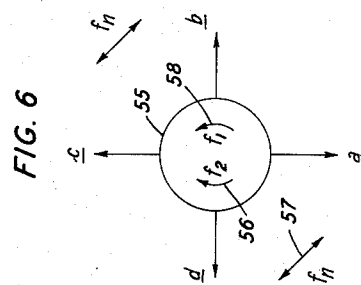


FIG. 6

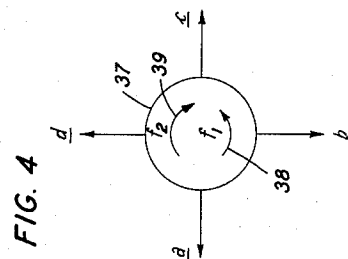


FIG. 4

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NON-RECIPROCAL WAVE TRANSMISSION

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1 Claim. (Cl. 333—73)

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

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 known as an isolator in that it has the property of transmitting wave energy freely in one direction between its terminals while resisting transmission in the opposite direction. It is thus advantageously used between any energy source and its load to prevent reflections from the load from returning to the source. Another of these components is a multibranch network known as a circulator circuit that has 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 circuit property has found use in numerous applications.

It is an object of the present invention to establish frequency selective, non-reciprocal connections between a plurality of branches of a multibranch network.

It is a further object to provide new types of isolator and circulator circuits.

It is a more specific object to establish a connection between the branches of a multibranch circuit for one direction of transmission at one frequency or band of frequencies and for the opposite direction at another frequency or band of frequencies.

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, first and second wave transmission structures are coupled through a resonant cavity tuned by such a gyromagnetic element. The transmission structures are coupled to the cavity in a special way so that wave energy propagated in a given direction in either structure will induce circularly polarized waves rotating in respectively opposite senses in the cavity. The strength of the polarizing field is adjusted so that the cavity is resonant at selected different frequencies for these oppositely rotating waves. Thus the coupling between the first structure and the second structure through the cavity is both selective as to the direction in which wave energy is propagating in each structure and also to its frequency.

In the first illustrative embodiment of the invention to be described in detail hereinafter, the cavity is resonant at a first frequency only for wave energy propagating toward it from the first structure and is resonant at a second frequency only for wave energy propagating to-

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ward it from the second structure. Thus only wave energy at the first frequency is coupled from the first structure into the second, whereas only wave energy at the second frequency is coupled from the second into the first. This results in a frequency selective isolator circuit. Energy traveling in the wrong direction and at the wrong frequency for coupling is reflected into particularly positioned dissipative means.

In a second illustrative embodiment of the invention, energy dissipated in the first embodiment is coupled into a pair of polarization selective connections, located one on either side of the cavity. This results in a four branch, frequency selective circulator in which a non-reciprocal connection is established in a given sequence between the four branches at a first frequency and in a reverse sequence at a second frequency.

In another illustrative embodiment of the invention a pair of rectangular wave guides are coupled to the cavity by means which induce circularly polarized waves in the cavity that rotate in senses determined by the direction of propagation of the energy in the guides. Thus, four branch, frequency selective circulator action is obtained in a structure of exceedingly simple construction.

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 the present invention showing the first and second wave guide structures interconnected 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 perspective view of the second embodiment of the invention showing two pairs of orthogonal polarization selective connections interconnected through the ferromagnetically tuned cavity;

Fig. 4 is a schematic representation of the circulator coupling characteristic for the embodiment of Fig. 3;

Fig. 5 is a perspective view of the third embodiment of the invention showing a pair of rectangular wave guides interconnected through a ferromagnetically tuned cavity; and

Fig. 6 is a schematic representation of the circulator characteristic for the embodiment of Fig. 5.

Referring more specifically to Fig. 1, a nonreciprocal two branch isolator circuit is shown as an illustrative embodiment of the present invention. This circuit comprises a first section 11 of 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. Guide 11 tapers smoothly and gradually into 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. The other end of guide 12 tapers into a third section 13 of rectangular wave guide identical to section 11.

In either end of guide 12 adjacent to guides 11 and 13, respectively, are means for dissipating wave energy polarized in planes perpendicular to the polarization supported by guides 11 and 13. As illustrated, these means comprise a pair of vanes 14 and 15 of resistive material

several wavelengths long, diametrically disposed in guide 12 in the plane of the wave energy to be dissipated. In accordance with the usual practice, the ends of vanes 14 and 15 may be tapered to prevent undue reflection from the edges thereof.

Suitable means for producing a conversion between the linearly polarized waves supported by guide 11 and the circularly polarized waves supported in guide 12 is located in the end of guide 12 adjacent vane 14. 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 16 and 17, each extending perhaps one fourth of the way across guide 12 and lying in a plane which is inclined at 45 degrees counterclockwise from the polarization of wave energy in guide 11, as viewed from guide 11. As is well known, if the lengths of fins 16 and 17 are such that a 90 degree phase shift is introduced to wave energy polarized parallel to the plane of the fins relative to the wave energy polarized perpendicular to the plane of the fins, the linearly polarized wave from guide 11 is converted to and from a counterclockwise rotating circularly polarized wave in guide 12. A similar pair of fins 18 and 19 is located in the end of guide 12 adjacent vane 15. Fins 18 and 19 lie in a plane which is inclined 45 degrees clockwise from the polarization in guide 11, placing them at right angles to the plane of fins 16 and 17.

The heart of the present invention consists of a gyromagnetically tuned resonator comprising a conductive cavity that is resonant at one frequency to circularly polarized waves rotating in one sense and resonant at another frequency to waves rotating in the other sense. Thus a cavity 20 is formed in the central portion of guide 12 between reactive iris 21 and reactive iris 22. Iris 21 is spaced from iris 22 at a multiple of one half of the guide wavelength of the rotating waves in cavity 20 under the conditions to be defined in detail hereinafter.

Cavity 20 is tuned by a slender cylindrical element 23 of gyromagnetic material which is supported axially in cavity 20 by a support 24. Support 24 may be made in any desirable shape of a material of low dielectric constant such as polyfoam. The term "gyromagnetic material" is employed here in its accepted sense as designating the class of materials having portions of the atom thereof that are capable of being aligned by an external magnetic field and capable of exhibiting a significant precessional motion at a frequency within the microwave range contemplated by the invention, this precessional motion having an angular momentum, a gyroscopic moment and a magnetic moment. As a specific example of a gyromagnetic material, element 23 may be made of any of the several ferromagnetic materials combined in a spinel structure. For example, element 23 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 23 may be made of nickel-zinc ferrite prepared in the manner described in the publication of C. L. Hogan, "The Microwave Gyrator," in the Bell System Technical Journal, January 1952, and in his copending application Serial No. 252,432, filed October 22, 1951, now United States Patent 2,748,353, issued May 29, 1956.

Element 23 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 25 mounted upon the outside of guide 12 and supplied by a source 26 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 on the end toward guide 13. Therefore, all reference to "clockwise" and "counterclockwise" hereinafter is taken as viewed in the positive direction of this field, i.e., as viewed from guide 11 looking toward guide 13. It should be noted, however, that element 23 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 23 may be permanently magnetized if desired.

The effect of element 23 upon circularly polarized waves in cavity 20 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. It will be seen from curve 30 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 31, and then levels off to a substantially constant value. A clockwise rotating wave as represented by curve 33 decreases from unity, through zero and further decreases to a negative value. At the magnetic field strength 32 producing ferromagnetic resonance in the material, the permeability suddenly changes to a positive value. Cavity 20 of Fig. 1 is therefore resonant at different frequencies for the oppositely rotating waves due to this difference in permeability experienced by these waves. Cavity 20 may therefore be made resonant at the frequency f_1 for circularly polarized waves rotating in the above defined counterclockwise direction. Simultaneously, it may be resonant at the frequency f_2 for clockwise rotating waves. The frequency difference between f_1 and f_2 may be controlled over relatively wide limits by the physical size of element 23 and by the strength of the applied magnetic field, which in the usual case is adjusted below the value producing ferromagnetic resonance. The location of frequencies f_1 and f_2 in the over-all frequency spectrum is determined by the spacing between iris 21 and iris 22. Thus this spacing is equal to a multiple of one half the guide wavelengths of both the clockwise and counterclockwise rotating waves in cavity 20. The band-pass characteristic of cavity 20 is determined by the size and shape of irises 21 and 22 in accordance with conventional resonator practice. It is therefore understood that reference hereinafter to f_1 and f_2 includes also the band of frequencies included within the band-pass characteristic of cavity 20 which have the center frequencies f_1 or f_2 .

It is now possible to describe the over-all mode of operation of the isolator circuit of Fig. 1 by following the path of microwave energy applied respectively to each of its output terminals. Thus, linearly polarized wave energy is applied to guide 11, which is assumed to include both the frequency components f_1 and f_2 . This wave energy travels past vane 14 inasmuch as it is normal to the plane of the vane and is converted into a counterclockwise rotating wave by differential phase shifters 16 and 17. The components f_1 of this energy pass through iris 21, will be resonant in cavity 20 and will be coupled through iris 22 into the right-hand portion of guide 12 as a counterclockwise rotating circularly polarized wave. This wave is reconverted into a linear polarization by phase shifters 18 and 19 in the proper polarization to pass vane 15 and appear in guide 13. The components f_2 , however, will not be resonant in cavity 20 and will therefore be reflected from iris 21 as a counterclockwise rotating wave traveling toward phase shifters 16 and 17. On its return trip, the same component of the wave is further shifted by phase shifters 16

and 17, giving to this component a total 180 degree differential phase shift so that the total wave polarization is rotated into the plane of resistive vane 14 by which it is absorbed. Thus only wave energy of the frequencies f_1 may pass through the isolator of Fig. 1 in a direction from left to right as shown, while the frequencies f_2 attempting to pass in this direction are dissipated.

On the other hand, if a similar wave including the frequencies f_1 and f_2 are applied to guide 13 it will be converted by phase shifters 18 and 19 into a clockwise rotating wave in guide 12. Cavity 20 is resonant at the frequency f_2 and these components are transmitted through the cavity to appear in guide 11 while the components f_1 are reflected from the cavity to be dissipated in vane 15.

In Fig. 3 a second embodiment of the invention is shown in which the energy dissipated in resistive vanes 14 and 15, respectively, of Fig. 1 is coupled into polarization selective connections 35 and 36, respectively. In other respects the embodiment of Fig. 3 is similar to that of Fig. 1 and corresponding reference numerals have been employed to designate corresponding components. As illustrated, polarization selective connections 35 and 36 each comprise a rectangular wave guide joined to guide 12 in a shunt or H-plane junction. Thus guides 35 and 36 are physically oriented with respect to guides 11 and 13, respectively, so that wave energy in guides 35 and 36 is coupled into circular guide 12 as waves polarized perpendicular to the energy introduced by guides 11 and 13, respectively. Thus guides 11 and 35 comprise a pair of polarization selective connecting terminals by which wave energy in two orthogonal polarizations may be coupled to and from one end of guide 12, while guides 36 and 13 comprise a second pair of such terminals.

In view of the detailed analysis of the embodiment of Fig. 1 given above, the operation of the circulator circuit of Fig. 3 may be conveniently explained with reference to the diagram of Fig. 4. Thus if wave energy is applied at terminal a to guide 11, the components f_1 thereof will be coupled to terminal b of guide 13, while the components f_2 thereof will be reflected from cavity 20 into guide 35 to appear at terminal d . These frequency selective connections are indicated on Fig. 4 by the radial arrows labeled a , b and d , respectively, associated with a ring 37 and the arrows 38 and 39. The arrow 38 indicates a progression at the frequency f_1 in the sense from a to b , while the arrow 39 indicates progression at the frequency f_2 in the sense from d to a . Should a similar wave be applied at terminal b to guide 13 it will similarly divide on the basis of frequency between terminals a and c as schematically indicated on Fig. 4. The same is true for a wave applied at terminal c or at terminal d . Thus a circulator characteristic is obtained for the components f_1 in the sequence $a-b-c-d-a$, while a similar circulator characteristic is obtained for the components f_2 in the sequence $a-d-c-b-a$.

In Fig. 5, another embodiment of the invention is shown comprising a pair of spaced, substantially parallel, rectangular wave guides 40 and 41. Guides 40 and 41 are coupled by a guide 42 which may have either a circular or a square cross section. Guide 42 abuts the wide walls 44 and 45 of guides 40 and 41, respectively. An aperture 48-49, the nature of which will be considered hereinafter, couples wave energy in guide 40 to and from guide 42, while an aperture 50-51 couples wave energy in guide 41 to and from guide 42. Thus a cavity 43 is formed between wall 44 of guide 40 and wall 45 of guide 41. Cavity 43 is tuned by a gyromagnetic element 46 and therefore has the properties for counterclockwise and clockwise rotating circularly polarized waves, respectively, as defined above for cavity 20 of Fig. 1.

The manner in which these waves are excited in cavity 43 may now be examined. For this purpose it will be convenient to locate guides 40 and 41 in a coordinate

system as represented by the divergent vectors 47, labeled x and z . The vector x indicates a positive sense along the transverse wide dimensions of guides 40 and 41 and z indicates a positive sense along their longitudinal direction of propagation. Therefore the predominantly transverse magnetic field components of a dominant mode wave in guide 41 at a particular instant of time are shown in Fig. 5 and labeled H_x , while the predominantly longitudinal components are labeled H_z . These components form loops which lie in planes parallel to the wide dimension of guide 41. The arrows on the individual loops 52 and 53 indicate their polarity at a given instant of time and their sense is arbitrarily defined by the coordinates 47.

Aperture 50-51 is located in the top wall of guide 41 at a point off the center line thereof which places the aperture at a point having both H_x and H_z components. Slot 51 of aperture 50-51 is parallel to and therefore effective for coupling the H_z components into cavity 43 of guide 42, while slot 50 thereof is parallel to and therefore effective for coupling the H_x components. The amplitudes of these two components in guide 42 should be equal and this is obtained if slots 50 and 51 are of identical sizes and their intersection is located at the point in the top wall of guide 41 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 precise center) if the size of slot 51 is correspondingly increased and slot 50 decreased. If the aperture is located at the exact point of equal H_z and H_x components in guide 41, the aperture may be simply one of circular or square shape. The abutting end of guide 42 may be centered above aperture 50-51. The shape of aperture 48-49 in wall 44 may be identical to aperture 50-51 if desired and if it comprises a crossed slot as shown, the slots may be aligned respectively with slots 50 and 51.

The relative phases of the components coupled from guide 41 into cavity 43 depend upon the direction of propagation of the wave energy in guide 41. When the wave in guide 41 is propagating in the positive direction the component H_z of loop 52 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 43 a counterclockwise rotating circularly polarized wave. Now, when the wave in guide 41 is propagating in the negative direction the component H_z of loop 52 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 43 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 50-51, the wave induced in cavity 43 will rotate in one sense, while for the opposite direction of propagation the induced wave will rotate in the opposite sense. Since guide 40 bears the same relationship to guide 42 as does guide 41, it also demonstrates that waves propagating in the same direction in both guides 40 and 41 will induce similarly rotating components in guide 42. In this respect the structure of Fig. 5 is symmetrical.

It is now possible to describe the over-all operation of the embodiment of Fig. 5 by following the path of wave energy applied at its several terminals. Therefore, assume that wave energy, including the frequency components f_1 for which cavity 43 is resonant for counter-

clockwise rotating components, the frequency components f_2 for which cavity 43 is resonant for clockwise rotating components, and the frequency components f_n which comprise other components outside the band of either f_1 or f_2 , is applied to the left-hand end of guide 41 by way of terminal a . This energy tends to produce a counterclockwise rotating wave in cavity 18. The f_2 and f_n components thereof are not resonant in cavity 18 and will pass on the right-hand end of guide 41 to appear in terminal d . This connection is indicated schematically on Fig. 6 by the arrows labeled a and d associated with ring 55 and the arrows 56 and 57 which indicate progression at the frequencies f_2 and f_n , respectively, in the sense from a to d .

The f_1 components of the applied wave energy produce a counterclockwise rotating wave which is resonant in cavity 43, will be coupled through aperture 48—49 into guide 40 as a positive z -direction component followed 90 degrees later in time by a positive x -direction component. As noted above, it is the wave transmitted in the positive z -direction in guide 40 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 40 toward terminal b . The necessary amplitude relationships between the exciting x and z components for excitation of such a wave at the position of aperture 48—49 is inherently obtained by the location of the aperture and the relative dimensions of slots 48 and 49 as defined above. Thus a portion of the wave energy in cavity 43 which is coupled into guide 40 will appear at terminal b only. The magnitude of this coupled energy is determined by the sizes and impedances of apertures 48—49 and 50—51. It is easily possible by well known techniques to match the impedance of terminals a and b to that of cavity 43 by enlarging the apertures until all wave energy at the frequency f_1 applied at terminal a will appear at terminal b . This connection is indicated schematically in Fig. 6 by the arrow 58 indicating progression at the frequency f_1 in the sense from a to b .

A similar analysis of wave energy applied at terminal d of guide 41 will show that the components f_2 , which now induce clockwise rotating components in cavity 43, are coupled to terminal c of guide 40. The components f_1 and the components f_n which are not now resonant in the cavity 43 pass on to terminal a of guide 41. A similar coupling exists for wave energy applied at terminals c and b of guide 40. Thus the resulting terminal connections are shown on Fig. 6 by which wave energy at the frequency or in the band of frequencies f_1 is coupled from terminal a to b , from terminal b to c , from terminal c to d , and from terminal d to a , successively. On the other hand, the components f_2 are coupled from terminal a to d , from terminal d to c , from terminal c to b , and from terminal b to a , successively. In addition, a reciprocal coupling exists for the components f_n between terminals a and d and between terminals c and b . This is a coupling characteristic similar to that shown in Fig. 4 for the embodiment of the invention shown in Fig. 3, but is obtained in Fig. 5 by a structure of substantially simplified construction.

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:

A two-branch directionally-selective microwave filter comprising a section of shielded transmission line adapted to support electromagnetic wave energy of circular polarization, a polarization selective connection at each end of said line for electromagnetic wave energy of linear polarization, means for applying wave energy within a first band of frequencies to said connection at one end and means for applying wave energy within a second band of frequencies to said connection at the other end, a pair of 90 degree differential phase shift elements disposed one in each end of said guide having the planes of phase shift thereof inclined at 45 degrees to said linear polarization, said planes of phase shift being inclined to each other 90 degrees so that wave energy within said first band is converted into a circularly polarized wave rotating in a first sense within said guide as viewed in one direction along the axis of said guide and wave energy within said second band is converted into a circularly polarized wave rotating in a sense opposite to said one sense as viewed in said one direction, a pair of conductive irises located in a center portion of said line and spaced apart by an effective guide wavelength that is longer than a multiple of one-half wavelengths of said energy within said first band and shorter than a multiple of one-half wavelengths of said energy within said second band, and means located between said irises for presenting a real permeability of one value to wave energy within said cavity rotating in a first sense of circular polarization and a different value to waves within said cavity rotating in an opposite sense of circular polarization, said means including an element of gyromagnetic material, and means for magnetizing said element to a point at which said effective guide wavelength is substantially equal to a multiple of one-half of the guide wavelengths of energy within both said bands.

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