Aug. 26, 1958 E. H. TURNER 2,849,686

FERROMAGNETIC DEVICES

Filed Aug. 17, 1953 2 Sheets-Sheet 1

FIG. 1

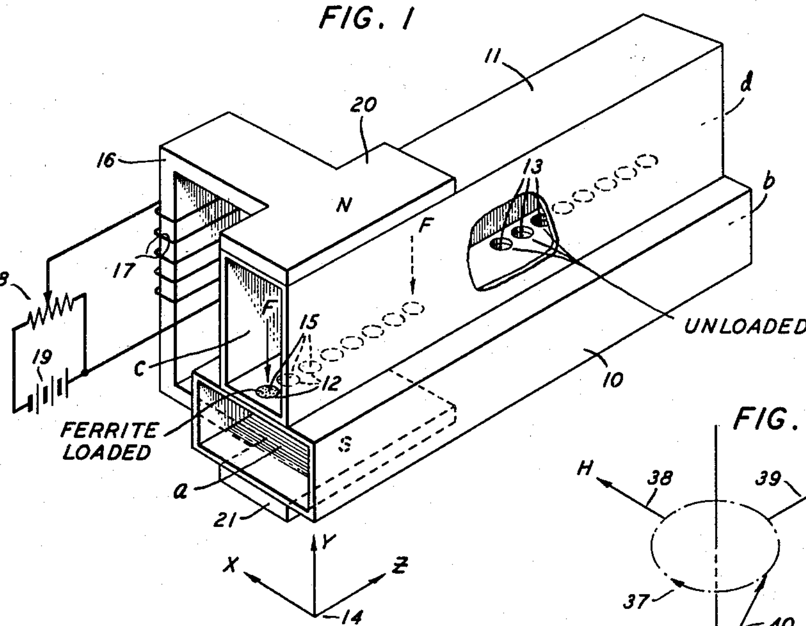


FIG. 3

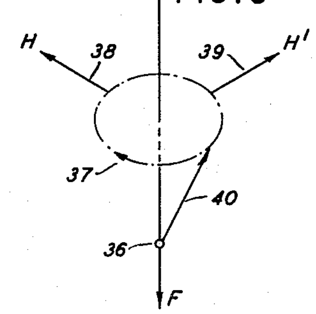


FIG. 2

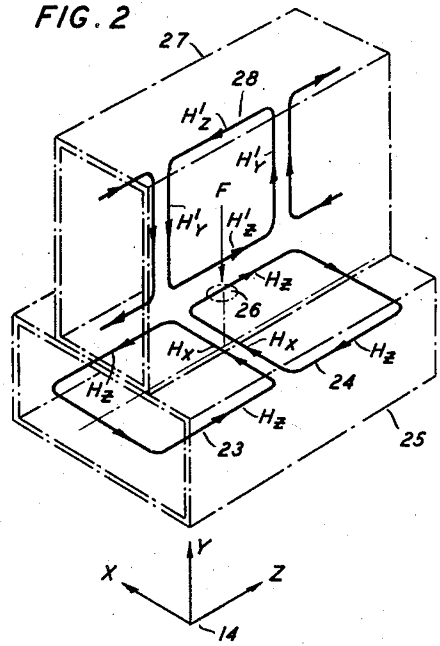


FIG. 5

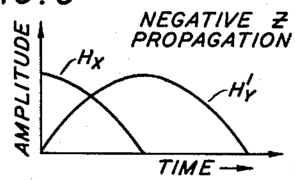
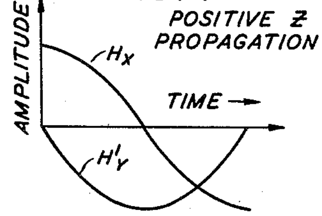


FIG. 4



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Filed Aug. 17, 1953 2 Sheets-Sheet 2

FIG. 6

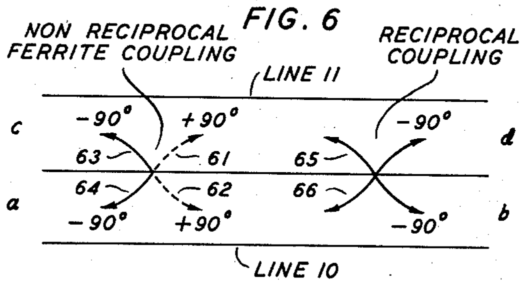


FIG. 7

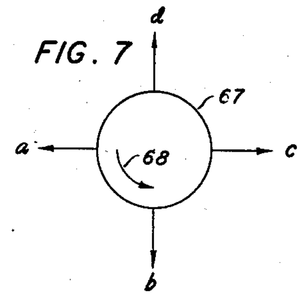


FIG. 8

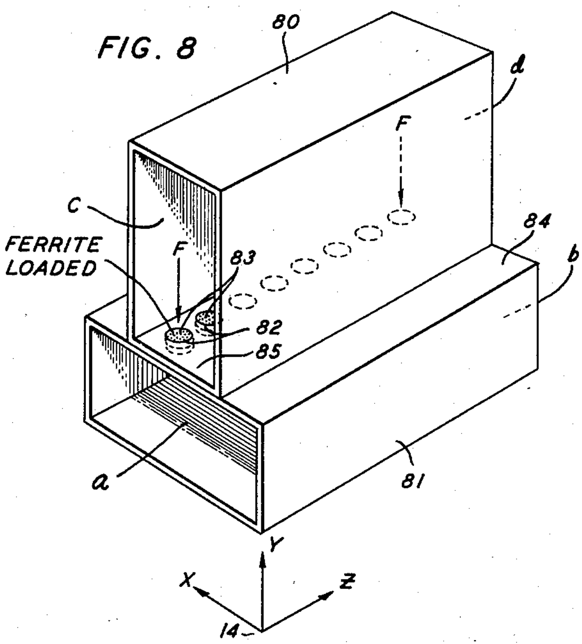


FIG. 10

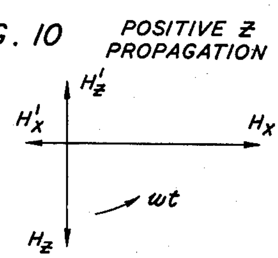


FIG. 11

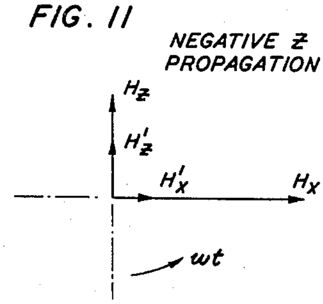
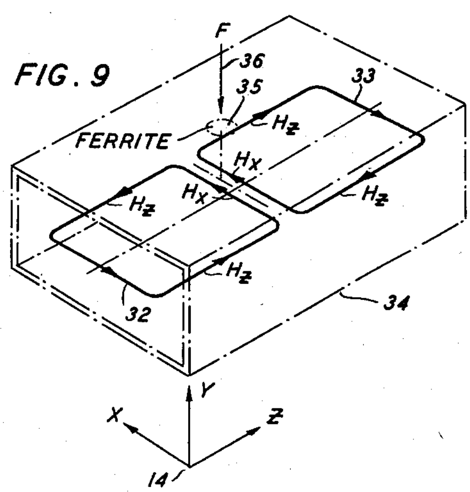


FIG. 9



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FERROMAGNETIC DEVICES

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Application August 17, 1953, Serial No. 374,529

15 Claims. (Cl. 333—10)

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. The ferromagnetic material has been employed to produce an antireciprocal rotation of the polarization of wave energy and to introduce non-reciprocal phase shift, or in other cases, a non-reciprocal attenuation to wave energy. It has been employed to produce a non-reciprocal displacement of the field pattern of wave energy. Other unusual effects of ferromagnetic material have also been discovered. It has now been found by the present inventor that when an element of polarized ferromagnetic material is employed as the coupling means between first and second electrical transmission structures, such as hollow conductive wave guides, it exhibits coupling properties quite different from the conventional coupling probe or aperture.

It is, therefore, an object of the present invention to non-reciprocally couple electrical transmission structures by ferromagnetic coupling means.

In several aspects, the structures of the present invention are similar to the wave-guide structures of the directional coupler, a familiar component in high frequency and microwave transmission systems for which countless uses and applications have been described in the published art. In general, presently known directional couplers are formed by a first section of wave guide coupled to a second section of wave guide. The coupling between the two sections is arranged so that an electromagnetic wave traveling in one direction along the first guide induces a principal secondary wave traveling in a single direction, usually in the same direction, along the second guide. In a practical directional coupler, the directivity is kept high so that any induced secondary wave traveling in the opposite direction from the principal secondary wave is very small. The directional coupler is completely reciprocal so that a wave traveling in the other direction in the first guide also induces a principal secondary wave traveling in the second guide.

In one aspect, it is an object of the present invention to eliminate the reciprocity in a directional coupler structure.

In accordance with the invention, elements of polarized ferromagnetic material are employed to couple a first wave-guide section to a second wave-guide section. The ferromagnetic coupling elements are not only capable of coupling each component of the magnetic field of the initial wave from the first guide into the second, but in effect generate new components corresponding to each initial component, at right angles to the initial component in space and displaced from it by 90 degrees in time. The amplitude of the new component depends upon the strength of the polarizing magnetic field. The relative phases of these components depend upon the direction of wave propagation through the guides.

In a first embodiment of the present invention, the two guides are oriented with respect to each other so that the principal secondary wave is induced only by one of the newly generated components. This provides a directional coupler structure in which the coupling factor may be varied at will by varying the strength of the polarizing magnetic field. Furthermore, the phase of the induced secondary wave for one direction of propagation of the wave in the first guide is 180 degrees different from the phase of the induced wave for the opposite direction of propagation in the first guide. This non-reciprocal phase characteristic was never found in conventional directional coupler structures.

A principal feature of the present invention resides in the four terminal "circulator circuit" that results from combining the magnetically controlled non-reciprocal directional coupler of said first embodiment with a directional coupler of conventional design. "Circulator circuit" is the generic designation of a group of non-reciprocal multibranch networks for which numerous applications have been deviced. All circulators have 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.

In a second embodiment of the present invention, the two ferromagnetically coupled guides are oriented so that that principal secondary wave in the second guide is induced only by coupled components that are in the same phase for one direction of propagation in the first guide, and equal in amplitude and opposite in phase for the opposite direction therein. Thus, wave energy in the first is coupled into the second for only said one direction of propagation of the energy in the first. Furthermore, coupling from the second into the first exists only for said opposite direction of propagation. This results in a simplified four terminal circulator circuit.

Certain primary advantages of the circulators in accordance with the present invention stem from the very small amount of ferromagnetic material required. In some other types of circulators, the ferromagnetic material is in the form of an element that fills or partially fills to a substantial extent the cross-section of the wave-guide structure. In still other types, the material is in the form of a member that extends longitudinally in the structure for an appreciable distance. In the present embodiments, however, the ferromagnetic material is limited to thin discs or wafers located within or near the coupling apertures. This allows more carefully compounded ferromagnetic material to be employed without unduly increasing the cost of the apparatus. Furthermore, all presently known ferromagnetic materials inherently introduce a certain amount of loss to wave energy passing therethrough. Therefore, a reduction in the amount of material employed is accompanied by a substantial increase in the efficiency of the apparatus.

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 present invention showing two sections of wave guide non-reciprocally coupled in a first interval by ferromagnetic coupling elements and reciprocally coupled in a second interval;

Fig. 2, given by way of illustration, shows the magnetic field configurations of waves in rectangular wave guides coupled by a ferromagnetic element;

Fig. 3 diagrammatically represents the precessing moment of a free electron and the magnetic fields associated therewith in a ferromagnetic coupling element;

Figs. 4 and 5 illustrate the amplitude versus time characteristics of the corresponding transverse magnetic field components for waves propagating in opposite directions, respectively, in the guides of Fig. 2;

Figs. 6 and 7 are schematic coupling characteristics, given by way of explanation, of the circulator characteristic for the embodiment of Fig. 1;

Fig. 8 is a perspective view of a second embodiment of the invention;

Fig. 9, given by way of illustration, shows the magnetic field configuration of a wave in the vicinity of a ferromagnetic coupling element of the embodiment of Fig. 8; and

Figs. 10 and 11 are vector diagrams representing the phase relationships of the coupled magnetic components of Fig. 9 for waves propagating in opposite directions, respectively.

Referring more specifically to Fig. 1, a non-reciprocal four branch microwave network or circulator circuit is shown as an illustrative embodiment of the present invention. This network comprises a magnetically controlled non-reciprocal directional coupler, in accordance with the present invention, having two of its four branches connected to two of the four branches of a reciprocal directional coupler of known construction. By way of illustrating a preferred embodiment of the invention, these two couplers are integrated into a single wave-guide structure with the non-reciprocal coupler constituting the left-hand portion of the structure, as shown in Fig. 1, and the reciprocal coupler constituting the right-hand portion. Thus, the integrated structure comprises a first section **10** of electrical transmission line for guiding wave energy which may be a rectangular wave guide of the metallic shielded type 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 adjacent line **10** and running for a portion of its length contiguous and parallel thereto is a second section **11** of transmission line substantially identical to guide **10**. As illustrated, one narrow wall of guide **11** is placed contiguous to and centered upon the wide wall of guide **10**; however, the precise location of guide **11** on guide **10** will not affect the operation of the invention.

For reference purposes hereinafter, guides **10** and **11** are located in a coordinate system represented by the divergent vectors **14** labeled x, y and z. Vector x indicates a positive sense along the transverse wide dimension of guide **10** and the transverse narrow dimension of guide **11**; y indicates a positive sense along the narrow transverse dimension of guide **10** and the wide dimension of guide **11**; and z indicates a positive sense along a longitudinal direction of propagation in both guides **10** and **11**. The left and right ends, respectively, of guide **10** are labeled a and b, respectively, and the left and right ends of guide **11** are labeled c and d, respectively.

Lines **10** and **11** are electromagnetically coupled over two intervals, constituting the reciprocal and non-reciprocal portions mentioned above, each extending several wavelengths along the longitudinal length of the lines. Coupling in the reciprocal portion is provided by a plurality of apertures **13** and will be considered in more detail hereinafter. Coupling in the non-reciprocal portion is provided by a plurality of polarized gyromagnetic coupling elements which may be, as illustrated, a plurality of apertures **12** extending through the contiguous walls of guides **10** and **11**, which apertures are loaded or filled by plug-like discs **15** of gyromagnetic material. Apertures **12** are located on substantially the contiguous wall center line of guide **10** and are distributed therealong at intervals of less than one-half wavelength apart. In the illustrated embodiment, this places apertures **12** also upon the center line of the wall of guide **11**.

Discs **15** each have a thickness substantially equal to the thickness of the walls of guides **10** and **11** and a diameter which is small compared to one wavelength. The thickness of discs **15** may be substantially increased, however, and may advantageously take the form of probes or posts extending a substantial distance into guides **10** and/or **11**. Alternatively, the gyromagnetic material may be one or several wafer-like strips placed next to the inside wall of either guide **10** or guide **11** to cover apertures **12**.

As a specific example of a gyromagnetic medium, discs **15** may be made of any of the several ferromagnetic materials combined in a spinel structure. For example, discs **15** may comprise an iron oxide with a small quantity of one or move bivalent metals such as nickel, magnesium, zinc, manganese or other similar material, in which the other materials combine 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, discs **15** 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, granted May 29, 1956.

Discs **15** are biased by a steady polarizing magnetic field of a strength to be described. As illustrated in Fig. 1, this field is applied transversely, i. e., at right angles to the direction of propagation of wave energy in guides **10** and **11**, and may be supplied by a solenoid structure comprising a C-shaped magnetic core **16** having pole pieces **20** and **21**, respectively. Turns of wire **17** on core **16** are so wound and connected through a rheostat **18** to a source of potential **19** that they produce an N pole in pole piece **20** and an S pole in pole piece **21**. Pole piece **20** bears against the top narrow wall of guide **11** in the area above apertures **12** and discs **15** and pole piece **21** extends underneath guide **10** so that the lines of magnetic field are substantially normal to the planes of discs **15** as the lines pass through them, as represented schematically by the vectors labeled F. This field may, however, be supplied by an electrical solenoid with metallic core of other suitable physical design, by a solenoid without a core, by a permanent magnet structure, or the ferromagnetic material of discs **15** may be permanently magnetized if desired.

Before proceeding with a detailed examination of the properties of the non-reciprocal portion of the circulator of Fig. 1 or of the preferred mode of operation of the circulator employing these properties, the unusual properties of a ferromagnetic coupling element, including within the term "coupling element" both the ferromagnetic disc and its associated aperture, as it serves to couple magnetic field components from within one guide into another, must be thoroughly understood. For this purpose, reference is made to the explanatory Fig. 2.

In Fig. 2 are shown representative loops **23** and **24** of the high frequency magnetic field of a dominant mode wave in rectangular wave guide **25** at a particular instant of time. These loops lie in planes which are parallel to the wide dimension of guide **25**. Guide **25** is located, for the purposes of explanation, in the x—y—z coordinate system defined with reference to Fig. 1. Therefore, the predominantly transverse magnetic field components of the wave are labeled H_x while the predominantly longitudinal components are labeled H_z. The arrows on the individual loops **23** and **24** indicate their polarity at a given instant of time and their senses are arbitrarily defined by the coordinates **14**. Located in the top wall of guide **25** on the center line thereof is a ferromagnetic coupling element **26** such as any one of discs **15** and apertures **12** of Fig. 1 described above. Element **26** is biased by a magnetic field as represented schematically by the vector labeled F.

The performance of element **26** under these conditions can be explained by the recognition that the ferromagnetic material of element **26** contains unpaired electron spins which tend to line up with the applied magnetic field. These spins have an associated magnetic moment which can be made to precess about the line of the biasing magnetic field keeping an essentially constant moment component in the direction of the applied biasing field but providing a moment component which may rotate in a plane normal to the field direction. Such a moment is shown schematically in Fig. 3 by vector **40** for an electron **36**. Thus, when a reciprocating high frequency magnetic field of electromagnetic wave energy as represented by the vector **38** labeled H on Fig. 3 is impressed upon the moment, the moment will commence to precess in one angular sense as represented by the arrow on orbit **37** and to resist rotation in the opposite sense. The combined effect of many such electrons and their associated moments produces in the ferromagnetic material not only a flux representing the impressed magnetic field H, but also a flux representing the reciprocating field at right angles in space and displaced by 90 degrees in time from the applied field H. The effective field produced by the induced flux may be thought of as an induced field and represented on Fig. 3 by a vector **39** labeled H′ at right angles to and 90 degrees around orbit **37** from the inducing magnetic component H. Note that if the inducing component H is applied along the x-direction as defined, the precessional motion brings the electrons' moment to the positive x-direction 90 degrees earlier in time than to the positive z-direction, but if the inducing component is applied along the z-direction, the motion brings the moment to the positive z-direction 90 degrees later in time compared to the time of reaching the positive x-direction. Thus the induced z-direction component lags the inducing x-direction component by 90 degrees while an induced x-direction component leads the inducing z-direction component by 90 degrees. The intensity of the induced magnetic field H′ depends upon the strength of the applied magnetizing field F.

Such is the coupling effect of element **26** in Fig. 2. It is noted that since element **26** is on the center line of guide **25**, it is excited only by the components H_x within guide **25**. Thus, an examination of the magnetic field components presented at the outside of guide **25** by element **26** will reveal a portion of the original transverse components H_x and a component in the z-direction induced by H_x which will be designated H_z'.

Consider now the wave that these components can excite in a rectangular wave guide **27** located above guide **25** and coupled on its narrow wall to element **26**. Only the z-direction components, i. e., H_z', can excite a mode which can be propagated in guide **27**. Since the component H_x in guide **25** has a sense in the positive x-direction, the component H_z' adjacent element **26** in guide **27** is shown in the positive z-direction. This take into account the 90 degree lag noted above between the induced z component and the inducing x component, a 90 degree lag caused by the inherent reradiation time of element **26**, and the inherent 180 degree phase relationship between components in coupled wave guides when the coupling is by way of magnetic field components. Magnetic loop **28**, representative of this dominant mode, is completed by drawing in the transverse components H_y' and giving to them senses consistent with H_z'.

The relative phase of the total waves propagating in guides **25** and **27** depend upon the direction of propagation of wave energy in these guides and may not most readily be determined separately with the aid of the digrams of the amplitudes of transverse magnetic field components as a function of time at element **26** in guides **25** and **27** shown in Figs. 4 and 5. Figs. 4 and 5 represent, respectively, the positive direction of propagation in guides **25** and **27** and the negative direction of propagation therein. An in phase condition for the waves is arbitrarily defined as that phase in which the transverse component at element **26** is guide **27** is in phase with the transverse component at element **26** in guide **25**, i. e., H_y' in phase with H_x.

Therefore, consider that the waves in guides **25** and **27** are propagating in the positive z-direction. At the initial instant of time pictured in Fig. 2, the component H_x of loop **23** has a maximum positive amplitude at the position of element **26** and is decreasing as the wave propagates. This condition may be represented by the amplitude versus time curve labeled H_x on Fig. 4. At the same instant of time and position in guide **27** the component H_y' of loop **28** is zero and is decreasing to its maximum negative value. This condition may be represented by the curve labeled H_y' of Fig. 4. In other words, the component H_y', and by definition the wave in guide **27**, is in a phase 90 degrees ahead in time from the component H_x and the wave in guide **25**.

Now consider that the waves in guides **25** and **27** are propagating in the negative z-direction. The component H_x of loop **24** is decreasing from its maximum positive value, as shown by the curve labeled H_x on Fig. 5. Now, however, the component H_y' of loop **28** is increasing to its maximum positive value and may be represented by the curve labeled H_y' of Fig. 5. In other words, the component H_y', and by definition the wave in guide **27**, is in a phase 90 degrees behind in time from the component H_x and the wave in guide **25**.

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 illustrated senses shown in Fig. 2. This explanation does, however, serve to demonstrate that for one direction of propagation past the coupling element the induced wave will have a phase 90 degrees ahead of the inducing wave and 180 degrees different from the phase of the induced wave for the opposite direction of propagation. The strength of the induced wave for either direction depends upon the strength of the magnetizing field F and is zero when the field is zero.

Returning now to Fig. 1, each of the coupling elements **15** thereof will couple wave components in the manner described for element **26** of Fig. 2. The collective effect of a large number of these elements provides a directional coupler structure having non-reciprocal phase characteristics and having a coupling factor which is variable in that the coupling is determined by the strength of the applied magnetic field. Thus, if wave energy is applied at terminal a of guide **10**, it will travel in guide **10** to the right. Portions of the energy will be successively transferred into guide **11** by coupling elements **15**. So far as transmission of this energy in guide **11** in the opposite direction toward terminal c thereof is concerned, the structure is inherently a directional coupler, i. e., a minimum transmission of energy in this direction in guide **11** will be found, since the colective effect of a large number of discrete coupling elements spaced at less than one-half wavelength apart is of itself directionally selective as is well known in the directional coupler art. As to the energy transmitted in the same direction in guide **11** toward terminal d thereof, the fractions of the energy transferred by elements **15** will be in phase and a summation according to directional coupler principles of such components eventually results in cancellation of all or a part of the energy in guide **10** and transfer thereof into guide **11**. The amplitude of this transferred energy may be selected from zero to complete power transfer by varying the strength of the magnetic field by tapping off the required magnetizing current from rheostat **18**. As particularly described with reference to Figs. 2 through 5, this energy in guide **11** will have a phase 90 degrees ahead of that in guide **10**. If, however, the initial energy in line **10** was propagating in the opposite direction, i. e., to the left toward terminal *a*, the transferred energy in guide **11** will propagate toward terminal *c* thereof in a phase 90 degrees behind that in guide **10**.

The structure of Fig. 1 thus far described constitutes a directional coupler in which the coupling factor may be varied at will by varying the strength of the applied magnetic field. As such, it may be employed in many of the presently known directional coupler applications in which the coupling factor of the coupler must be set at some unusual ratio of power division or must be variable. It may also be employed as a modulator by applying the modulating current to solenoid **17**. A modulated output would be obtained at one end of either guide when the source of carrier signal is applied at the other end of either guide. Furthermore, it may serve as a switch by suitably connecting solenoid **17** to means for increasing the magnetizing current from zero to the value producing a complete transfer of power from one guide to the other.

In addition to the above-described variable coupling factor, the structure of Fig. 1 thus far described has a non-reciprocal phase characteristic which is not found in any conventional directional coupler structure. The phase shift experienced in passing across the coupler in one direction is 180 degrees different from the phase shift experienced in passing across the coupler in the other direction. Since this phase shift depends upon the sense of the applied biasing magnetic field, reversing the field has the effect of reversing the direction through the coupler in which the additional phase reversal is found.

One particularly useful combination making use of this non-reciprocal phase shift property of a ferromagnetically coupled directional coupler is further illustrated by Fig. 1 by connecting two of the four branches of the non-reciprocal coupler to two of the four branches, respectively, of a reciprocal coupler and adjusting the magnetic field of the non-reciprocal coupler to produce an equal division of power between the induced wave and the inducing wave. This is known as a three decibel division of power. The reciprocal coupler may be one of the many directional couplers known to the art which can be adjusted to a three decibel power division. It may alternatively be one of the microwave structures known as hybrid junctions which structures inherently provide a three decibel division.

As noted above, however, a preferred embodiment of the invention is illustrated in Fig. 1 in which a single wave-guide structure includes both the reciprocal and non-reciprocal coupling sections. Thus, the right-hand extensions of guides **10** and **11** are reciprocally coupled by one of the several broad band coupling means familiar to the directional coupler art. This coupling may be, as illustrated on Fig. 1, a plurality of unloaded apertures **13** extending through contiguous walls of guides **10** and **11** and distributed at intervals of less than one-half wavelength along the longitudinal length thereof. In order that apertures **13** may intercept longitudinal magnetic components in guide **10** (which would be zero along the center line thereof), apertures **13** are displaced from the center line of the wall of guide **10** and coupling is thereby established between the longitudinal components in both guides. The number and size of the apertures are chosen according to principles well

known to the directional coupler art to provide a three decibel transfer of energy. Thus, the second interval of coupling constitutes an ordinary directional coupler by means of which one-half of the wave energy traversing in one direction in either guide **10** or guide **11** is transferred into the other guide and launched directionally therein with a 90 degree phase delay caused by the inherent reradiation time of the apertures **13**. As is well known in the directional coupler art, this coupling is reciprocal in every respect.

The circulator circuit connection as it results from the combined reciprocal and non-reciprocal coupling sections of the structure of Fig. 1 may now be examined. This examination may most readily be followed by reference to Figs. 6 and 7. On Fig. 6, wave guides **10** and **11** are schematically represented by corresponding transmission lines bearing similar reference numerals and terminal designations to those of Fig. 1. The coupling phases of the non-reciprocal ferromagnetic coupling of elements **15** is shown on the left-hand portion of lines **10** and **11** by the arrows **61** through **64**. Broken line arrows **61** and **62** indicate the above-described 90 degree phase advance received by wave energy along the paths *c* to *b* and *a* to *d*, respectively. Arrows **63** and **64** indicate the above-described phase delay of 90 degrees along the opposite paths *b* to *c* and *d* to *a*, respectively. Likewise the reciprocal coupling of apertures **13** is represented at the right-hand extension of lines **10** and **11** by the arrows **65** and **66** indicating the 90 degree phase delay for reciprocal directions of energy transfer.

Thus, if a microwave signal is applied to terminal *a* of line **10**, one-half of it will be transferred into line **11** with a phase 90 degrees ahead of the portion in line **10**, as indicated by arrow **61**. At the reciprocal coupling interval, all voltages transferred from one line into the other would receive a phase delay of 90 degrees, as shown by arrows **65** and **66**. Therefore, the two portions of energy in line **10** at terminal *b* thereof will be in phase and will combine. No energy will appear at terminal *d* of line **11** since the voltage of the portion of the energy which came through the non-reciprocal coupling (arrow **61**) was advanced in phase placing it out of phase with the voltage which came through the reciprocal coupling (arrow **66**) and was delayed. Substantially free transmission is, therefore, afforded from terminal *a* to terminal *b* and this condition is indicated schematically on Fig. 7 by the radial arrows labeled *a* and *b*, respectively, associated with the ring **67** and an arrow **68** diagrammatically indicating progression in the sense from *a* to *b*.

Tracing the phase shifts of a wave applied to terminal *b* will show a 90 degree phase delay in the energy transferred from line **10** to line **11** as indicated by arrow **65**, and a like phase delay in the energy transferred therebetween as indicated by arrow **63**, so that the two portions of energy are in phase to combine at terminal *c* of line **11**. The energy will not appear at terminal *a* of line **10** since the portion transferred from line **10** to line **11** and back to line **10** receives a first 90 degree phase delay, as indicated by arrow **65**, and a second 90 degree phase delay on returning to line **10**, as indicated by arrow **64**, placing it out of phase with the energy which passes straight through line **10**. This transmission is indicated by arrow **68** on Fig. 7 which tends to turn the arrow *b* in the direction of the arrow *c*.

To a limited extent the structure of Fig. 1 as shown schematically in Fig. 6 is symmetrical so that the same coupling characteristic is found between terminal *c* and terminal *d* as was described above between terminals *a* and terminal *b*. This coupling is schematically indicated on Fig. 7 by arrow **68** coupling from terminal *c* to terminal *d*. Likewise, the same coupling is experienced from terminal *d* to terminal *a* as was described above from terminal *b* to terminal *c* and this coupling is likewise schematically indicated on Fig. 7. The coupling characteristic thus represented by Fig. 7 is the characteristic of the group of networks heretofore designated circulator circuits.

An alternative and somewhat simplified embodiment of a four terminal circulator is shown in Fig. 8. In Fig. 8, a pair of parallel and contiguous wave-guide sections **80** and **81** are shown. One narrow wall **85** of guide **80** is located on the center line of the wide wall **84** of guide **81**. The guides are coupled by a plurality of apertures **82** containing ferromagnetic coupling elements **83** distributed longitudinally over an interval of several wavelengths and spaced from each other by less than one-half wavelength along contiguous walls **84** and **85**. Elements **83** are displaced to one side of the center lines of both walls **84** and **85** by a distance to be defined more precisely hereinafter, but which will in practical embodiment be in the order of one-fifth of the wide dimensions of the guides. Elements **83** are biased by a transverse magnetic field as represented schematically by the vectors labeled F. It should be noted that guide **80** may be displaced on wide wall **84** of guide **81** so that elements **83** will lie along the center line of wall **85**. As will appear more clearly hereinafter, it is the above-defined displaced location of apertures **82** on wall **84** that affects the operation of the invention and only secondarily the location of these apertures on wall **85**. Therefore, inasmuch as mechanical assembly is facilitated thereby, guide **80** may be located symmetrically upon wall **84** of guide **81** as shown.

Before proceeding with a detailed examination of the preferred mode of operation of the circulator of Fig. 8 and the several adjustments necessary to obtain this operation, the unusual properties of a ferromagnetic coupling element when located in a position having both transverse and longitudinal magnetic field components must be thoroughly understood. For this purpose, reference is made to the explanatory Fig. 9, which is similar in a general way to Fig. 2 already considered.

Thus, in Fig. 9, representative loops **32** and **33** of the dominant mode of a wave in rectangular wave guide **34** at a particular instant of time are shown. Located in the top wall of guide **34** at a point off the center line thereof and, therefore, at a point having both H_x and H_z components is a ferromagnetic coupling element **35** corresponding to any one of the coupling elements **83** of Fig. 8. Element **35** is biased by a magnetic field as represented schematically by vector **36** labeled F.

As in the preceding embodiments the precessing electrons in element **35** produce an induced field at right angles in space to and displaced 90 degrees in time from the inducing field. However, element **35** is now excited by both H_z and H_x components within guide **34**. An examination of the magnetic field components presented at the outside of guide **34** by element **35** will reveal the following components: a portion of the original transverse components H_x, a component in the z-direction induced by H_x which will be designated H_z', a portion of the original longitudinal components H_z, and a component in the x-direction induced by H_z which will be designated H_x'.

The relative phases of these components depend upon the direction of propagation of the wave energy in guide **34** and may most readily be determined separately with the aid of the vector diagrams of Figs. 10 and 11, representing respectively, the positive direction of propagation in guide **34** and the negative direction of propagation therein.

In Figs. 10 and 11 the following convention is adopted. The passage of time ωt is represented by rotation in a counter-clockwise direction with the initial instant of time pictured in Fig. 9 represented by the right-hand extension of the abscissa. The vectors represent maximum positive values of the various field components. Therefore, the component H_x which in Fig. 9 has its maximum positive amplitude at the position of element **35** is represented by the vector H_x extending horizontally to the right on both Figs. 10 and 11. The component H_z' induced by H_x is also shown on Figs. 10 and 11 by the vector H_z' extending upward indicating that this induced component reaches its maximum positive amplitude in the z-direction 90 degrees later in time, as shown by Fig. 3, than the component H_x which produced it. This relationship may be assumed as fixed, therefore, regardless of the direction of propagation.

Note, however, on Fig. 9, that when the wave in guide **34** is propagating in the positive direction, the component H_z of loop **32** 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 may be represented by the downward vector H_z on Fig. 10. The maximum positive value of the component H_x' induced by H_z occurs, as shown hereinbefore with reference to Fig. 3, 90 degrees ahead in time from the component H_z which induced it, and is so represented by the vector H_x' extending to the left. Thus, the components H_z' and H_z as well as the components H_x' and H_x are out of phase for the positive direction of propagation.

Now, when the wave in guide **34** is propagating in the negative direction, the component H_z of loop **33** 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 would for this direction of propagation be represented by an upward vector H_z on Fig. 11. Since the maximum positive component H_x' induced by H_z is 90 degrees ahead in time from H_z, it is represented by a positive vector 90 degrees ahead in time and, therefore, extending to the right. Thus, for the negative direction of propagation, the H_z and H_z' components as well as the H_x and H_x' components are in phase.

As in the preceding embodiments, the conventions adopted are arbitrary and apply only to the illustrative senses shown on Fig. 9. Also the 90 degree phase delay inherent in coupling through an aperture has been disregarded inasmuch as in this particular case the delay affects all components alike. This explanation does, however, serve to demonstrate that for one direction of propagation past the coupling element **35**, the initial and induced x-direction and z-direction components are in phase, respectively. For the opposite direction of propagation, the situation is reversed. It also serves to indicate that for said one direction the H_z component of the inducing wave is ahead of the H_x component thereof while in said opposite direction H_z is behind H_x.

Returning now to Fig. 8, each of the coupling elements **83** thereof could, under suitable circumstances, couple all four of the above-described components into a connected wave-guide structure. However, since the coupling to guide **80** is along the narrow wall thereof, only the H_z and H_z' components can excite a mode which can be supported in guide **80**. Now, the amplitude of the component H_z in guide **80** depends upon the position of elements **83** upon wall **84**, this component being zero when elements **83** extend along the center line of wall **84** and maximum at the edges thereof. On the other hand, the amplitude of the component H_z' depends both on the value of H_x which is a maximum along the center line of wall **84** and upon the strength of magnetizing field F. In accordance with the present invention, the strength of the magnetizing field F is selected with respect to the location of elements **83** so that the components H_z and H_z' are equal. In a typical embodiment in which elements **83** are displaced away from the center line of wall **84** by one-fifth of the wide dimension of the guides, the strength of the magnetizing field required is substantially that required to saturate the ferromagnetic material of elements **83**. This field is substantially below that required to produce ferromagnetic resonance in the material.

Thus, microwave energy applied to guide **81** by way of terminal *a* would produce H_z and H_z' components in guide **80** which are equal in amplitude, but as demonstrated with reference to Figs. 9 and 10, opposite in phase. Therefore, no energy will couple into guide **80** and all energy applied at terminal *a* will appear at terminal *b* of guide **81**. This is the coupling condition indicated schematically on Fig. 7 between terminals *a* and *b*.

A wave applied to terminal *b* of guide **81** will produce in phase H_z and H_z' components in guide **80** at each of elements **83**. So far as transmission of this energy in guide **80** in the opposite direction toward terminal *d* thereof is concerned, the structure is inherently a directional coupler as in the embodiment described above. As to energy transmitted in the same direction in guide **80** toward terminal *c* thereof, the *z*-direction components transferred by each of the elements **83** will be in phase with each other, and a summation of such components eventually results in cancellation of the energy in line **81** and transfer thereof into line **80**. This power transfer is dependent upon the integrated coupling strength factor of the coupling which, in turn, is a function of the strength and distribution of the coupling between lines **80** and **81**, as described in detail in the copending application of S. E. Miller, Serial No. 235,488, filed December 11, 1952. As there disclosed, this factor is expressed as $n \sin^{-1} C$, in which *n* represents the number of discrete coupling points, and C the coupling factor of each of these points. All power is transferred from line **81** into line **80** when the integrated coupling strength factor is equal to

$$\frac{m\pi}{2}$$

wherein *m* is any odd integer. Substantially free transmission is, therefore, afforded from terminal *b* to terminal *c* and this condition is schematically represented on Fig. 7.

A wave applied to terminal *c* of guide **80** will have substantially only *z*-direction components along the line of elements **83**. Thus, each element will produce in guide **81** a *z*-direction component and also an induced component in the *x*-direction which is 90 degrees later in time than the *z*-direction component which produced it. As noted above, with reference to Figs. 9 and 11, it was the wave traveling in the negative *z*-direction that had this phase relationship, i. e., and *x*-direction component 90 degrees behind the *z*-direction component. Conversely, this phase relationship between the exciting components would produce a wave propagating only in the negative direction in guide **81** except, however, that for the negative direction of propagation the collective effect of all coupling elements **83** is directionally selective so that no energy will be transferred into guide **81**. Therefore, all energy applied to terminal *c* of guide **80** will appear at terminal *d* thereof as shown schematically on Fig. 7.

Energy applied at terminal *d*, however, will produce in guide **81** an *x*-direction component 90 degrees behind the *z*-direction component. For this direction of propagation, the components transferred by each of the elements **83** will be in phase, and their summation will result in transfer of the energy into guide **81**. The necessary amplitude relationship between the exciting *x* and *z*-direction components for excitation of such a negative traveling wave is inherently obtained by the location of elements **83** and the setting of the magnetic field strength F defined above. The resulting terminal connections are indicated schematically on Fig. 7 which shows that all energy applied to terminal *d* will be coupled to terminal *a*. The coupling characteristic thus represented is the characteristic of a group of networks heretofore designated circulator circuits.

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 an electromagnetic wave energy transmission system, a first section of shielded transmission line for guiding said wave energy having an aperture in the shield thereof, an element of gyromagnetic material closing said aperture, means for exciting said first line with electromagnetic wave energy having a primary component of magnetic field in a first direction, means for magnetizing said element in a second direction different from said first direction, said primary field and said magnetizing means inducing in said element a secondary field having a third direction different from said first and second direction, and a second section of shielded transmission line coupled to said aperture with said induced field in a direction in said second section parallel to and coincident in space and phase with a magnetic field component of a propagating electromagnetic wave therein.

2. In combination, transmission means for supporting electromagnetic wave energy with longitudinally and transversely extending magnetic fields, means for coupling a first component of one of said magnetic fields from said transmission means and for inducing from the other of said fields a second component at right angles thereto at the common points in space wherein said inducing field and said induced field exist simultaneously and delayed therefrom by 90 degrees in time, said first and second components being of equal amplitude, and a second transmission means for supporting electromagnetic wave energy with longitudinally and transversely extending magnetic fields, said second transmission means being related to said inducing field with the field corresponding to the other of said fields in said first-mentioned transmission means being aligned with said induced component.

3. The combination according to claim 1, wherein said element is a disc of ferromagnetic material disposed within said aperture.

4. In combination, transmission means for supporting electromagnetic wave energy with longitudinally and transversely extending magnetic fields, means for inducing from one of said fields a component at right angles thereto at the common points in space wherein said inducing means and said induced field exist simultaneously and delayed therefrom by 90 degrees in time, and a second transmission means for supporting electromagnetic wave energy with longitudinally and transversely extending magnetic fields, said second transmission means being related to said inducing means with the field corresponding to the other of said fields in said first mentioned transmission means being aligned with said induced component.

5. In an electromagnetic wave energy transmission system, first and second sections of shielded transmission line, each of said lines supporting wave energy having longitudinally and transversely extending magnetic field components, said lines being orientated relative to each other such that the longitudinal and transverse field components in said first line are perpendicular respectively to the transverse and longitudinal components in said second line, and a plurality of gyromagnetic coupling elements longitudinally distributed along said lines to couple between one of said field components in one of said lines and the other of said field components in the other of said lines.

6. The combination according to claim 5, including a second plurality of coupling elements coupling between

both of said field components in said one line and said other component in said other line.

7. The combination according to claim 6, wherein a three decibel coupling is provided between said lines by each plurality of coupling elements.

8. In an electromagnetic wave energy transmission system, first and second sections of shielded transmission line, each of said lines supporting wave energy with longitudinally and transversely extending magnetic field components, said lines being orientated relative to each other such that the longitudinal and transverse field components in said first line are perpendicular respectively to the transverse and longitudinal components in said second line, and a plurality of gyromagnetic coupling elements longitudinally distributed along said lines to couple between one of said field components in one of said lines and both of said field components in the other of said lines.

9. In combination, a pair of wave guides for electromagnetic wave energy, said guides having a common conductive wall portion, said common wall having at least one aperture interconnecting said guides, an element of gyromagnetic material closing said aperture, means for exciting one of said guides with electromagnetic wave energy having a primary component of magnetic field in a first direction, means for magnetizing said element in a second direction different from said first direction, said primary field and said magnetizing means inducing in said element a secondary field having a third direction different from said first and second direction, said guides being orientated relative to each other such that said induced field excites an electromagnetic wave of energy capable of propagation in the other of said guides.

10. The combination according to claim 9, wherein said common wall has a plurality of apertures therein distributed along an interval of a plurality of wavelengths thereof, and an element of ferromagnetic material disposed in each of said apertures.

11. The combination according to claim 9, wherein said guides are rectangular in cross-section, said common wall including a narrow wall of one of said guides and a wide wall of the other.

12. The combination according to claim 11, wherein said aperture is located on the center line of said wide wall.

13. The combination according to claim 11, wherein said aperture is displaced from the center line of said wide wall.

14. In combination, first and second sections of wave guide of rectangular cross-section, each of said guides having a pair of wide and a pair of narrow conductive walls, a narrow wall of one of said guides being contiguous and parallel to a wide wall of the other of said guides, said contiguous walls having a plurality of apertures extending therethrough and displaced from the center lines thereof, the apertures of said plurality being spaced from each other by less than one-half wavelength of the energy to be conducted by said guides and being distributed along a longitudinal length of said guides of several wavelengths of said energy, an element of ferromagnetic material disposed within each aperture of said plurality, and a magnetizing field applied to each of said elements.

15. In combination, first and second sections of wave guide of rectangular cross-section, each of said guides having a pair of wide and a pair of narrow conductive walls, a narrow wall of one of said guides being contiguous and parallel to a wide wall of the other of said guides, said contiguous walls having a first plurality of apertures extending therethrough along the center lines thereof and a second plurality of apertures extending therethrough displaced from the center lines thereof, the apertures of each plurality being spaced from each other by less than one-half wavelength of the energy to be conducted by said guides and being distributed along a longitudinal length of said guides of several wavelengths of said energy, an element of ferromagnetic material disposed within each aperture of said first plurality, and a magnetizing field applied to each of said elements.

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