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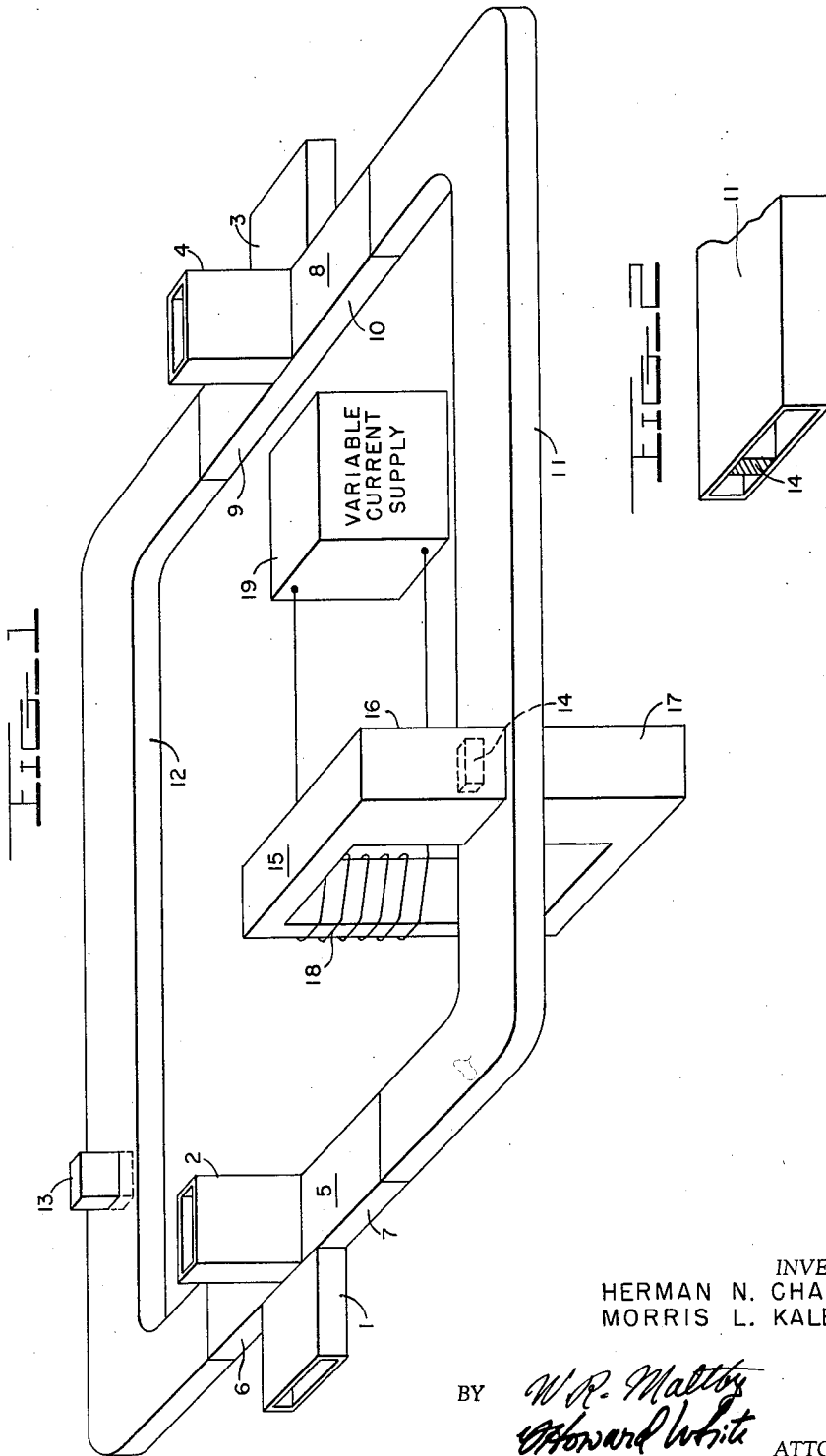
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3,036,278

RECTANGULAR WAVEGUIDE CIRCULATOR

Filed April 29, 1955

3 Sheets-Sheet 1



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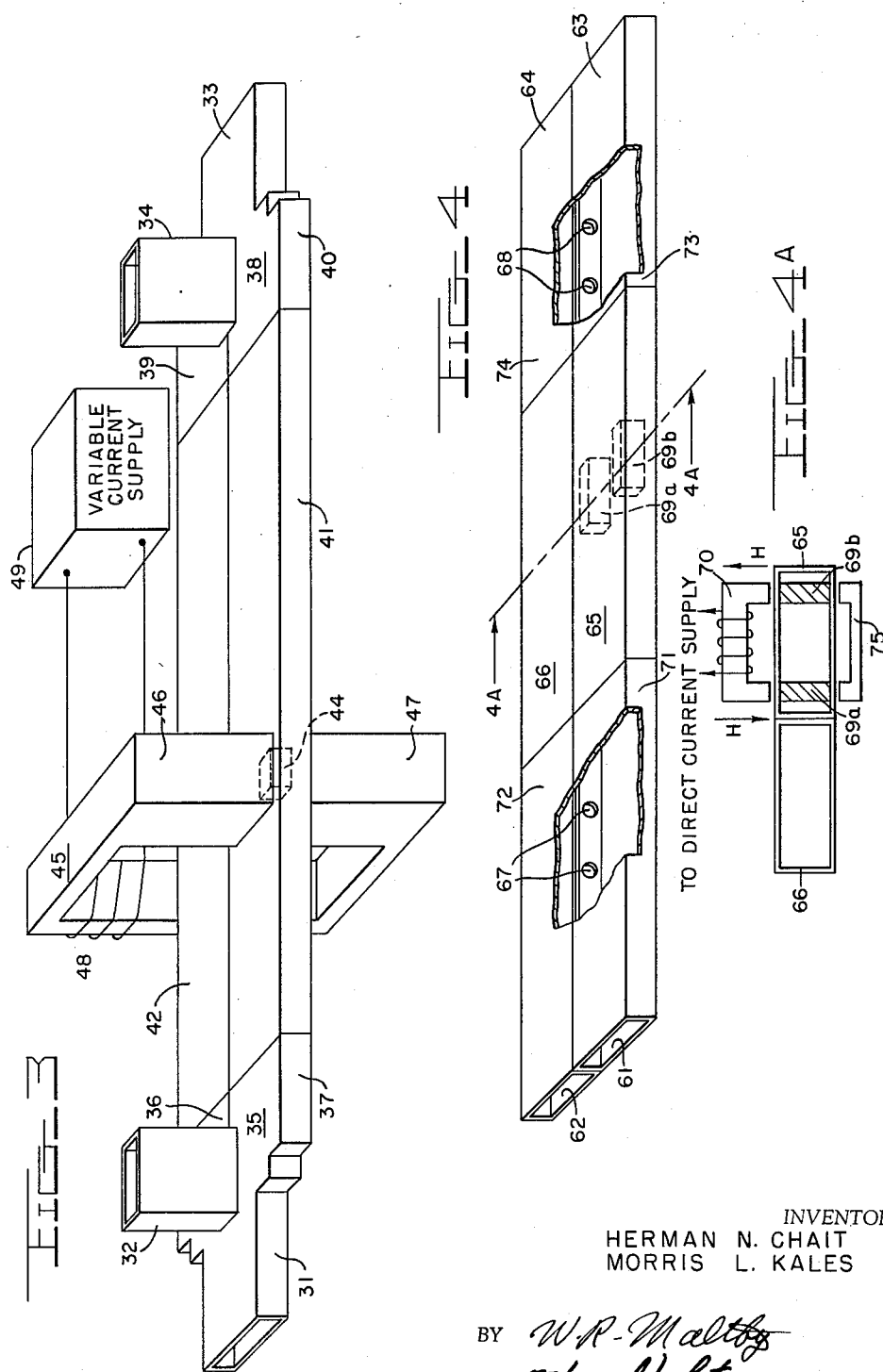
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RECTANGULAR WAVEGUIDE CIRCULATOR

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3 Sheets-Sheet 2



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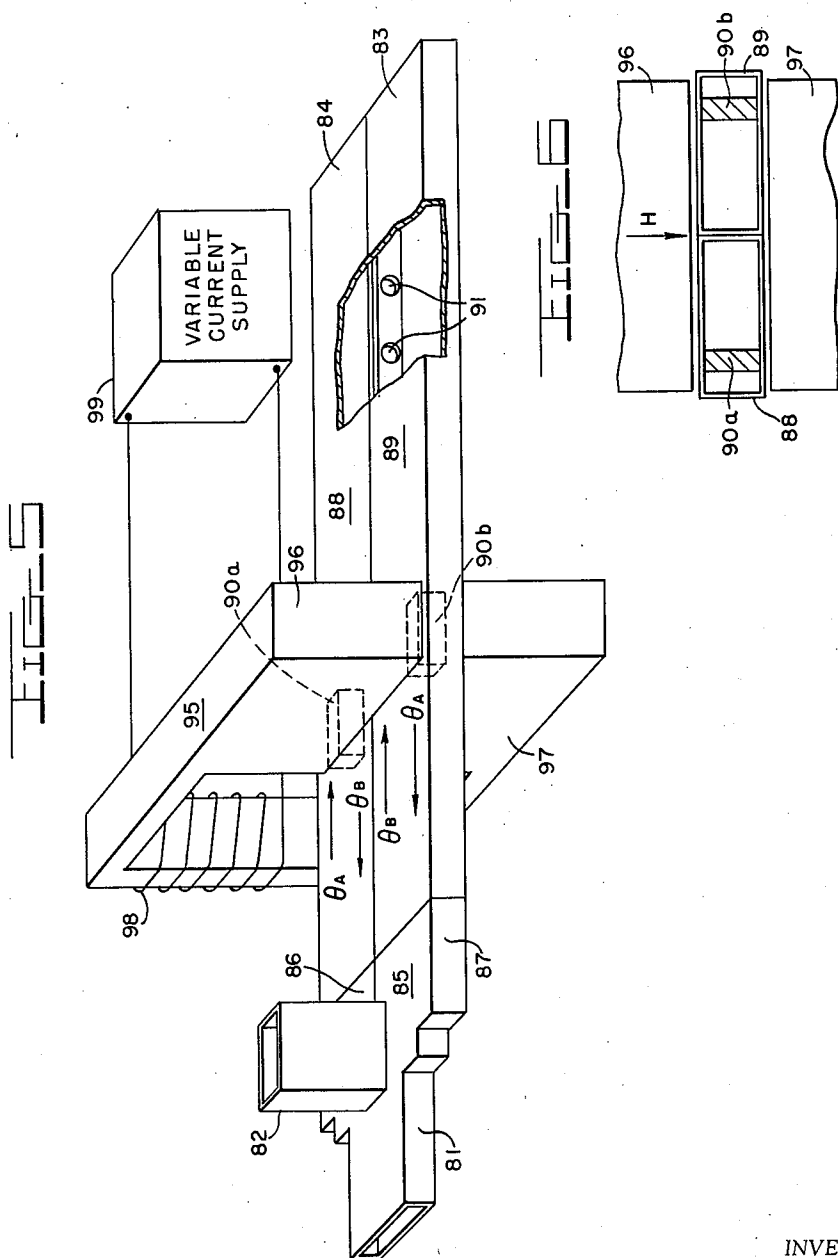
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RECTANGULAR WAVEGUIDE CIRCULATOR

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3 Sheets-Sheet 3



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3,036,278

RECTANGULAR WAVEGUIDE CIRCULATOR
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1 Claim. (Cl. 333-9)

(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

This invention relates to electromagnetic transmission systems known as circulators and more particularly to circulators using only rectangular waveguide.

With the advent of the microwave gyrator it soon became apparent that this new circuit element, because of its non-reciprocal characteristics, had any number of possible applications in microwave frequency systems. One suggested application of this new circuit element was in combination with several hybrid junction devices, the combination being called a polarization circulator. As has been pointed out, one very practical application of such a combination is as a T.R. box in a radar system. Another, is a device for separating the various channels in a multichannel communication system; see R. Alley: A Review of New Magnetic Phenomena, 32 Bell System Technical Journal 1155 (1953).

The polarization circulators suggested and used heretofore have, as the name indicates, relied for their operation upon the shifting or rotation of the plane-of-polarization of the propagated energy. To rotate the plane-of-polarization, however, it is customary to use circular waveguide, whereas, in most microwave transmission systems rectangular waveguide is primarily used. Thus, initially in the use of polarization circulations an impedance matching problem is encountered due to the difference in impedance of circular and rectangular waveguide. Further, it has been our experience that the polarization circulators heretofore used do not possess the extremely broad banded characteristics possessed by the purely rectangular waveguide circulators to be described.

It is therefore a first object of this invention to provide a circulator using only rectangular waveguide;

It is another object of this invention to provide a circulator possessing extremely broad banded characteristics;

It is yet another object of this invention to provide a circulator wherein the matching problems, generally accompanying the use of waveguides of different configuration, are substantially reduced;

A further object of this invention is to provide a circulator wherein the phase of the transmitted electromagnetic energy is shifted with no change in its plane-of-polarization;

A still further object of this invention is to provide an improved microwave circulator using only rectangular waveguide sections and a transverse magnetic field;

An additional object of this invention is to provide a rectangular waveguide circulator for use with dominant mode electromagnetic energy and which functions to shift the phase of said energy without affecting any change in the plane-of-polarization thereof.

Other objects and features of the present invention will become apparent upon consideration of the following detailed description when taken in connection with the accompanying drawings which illustrate various embodiments of the invention. It is to be expressly understood, however, that the drawings are designed for purposes of illustration only and not as a definition of the limits of the invention, reference for the latter purpose being had to the appended claim.

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In the drawings:

FIG. 1 is a perspective view of a representative embodiment of the instant invention;

FIG. 2 is a perspective view of a portion of the waveguide shown in FIG. 1 taken with the magnet removed to better illustrate the placement of the phase shifting element;

FIG. 3 is a perspective view of another embodiment of the instant invention;

FIG. 4 is a perspective view of still another embodiment of our invention shown with the magnet removed for purposes of illustration;

FIG. 4a is a view taken on the line 4A-4A of FIG. 4 and showing further the magnet and keeper element in position;

FIG. 5 is a perspective view of yet another embodiment of our invention; and

FIG. 6 is a plan view of the waveguides and magnet of FIG. 5 and illustrating in addition the placement of the ferromagnetic spinel cores in each waveguide.

In accordance with the present invention there is provided a pair of hybrid junction devices interconnected by two separate rectangular waveguide transmission paths. A ferromagnetic spinel element is disposed, asymmetrically, in at least one of these waveguide transmission paths and a magnetic field is set up across the waveguide to magnetize the spinel element transversely to the direction of energy propagation. The spinel element, so magnetized, will function to shift the phase of the electromagnetic energy in the waveguide without altering its plane-of-polarization. Because no rotation of the plane-of-polarization is attempted, rectangular waveguides can be used throughout.

In the more general case, the parameters, e.g., the position of the ferromagnetic spinel element within the waveguide, the physical dimensions of said spinel element and the intensity of the magnetic field, are chosen to provide a differential phase shift of 180° . That is, with a constant applied magnetic field, the phase shift in one direction minus the phase shift in the opposite direction should be 180° . Now, energy fed into a branch arm of one of the hybrid junction devices will divide equally between the separate waveguide transmission paths and eventually arrive at the second hybrid junction device either in-phase or 180° out-of-phase, depending upon which branch arm of the first hybrid junction device the energy was fed to as well as the phase shift produced by the magnetized ferromagnetic spinel element. Energy arriving in-phase at the second hybrid junction device will combine and leave together through a first branch arm of the second junction device. Whereas, energy arriving out-of-phase will combine and leave together through a second branch arm of this junction device. Now assuming energy is reinserted into the branch arm through which the initial energy left the system, this energy will likewise divide equally between the separate waveguide transmission paths and eventually arrive back at the first hybrid junction device. This return energy, however, because of the differential phase shift resulting from the non-reciprocal characteristics of the magnetized spinel element, will not leave through the first-mentioned branch arm but rather will combine and leave through the other branch arm of the first hybrid junction device. The applicability of such a circuit, particularly as a passive duplexer or isolator in a pulsed or C.W. radar system, is thought apparent.

Referring now to FIG. 1 in detail, a first hybrid junction device of the magic-tee type is shown at 5 having collinear arms 6 and 7, a first branch arm 1 and a second branch arm 2. Associated with it by two separate waveguide transmission paths is a second magic-tee type hybrid junction device 8 having two collinear arms 9 and 10, a

first branch arm 3 and a second branch arm 4. Arms 7 and 10 of these two junction devices are interconnected by a section of rectangular waveguide 11, and arms 6 and 9 are interconnected by a section of rectangular waveguide 12. To aid in explaining the operation of the device, it shall be assumed that these separate rectangular waveguide transmission paths are of equal lengths. However, as will become more apparent at the conclusion of this explanation, this embodiment, as well as the others illustrated in other figures of the drawings, can be used satisfactorily with rectangular waveguide sections differing in length by an integral number of half wavelengths.

Partially disposed within the waveguide 12 is a dielectric phase shifting element 13. For reasons to be later set forth, the extent to which this slab of dielectric material projects into the waveguide can be adjusted to provide a predetermined phase shift in the propagated energy. Such a phase shifter of course possesses reciprocal characteristics.

Disposed within waveguide 11 is a core 14 of ferromagnetic spinel material. As is more clearly illustrated in FIG. 2, core 14 is asymmetrically positioned in the waveguide. An electromagnet 15 having poles 16 and 17 is positioned so that the rectangular waveguide is between poles 16 and 17 and within the air gap. A solenoid 18 is wound around the right portion of the electromagnet 15 and a variable source of direct current 19 is coupled to the solenoid to provide an adjustable magnetic field transverse to the direction of propagation of electromagnetic energy through the waveguide. In practice, the electromagnet is generally arranged so that its field parallels the "E" vector of the wave being propagated through the waveguide, but this is not critical and the magnet could be rotated about the axis of the guide by as much as 90° if desired. This, of course, may necessitate a change in location and size of the ferromagnetic spinel material. With such an arrangement it is understood that the waveguide will be made of brass or some other diamagnetic material and the core 14 will be located within the transverse magnetic field within the waveguide.

To better understand the operation of the invention, an explanation of the non-reciprocal, phase-shifting device utilized herein will be set forth. The phase shifter itself is the subject of a patent application entitled "Microwave Phase Shifting and Attenuation Device," Serial No. 389,896, filed November 2, 1953 in behalf of H. N. Chait and M. L. Kales. Reference should be had therefore to this earlier application for a detailed discussion of the phase shifter per se. Basically, this non-reciprocal phase shifter comprises a length of rectangular waveguide, a transverse magnetic field established within said waveguide and a core member of ferromagnetic spinel material located in said transverse field and asymmetrically disposed with respect to the longitudinal axis of the waveguide. That is, the core is positioned closer to one of the narrow walls of the waveguide than to the other. This arrangement possesses non-reciprocal phase shifting characteristics, the phase shift for one direction of propagation of electromagnetic energy differing from that for the other direction of propagation. The degree of phase shift in any direction has been found to be determined by several factors the most important of which are the direction and intensity of magnetization of the ferromagnetic spinel core, the position of the core within the waveguide, and the length and cross-sectional area of the ferro-spinel.

Should the direction of the static magnetizing field be reversed, by reversing the direction of current flow through the solenoid, the direction of propagation for which the largest degree of phase shift occurs will be reversed. The same result occurs if the spinel core is moved to the other side of the longitudinal or central axis of the waveguide. And, if both the direction of the magnetizing field and the position of the core are changed, as suggested above, the direction of propagation for which the largest degree of phase shift occurs will not change.

While the strength of the magnetic field necessary to produce the desired phase shift will depend on the size and shape of the spinel core and its location in the waveguide, it may be desirable to work with a magnetic field of sufficient intensity to drive the spinel core beyond magnetic saturation. In this manner minor fluctuations in the supply current will not affect the operation of the system.

Lastly, with regard to the ferromagnetic spinel core, it is desirable, though not a necessity, that the core be of sufficient height to contact the inner surfaces of the waveguide, see FIG. 2. In this way, the heat energy which would develop in the core is readily dissipated through the waveguide. This maintains the core at a substantially constant temperature thus insuring uniform operation of the system even under extended periods of use.

Returning to the embodiment of the invention illustrated in FIG. 1, after the core, of predetermined size and shape, has been properly positioned in the waveguide the magnetic field will be adjusted to provide a differential phase shift of 180°. That is, if the energy propagated in one direction is shifted say 10° the energy traveling in the other direction will be shifted 190°. For purposes of explanation it shall be assumed that the energy traveling from junction device 8 to junction device 5 is retarded 180° more than the energy traveling in the opposite direction. Thus electromagnetic energy inserted into branch arm 1 will be divided equally in the hybrid junction device 5 and will appear at collinear arms 6 and 7 as equal in phase components. By adjusting the dielectric phase shifter to provide the same degree of phase shift to the energy in waveguide 12 as that resulting from the spinel core in waveguide 11, these equal components will arrive at the collinear arms 9 and 10 in-phase. At junction device 8 the components will combine and leave the system through branch arm 3 with only a negligible amount of energy appearing in branch arm 4.

Now, should the energy or some portion of it, after being used in a system exterior to that illustrated in FIG. 1, be reinserted into arm 3 it will divide in junction device 8 and will appear in collinear arms 9 and 10 as equal in-phase components. After retracing their previous course through waveguides 11 and 12 the energy components will arrive at collinear arms 6 and 7, but will however be 180° out-of-phase due to the differential phase shifting action of magnetized core 14. The out-of-phase energies will then combine and leave the system through branch arm 2, only a negligible amount of energy appearing in branch arm 1.

It will be apparent that the same performance, as that recited above, can be achieved by initially inserting the energy into branch arm 2 rather than arm 1. In this case, the energy will combine at junction device 8 and leave the system through branch arm 4.

From the foregoing the uses to which such a circuit arrangement can be put is thought apparent. For example, for use with a radar system the transmitter would be coupled to branch arm 1, the receiver to branch arm 2, and the antenna to branch arm 3. So connected the circulator described would serve as a passive duplexer.

In using the circuitry shown in FIG. 1 in a radar system, as an added protection it might be desirable to insert a T.R. box in branch arm 2. Thus the receiver would be additionally protected from any of the high powered transmitted energy which may leak into branch arm 2 from arm 1. In conjunction with this, a dummy load can be connected to branch arm 4. Thus, any high powered energy leaking into branch arm 2 would fire the T.R. box and hence be reflected. This energy upon reflection would appear in collinear arms 6 and 7 as equal, out-of-phase components. These components after traversing the separate waveguide transmission paths would arrive at arms 9 and 10 out-of-phase and hence would combine in branch arm 4 and be absorbed by the dummy load coupled thereto.

Turning to the embodiment illustrated in FIG. 3, it will

be noted that this circuit arrangement is somewhat similar to that illustrated in FIG. 1. In this figure, a first hybrid junction device of the folded magic-tee type is shown at 35 having folded arms 36 and 37 and a pair of branch arms 31 and 32. Associated with it by two separate waveguide transmission paths is a second folded magic-tee type hybrid junction device 38 having folded arms 39 and 40 and a pair of branch arms 33 and 34. Arms 37 and 40 and arms 36 and 39 are interconnected by two parallel sections of rectangular waveguide 41 and 42, respectively. Although not shown in the figure, it is understood that a dielectric phase shifter would be adjustably positioned in waveguide 42.

Asymmetrically positioned in waveguide 41 is the core 44 of ferromagnetic spinel material. Electromagnet 45 is positioned so that waveguide 41 lies between poles 46 and 47. Solenoid 48 and the variable current supply 49 supply the necessary transverse magnetic field. In this embodiment, as well as in the other embodiments of the invention, the spinel core element and the dielectric phase shifter can be located at any position along their respective waveguides.

Folded magic-tee type junction devices function in a manner similar to the magic-tee devices illustrated in FIG. 1. For example, electromagnetic energy inserted into branch arm 31 will be divided equally in the junction device 35 and will appear at the folded arms 36 and 37 as equal in-phase components. Likewise, equal in-phase energy components arriving at the folded arms 39 and 40 will combine and leave the system through branch arm 33. Since this embodiment therefore functions in a manner similar to the circuit arrangement of FIG. 1 further explanation thereof is considered unnecessary.

Referring now to FIGS. 4 and 4A, another embodiment of this invention is shown therein. Initially it should be noted that a different type of four terminal hybrid junction device has been employed herein. These four terminal junction devices are known as directional couplers and are designated in the figure by reference numerals 67 and 68. The directional coupler type junction device 67 has branch arms 61 and 62 and waveguide coupling arms 71 and 72. Associated with it by two separate transmission paths is the second directional coupler type junction device 68 having branch arms 63 and 64 and waveguide coupling arms 73 and 74. Arms 71 and 73 of these two junction devices are interconnected by rectangular waveguide 65, and arms 72 and 74 are interconnected by rectangular waveguide 66.

While the above designation has been employed to retain a consistent terminology throughout the specification, it should be apparent that in practice the embodiment can comprise simply two adjacent parallel rectangular waveguide sections interconnected by means of coupling holes 67, 68 or the like.

The junction devices of this embodiment are of the 3 db. directional coupled type, the 3 db. signifying the fact that energy arriving at the coupler will be equally divided between the two paths. In this regard, the magic-tees discussed above are likewise 3 db. junction devices. Further, while the directional couplers have been shown as comprising several adjacent holes, there are any number of arrangements of holes and slots for providing the desired coupling effect. For a more detailed discussion of directional couplers, attention is invited to Mumford: Directional Couplers, 35 Proc. of the I.R.E. 160 (1947); and Riblet: A Mathematical Theory of Directional Couplers, 35 Proc. of the I.R.E. 1307 (1947). For use with the present invention, the couplers should be designed to provide the energy, in going from one waveguide to the other, with a 90° phase shift.

Two asymmetrically disposed ferromagnetic spinel cores 69a and 69b are placed in waveguide 65 to provide the desired 180° differential phase shift. While in FIGS. 4 and 4A these cores are shown as being identical in size and shape they can, if desired, possess different

configurations. As illustrated in FIG 4A, the electromagnet 70, the magnetic circuit of which is completed by spinel cores 69a—69b and keeper element 75, may be utilized to furnish the requisite magnetic field. Inasmuch as the direction of magnetization of the spinel core 69a is opposite that of core 69b, a non-reciprocal phase shifter is provided.

As with the other embodiments, it may be necessary to provide waveguide 66 with an adjustable dielectric phase shifting element. For an understanding of the invention however it may be assumed that in one direction of energy propagation the spinel core will have negligible phase shifting effect, thus eliminating the need for the dielectric phase shifter. Also, as with the other embodiments, neither the coupler junction devices 67, 68 nor the spinel cores 69a—69b are necessarily placed at any particular position along the length of the waveguides. Nor for that matter is it necessary that the couplers be symmetrically disposed on either side of the ferrite cores.

Electromagnetic energy inserted into the branch arm 61 will upon arrival at the directional coupler type junction device 67 divide equally and will appear in waveguides 65, 66 as equal 90° out-of-phase components. As has been explained previously, the couplers are designed to provide this degree of phase shift. Continuing, it will be assumed for purposes of the present explanation that the spinel cores 69a—69b produce no shift in the energy traveling in the direction of junction device 68 but will retard the energy traveling in the direction of junction device 67 by 180°. In this limited case therefore it is unnecessary to provide the guide 66 with a dielectric phase shifter. The energy components thus arrive at the directional coupler type junction device 68 as equal 90° out-of-phase components, the energy in waveguide 66 leading that in waveguide 65. The 90° leading component in waveguide 66 would upon traversing the coupling junction device 68 gain an additional 90° in-phase and thus would appear in branch arm 63 as an equal 180° out-of-phase component. Whereas, the energy in waveguide 65 will, upon traversing the coupling junction device 68, gain 90° phase and thus will appear in branch arm 64 in phase with the energy component therein. Thus the components combine and leave the system through output branch 64, none appearing in branch arm 63.

Energy reinserted into branch arm 64 will upon reaching the directional coupler type hybrid junction device 68 divide equally and appear in waveguides 65, 66 as equal 90° out-of-phase components, the energy in waveguide 65 leading by 90° that in waveguide 66. However, after the 180° phase retardation, provided by the magnetized spinel cores 69a—69b, the energy component in waveguide 65 lags by 90° the energy component in waveguide 66. Upon arriving at the directional coupler type junction device 67 these energies will combine and leave the system through branch arm 62. The energy from waveguide 66 coupled to waveguide 65 would be 180° out-of-phase with the energy in waveguide 65 and since equal amplitude 180° out-of-phase components cancel each other, input branch arm 61 receives no energy.

As explained above with regard to the embodiment of FIG. 1, should this last described embodiment or any of the other embodiments be used in a radar system, it would be desirable, for added protection, to provide a T.R. box in the receiver connected waveguide. In the present case a T.R. box would be placed in branch arm 62 and a dummy load connected to branch arm 63. The transmitter would of course be coupled to input branch arm 61 and the antenna to branch arm 64.

It should be clear at this point that any of the commonly known and used hybrid junction devices can be used in place of those illustrated in the various figures. For example, the folded magic-tee type junction devices of FIG. 3 could be substituted for the directional couplers of FIG. 4, and vice versa.

Lastly, with reference to FIGS. 5 and 6 another embodiment of this invention is illustrated therein. In FIG. 5, a first hybrid junction device of the folded magic-tee type is shown at 85 having folded arms 86 and 87, and first and second branch arms 81 and 82. Associated with it by two separate waveguide transmission paths is a second hybrid junction device of the directional coupler type. This second hybrid junction device is shown at 91 having branch arms 83, 84 and waveguide coupling arms (undesigned). These waveguide coupling arms, in practice, constitute part of waveguides 88 and 89, as does branch arms 83 and 84. Waveguide 88 is coupled to folded arm 86 and waveguide 89 to arm 87. The directional coupler junction device 91 provides the energy, in going from one waveguide to the other, with a 90° phase shift.

Asymmetrically disposed in waveguides 88 and 89 are ferromagnetic spinel cores 90(a) and 90(b). Electromagnet 95 is positioned so that the waveguides 88 and 89 lie between poles 96 and 97. Solenoid 98 and the variable current supply 99 supply the necessary transverse magnetic field. After the spinel cores of predetermined size and shape have been properly positioned in their respective waveguides the magnetic field will be increased to provide a 90° differential phase shift for each waveguide. Thus, the phase shift for energy traveling in one direction will be 90° larger than the phase shift in energy traveling in the opposite direction ($\theta_A = \theta_B + 90^\circ$). However, because the positioning of the cores differ for each waveguide, the direction of propagation of energy for which the largest degree of phase shift occurs is different for each waveguide. Again for convenience in explanation it will be assumed that the phase shift in the one direction (θ_A) is negligible, thus the phase shift in the other direction (θ_B) is -90°, which is in effect a phase retardation; see FIG. 5. Therefore, the largest degree of phase shift (θ_B) occurs for energy in waveguide 89 when the energy is traveling toward the coupler type junction device 91. Whereas, for the energy in waveguide 88 the largest degree of phase shift occurs when the energy is traveling toward the magic-tee type junction device 85.

Electromagnetic energy inserted into branch arm 81 will be divided equally in the hybrid junction device 85 and will appear at folded arms 86 and 87 as equal in-phase components. These equal, initially in-phase components will travel the length of their respective waveguide sections and arrive at the directional coupler type junction device 90° out-of-phase. This relative shift is due to the phase retardation produced by the spinel core located in waveguide 89. At junction device 91 the components combine and leave the system through output branch arm 84 in the manner previously described. The 180° out-of-phase components in branch arm 83 would of course cancel and thus no energy appears in this arm.

Energy reinserted into branch arm 84 will divide equally in the junction device 91 and will appear in waveguide sections 88 and 89 as equal 90° out-of-phase components, the energy in waveguide 89 leading that in waveguide 88. These components will arrive at hybrid junction device 85, however, as 180° out-of-phase components due to the 90° phase retardation of the energy in waveguide 88 provided by magnetized spinel core 90(a). The 180° out-of-phase components will then combine and leave the system through branch arm 82 with negligible energy appearing in branch arm 81.

With regard to this last embodiment, it should be noted that the junction devices may be interchanged if desired or other types of hybrid junction devices may be substituted, the only requirement being that for broad band operation the junction devices be equally as broad banded

as the phase shifter. The invention, however, in no way depends upon the functioning of any one particular type of hybrid junction device.

Although not previously stated, it will be apparent to one skilled in the art that an impedance match should be preserved between the various junction devices and the waveguides associated therewith. Further, when using the spinel cores, tapered transition elements disposed on either side of the core will undoubtedly be necessary to reduce reflections.

This invention is not to be considered as limited to the geometry of the ferromagnetic spinel cores illustrated in the drawings; the spinel cores may be spherical, toroidal, conical, or any of a number of other shapes and configurations.

Obviously, many other modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claim the invention may be practiced otherwise than as specifically described.

What is claimed is:

A microwave circulator comprising a first hybrid junction of the variety having first and second pairs of circuit arms and adapted to divide microwaves applied to either circuit arm of said first pair thereof into substantially equal portions to exit via said second pair thereof in phase quadrature; a second hybrid junction of the variety having first and second pairs of circuit arms and adapted to divide microwaves applied to a selected circuit arm of said first pair thereof into substantially equal portions to exit said second pair thereof in phase opposition; dual path waveguide means separately connecting respective arms of said second pairs of circuit arms of said first and second hybrid junctions respectively; said dual path waveguide means including differential phase shift means for shifting the phase of wave energy in one of said paths of said waveguide means with respect to the phase shift introduced to wave energy in the other of said paths of said waveguide means by a phase angle of substantially 90 degrees for propagation in one direction along said paths of said waveguide means; said differential phase shift means being nonreciprocal and adapted for shifting the phase of wave energy propagating in a direction opposite to said one direction in said one of said paths of said waveguide means with respect to the phase shift introduced to wave energy propagating in said opposite direction in said other path of said waveguide means by a phase angle of substantially 90 degrees.

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