

Aug. 26, 1958

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2,849,685

NON-RECIPROCAL MULTIBRANCH WAVE GUIDE COMPONENT

Filed Aug. 17, 1953

3 Sheets-Sheet 1

FIG. 1

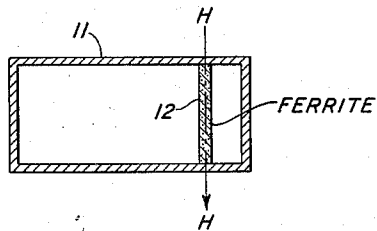


FIG. 2

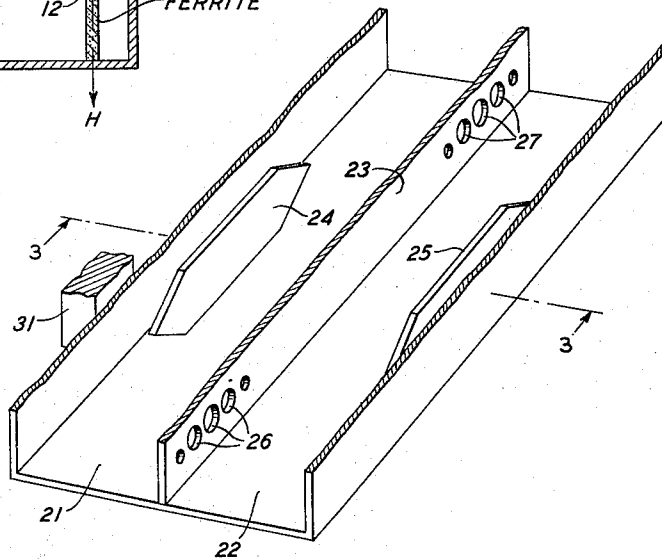
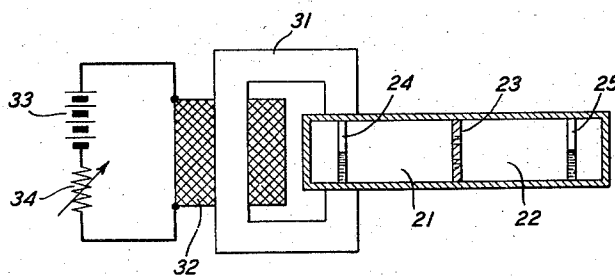


FIG. 3



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FIG. 4

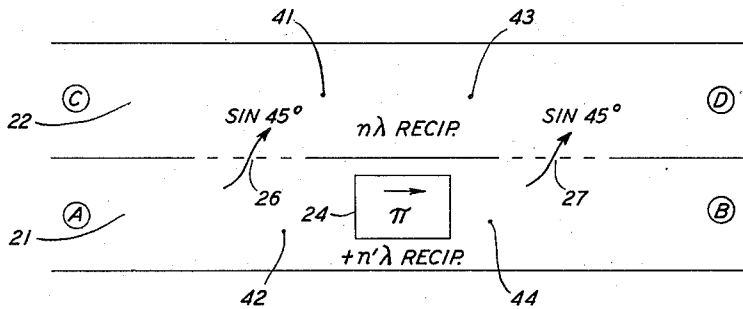


FIG. 5

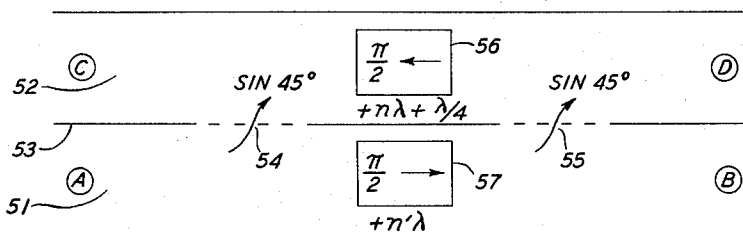
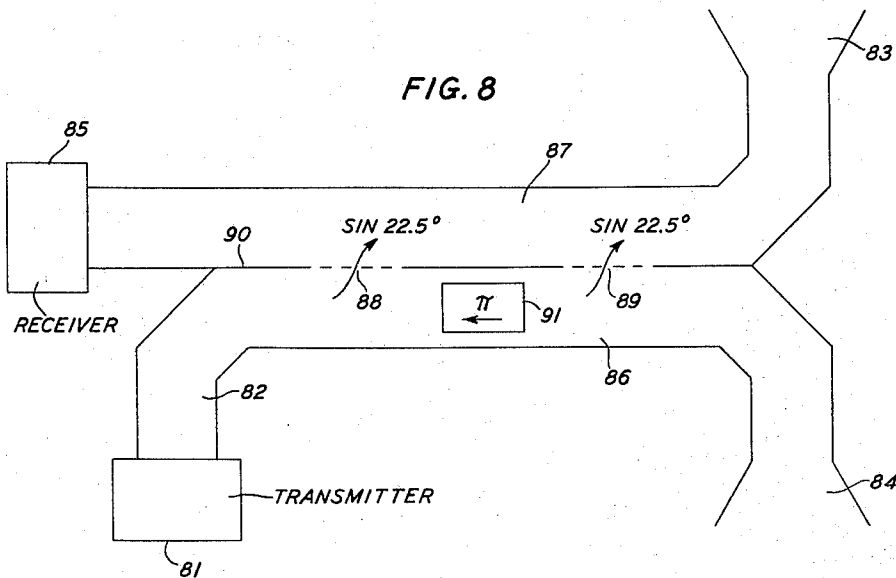


FIG. 8



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FIG. 7

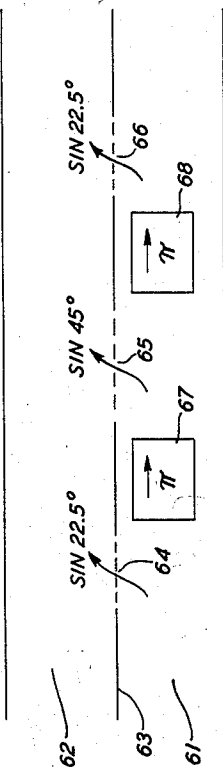


FIG. 6

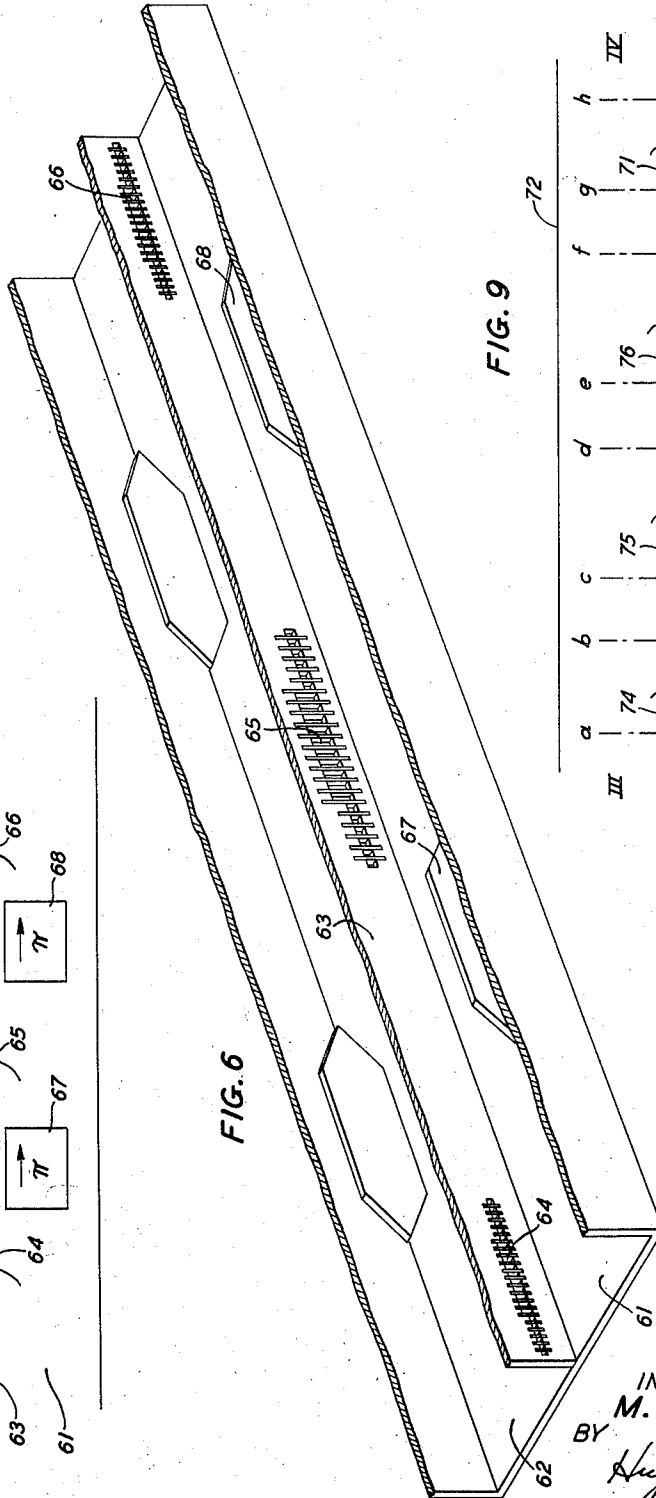
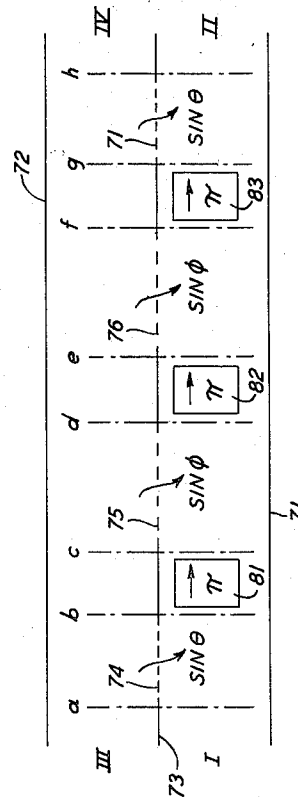


FIG. 9



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NON-RECIPROCAL MULTIBRANCH WAVE GUIDE COMPONENT

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Application August 17, 1953, Serial No. 374,511

11 Claims. (Cl. 333—10)

The present invention relates to multibranch waveguide components which have nonreciprocal properties.

The so-called "Theorem of Reciprocity" states that:

"In any network composed of linear impedances, if an electromotive force E applied between two terminals produces a current I at some branch in the network, then the same voltage E acting at the second point in the circuit, will produce the same current I at the first point."

As applied to a waveguide unit having three or more terminals, this theorem indicates that if electromagnetic energy applied at a first terminal appears at a second terminal, then energy applied to this second terminal would appear at the first terminal. In nonreciprocal multibranch waveguide circuits, however, these relationships do not hold and energy applied at the second terminal might appear at still another terminal, or the energy could be split between the first terminal and another terminal. Nonreciprocal multibranch waveguide components can be used for many purposes including, for example, the coupling of both a transmitter and a receiver to a single antenna. In such an arrangement, energy from the transmitter is coupled in its entirety to the antenna and simultaneously energy received at the antenna is coupled solely to the receiver.

It has previously been proposed to construct a nonreciprocal multibranch circuit employing magic tee hybrid junctions and a Faraday rotation nonreciprocal element (see C. L. Hogan's article "The microwave gyrator," Bell System Technical Journal, volume 31, January 1952, pages 1-31). However, such a structure is somewhat cumbersome and bulky, as it involves the mutually orthogonal arms of the magic tee, the rectangular to round transitions and the large magnet of the Faraday effect rotator, and the necessary waveguide fittings to interconnect the foregoing elements.

Accordingly, a principal object of the present invention is to simplify nonreciprocal multibranch circuits.

A known nonreciprocal multibranch circuit of the prior art has employed a single pencil of ferromagnetic material mounted in dielectric as the non-reciprocal element. Although this type of device operated satisfactorily at relatively low power levels and at a given frequency, changes in ambient temperature at high power levels or other changes in operating conditions severely impaired the operating qualities of the units.

A collateral object is to reduce the adverse effect of temperature, frequency or other deviations on the operating qualities of a non-reciprocal multibranch waveguide component.

In accordance with the invention, a nonreciprocal multibranch waveguide component is made up of two adjacent waveguides which have appropriate coupling along their lengths and at least one non-reciprocal phase shifting element associated with one of the waveguides. More specifically and in accordance with one illustrative embodiment of the invention discussed in detail hereinafter, two rectangular waveguides having a common wall

are provided with spaced groups of apertures through the common wall and with transversely biased ferromagnetic elements in one or both of the guides between the groups of apertures. With the groups of apertures being of the directional coupler type and the transversely biased ferromagnetic elements providing non-reciprocal phase shift, the result is a simple, compact nonreciprocal multibranch circuit having excellent stability of operation over a broad range of frequencies and temperatures.

In the prior art nonreciprocal multibranch waveguide circuits, the coupling structures are relatively inflexible and can only couple energy in its entirety from one terminal to another. This is a result of the standardized nature of the sub-component hybrid junctions which have been employed in these structures.

Another advantage of the present invention lies in its applicability to microwave systems requiring nonreciprocal power splitting as well as to waveguide coupling arrangements in which the input power is coupled in its entirety to a single output terminal. This feature, which results from the use of directional coupling apertures of a particular configuration, is particularly useful in multiple antennae wave-transmission systems.

Other objects, features and advantages will be developed in the course of the detailed description of the drawings, in which:

Fig. 1 is a cross-sectional view of a nonreciprocal phase shifter;

Fig. 2 is a cut away isometric view of a rectangular waveguide circulator in accordance with the invention;

Fig. 3 is a cross-sectional view of the device of Fig. 2 taken along line 3-3 of that figure;

Fig. 4 is a schematic representation of the circulator of Figs. 2 and 3;

Fig. 5 shows an alternative circulator in which two 90 degree phase shifting elements are employed instead of the single 180 degree phase shifter shown in Figs. 2 through 4;

Fig. 6 is an isometric representation of a broadband circulator;

Fig. 7 is a schematic diagram of the device of Fig. 6;

Fig. 8 shows a nonreciprocal multibranch coupler in a waveguide circuit; and

Fig. 9 represents a circulator having excellent stability of operation.

Referring more particularly to the drawings, Fig. 1 shows a hollow waveguide 11 having an element of ferromagnetic material 12 located therein. When this ferromagnetic element, which may be, for example, a polycrystalline ferrite element, is transversely magnetized as indicated by the arrow H in Fig. 1, the phase shift for one direction of propagation through the waveguide 11 is greater than for the opposite direction of propagation. This phenomenon is now well known and is discussed in greater detail in S. E. Miller application Serial No. 362,193, filed June 17, 1953. The ferrite element 12 is located asymmetrically in the waveguide and is preferably spaced from the side wall but by a distance not greater than one-quarter of the distance across the waveguide. As the length of the septum 12 is increased, the amount of the difference in phase shift for the two directions of propagation is correspondingly increased. At the critical length of the ferrite septum, the difference in phase shift for the two directions of propagation is exactly 180 degrees as set forth in greater detail in the above-noted S. E. Miller application. A device which has 180 degrees difference in phase shift for the two directions of propagation has been termed a gyrator.

While the structure of Fig. 1 is perhaps the simplest nonreciprocal phase shifting arrangement for rectangular waveguides, other configurations of ferromagnetic material and steady transverse magnetic field will also pro-

duce this result. For example, referring to Fig. 1, the non-reciprocal effect would be enhanced if another element of ferrite biased in the upward direction were placed adjacent the left-hand narrow side wall of the waveguide 11. When the waveguide is filled with ferrite and an asymmetric transverse magnetic field applied thereto, a similar result obtains. In addition it may be noted that the transverse magnetic field may be supplied by an external magnetic field from a permanent magnet or an electromagnet, or by permanently magnetizing the ferromagnetic septum itself. Still other alternative structures and an analysis of their operation may be found in the above identified application of S. E. Miller.

Figs. 2 through 4 represent a nonreciprocal multibranch waveguide circuit in accordance with the invention which makes use of nonreciprocal phase shifting elements of the type disclosed in Fig. 1. Fig. 2 shows two parallel waveguides 21 and 22 which have a common narrow wall 23. In the waveguide 21 is a transversely biased ferromagnetic septum 24 having 180 degrees difference in phase shift for the two directions of transmission through waveguide 21. A dielectric counterpoise 25 is located in waveguide 22 and is the same size and shape as the ferrite element 24. In addition, these two elements are symmetrically located with respect to the plane of the common wall 23 between the two waveguides. It is, however, not necessary that the counterpoise be of exactly the same form as the ferrite element, as long as it has substantially the same effective electrical length. Before and after the ferrite plate and the dielectric counterpoise the common wall 23 is apertured. These apertures 26 and 27 are of a type known as directional couplers and are described in articles by S. E. Miller and W. W. Mumford in the Proceedings of the Institute of Radio Engineers, volume 40, pages 1071-1078, September 1952, and by H. J. Riblet in the Proceedings of the Institute of Radio Engineers, volume 40, pages 180-184, February 1952.

Fig. 3 is a cross-sectional view along lines 3-3 of Fig. 2 and also shows the magnetic structure for magnetically polarizing the ferrite element. As shown in this view the biasing field for the ferrite septum 24 may be supplied by the electromagnet made up of the core 31 and the coil 32 energized by a suitable source of electric voltage 33 controlled by the variable resistance 34.

The operation of the nonreciprocal multibranch circuit may be more readily described with reference to Fig. 4 which is a schematic view of this device. In this figure it may be noted that the ferrite plate 24 is shown as a box with the Greek letter π and an arrow therein to indicate that this section of waveguide has 180 degrees more phase shift for transmission from left to right in the direction of the arrow than for the opposite direction of propagation. The directional coupling apertures 26 and 27 have the property that energy transmitted from terminal A will be split at the aperture 26 and will travel toward terminals B and D but no energy will be coupled to terminal C. This property of directional couplers is developed in detail in the above-noted article by W. W. Mumford and S. E. Miller.

Using two 3 db (.707 amplitude) coupling apertures at 26 and 27 it can be rigorously shown that energy applied at terminal A appears at terminal B; energy applied at terminal B appears at terminal C (not, as might be expected, at terminal A), energy applied to terminal C appears at terminal D, and finally, energy applied at terminal D appears at terminal A.

To see the physical reason why no energy applied at terminal A appears at terminal D, for example, the voltage amplitude and phase shift at various points through the waveguide structure must be traced. Starting with units voltage applied at terminal A the coupler 26 splits the power equally so that the peak voltage at point 41 and at point 42 is .707 of unity. The directional coupler structure 26 has the property of shifting the phase of wave energy passing through it by 90 degrees so the

wave at point 41 will be 90 degrees displaced in phase from that at point 42.

The symbols $n\lambda$ and $n'\lambda$ represent reciprocal phase shifts required to obtain a convenient length between the apertures 26 and 27. Therefore, at point 43 just before the aperture 27, the energy in the waveguide 22 will have been shifted by 90 degrees plus $n\lambda$ reciprocal phase shift, while the energy at the comparable point 44 of waveguide 21 will be shifted by 180 degrees plus $n'\lambda$ reciprocal phase shift. Inasmuch as $n\lambda$ and $n'\lambda$ are equal or differ by an integral number of full wavelengths, these phase shifts may be ignored. At the second directional coupling aperture 27 the power again splits with one-half of the energy in each waveguide being coupled to the opposite waveguide. More explicitly, when each of the two .707 amplitude waves are split, the result is two waves each having a voltage amplitude equal to .5 that of the original coherent source. The energy which passes from the waveguide 21 to the waveguide 22 will undergo another 90 degree shift and thus will be in 180 degree phase opposition to the portion of the energy in waveguide 22 which is not coupled back to the waveguide 21, and thus the two wave forms will completely cancel each other out. The energy from waveguide 22 which is coupled over to waveguide 21 will also undergo another 90 degree phase shift, and this will place it in phase with the energy in waveguide 21 and they will combine to give unity output at terminal B. By a similar procedure it can readily be developed that energy applied at terminal B will appear only at terminal C, etc., as set forth hereinbefore.

In the schematic diagram of Fig. 4 the slots 26 and 27 have arrows and the indication sin 45 degrees associated therewith. This indicates the amplitude of coupling (.707 amplitude) between the two guides. The product of the amplitude coupling per unit length times the length of the directional coupling apertures may be expressed as an angle and the coupling would then be proportionate to the sin of this angle. Full coupling is obtained if the sum of these angles is 90 degrees. Reference is made to the above-cited Miller-Mumford article for further details of this method of analysis.

The alternative arrangement of Fig. 5 shows two waveguides 51 and 52 having a common wall 53 and two spaced 3 db coupling apertures 54 and 55. Instead of the single 180 degrees nonreciprocal phase shift element employed in the device of Figs. 2 to 4, two 90 degree phase shifting elements 56 and 57, one in each of waveguides 51 and 52 are used in this structure of Fig. 5. However, as indicated by the symbol

$$\frac{\lambda}{4}$$

under the element 56 the effective electrical length of the waveguide 52 between coupling apertures must now be a quarter wavelength greater than the comparable section of waveguide 51. With this arrangement, the same circulator action is again obtained, with energy passing from terminal A to terminal B, B to C, C to D, and from D to terminal A, just as in the device of Figs. 2 through 4.

In Figs. 6 and 7 an improved version of the circulator is illustrated. In this case guides 61 and 62 have the usual common wall 63 and are provided with three coupling apertures 64, 65 and 66 and two gyrator elements 67 and 68. In this instance the directional coupling structures are of a broad band type such as are disclosed in the article by S. E. Miller and W. W. Mumford in the proceedings of the Institute of Radio Engineers, volume 40, pages 1071-1078, September 1952. By employing an additional nonreciprocal 180 degree phase shift section it will be shown that any change in the value of this phase shift, due to factors such as temperature or frequency variations, which affect both phase shift sections equally, is cancelled out to the first

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order. As contrasted with the circulators of Figs. 1 through 5, the structures of Figs. 6 and 7 show that for the cost of broad band coupling apertures and an extra 180 degree nonreciprocal section the overall stability of the device is greatly improved. In passing, it may be noted that the amplitude coupling of the slots 64, 65 and 66 are equal to sine 22.5 degrees, sine 45 degrees, and sine 22.5 degrees respectively. Because these angles add up to 90 degrees, this structure is a true circulator, and full coupling may be expected.

The device indicated schematically in Fig. 8 is a non-reciprocal multibranch coupling circuit which is not a true circulator. In this arrangement, the sum of the angles associated with the coupling slots only add up to 45 degrees, and therefore only part of the power is coupled over in a non-reciprocal manner. Thus, for example, power from the transmitter 81 is transmitted through the waveguide section 82 to two differently oriented antennae 83 and 84. Power picked up by the antenna 83, however, goes only to the receiver 85. The multibranch coupling circuit which makes this possible includes the usual parallel waveguides 86 and 87, the directional coupling apertures 88 and 89 through the common wall 90, and the gyrator element 91. The coupled apertures in the present instance, however, are 8.34 db (.383 amplitude) couplers and hence only one-half of the power is coupled across to the other waveguide in the entire coupling structure.

The circulator of Fig. 9 is patterned after the structures of Figs. 1 through 8 but has an additional gyrator section, and hence has an even higher order of stability than the circulator of Figs. 6 and 7. Structurally, the circulator has two parallel waveguides 71 and 72 having a common wall 73 which in turn has four sets of directional coupling slots 74 through 77. In each of the intervals between the coupling slots gyrator elements 81, 82 and 83 are located.

The exact manner of splitting the coupling between the various directional coupler slots can be calculated in the manner shown by the following example for the three section circulator of Fig. 9.

The amplitude coupling in the first and last sections is equal to $\sin \theta$, while the two middle sections each have a coupling equal to $\sin \phi$. In order that complete coupling take place in the desired direction, $2\theta + 2\phi$ must equal 90 degrees.

From the above it follows that $\cos 2\theta = \sin 2\phi$ and $\sin 2\theta = \cos 2\phi$. Let us assume that all the π sections have a phase shift of $\pi + \Delta$. With an input of unit amplitude at III, let us calculate the output at II. The following table shows how one proceeds, taking into account only differences in phase shift between top and bottom guides:

Table I

	At a	At b	At c	At d
Upper guide.	1	$\cos \theta$	$\cos \theta$	$\cos \theta \cos \phi + \sin \theta \sin \phi e^{i\Delta}$
Lower guide.	0	$j \sin \theta$	$-j \sin \theta e^{i\Delta}$	$[-j \sin \theta \cos \phi e^{i\Delta} + j \sin \phi \cos \theta]$

and so on until we reach the output at II. This is given by

$$\sin \theta \cos \theta \cos^2 \phi [1 - e^{i3\Delta}] - [\cos^2 \theta \sin \phi \cos \phi - \sin^2 \theta \sin \phi \cos \phi - \cos \theta \sin \theta \sin^2 \phi] [e^{i\Delta} - e^{i2\Delta}]$$

which we want to equal 0 + terms in Δ^3 and higher so as to depart from 0 at a minimum rate. We thus have an equation which we shall write for simplicity as

$$A - Be^{i\Delta} + Ce^{i2\Delta} + De^{i3\Delta}$$

It is well known that if A, B, C, D form a binomial relation, then the above equation will be equal to

$$A(1 - e^{i\Delta})^n$$

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which is equal to $+(j\Delta)^n$ + higher order terms since

$$1 - ne^{i\Delta} + \frac{n(n-1)}{1.2} e^{i2\Delta} - \frac{n(n-1)(n-2)}{1.2.3} e^{i3\Delta} + \dots + (-1)^n \frac{n(n-1)\dots 1}{1.2.3\dots n} e^{in\Delta} = (1 - e^{i\Delta})^n = (j\Delta)^2 + \dots$$

higher order terms

Therefore we can solve the equation for θ so as to obtain the binomial relation. The result is, after some trigonometric substitutions,

$$2 \sin^2 2\theta + 2 \sin 2\theta - 1 = 0$$

$$\text{or } \sin 2\theta = .366025$$

$$2\theta = 21.466^\circ$$

$$\theta = 10.73^\circ$$

$$2\phi = 68.534^\circ$$

$$\phi = 34.27^\circ$$

With this design the unwanted output at II with input at III will therefore be proportional to $(j\Delta)^3$ which is, of course, much smaller than for the single section circulator for which the output at II is proportional to $j\Delta$. The above scheme can be used for designing an n section circulator which will be compensated for changes in the π phase shift to $(j\Delta)^n$.

Concerning the materials used in the nonreciprocal phase shifting elements, they can be made from any suitable ferromagnetic material of low conductivity. When the term "low conductivity" is employed in the present specification and claims it means that the material in question has an overall resistivity of 10 to 100 ohm-centimeters or more. While polycrystalline ferrites are preferred, the phase shifting effect has been observed in other materials such as very finely divided iron particles in an insulating dielectric matrix. In regard to the structure of nonreciprocal phase shifting elements in each of the figures of the drawing, these may be of any known type, and specifically may be of any of the forms disclosed in conjunction with Figs. 1 through 4. For a more thorough treatment of these phase shifting phenomena, reference is again made to the application of S. E. Miller, Serial No. 362,193 which is assigned to the assignee of the present invention.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, a first and a second substantially parallel rectangular waveguide for electromagnetic wave energy having a common wall therebetween, " n " spaced directional coupling apertures through said common wall where n is greater than two, means including elements of gyromagnetic material magnetized transversely to said common wall interposed between said coupling apertures in at least one of said waveguides for shifting the phase of wave energy in said first waveguides with respect to wave energy propagating in said second waveguide by a phase angle in one direction of x degrees, said phase shift being nonreciprocal for shifting the phase of wave energy propagating in said first waveguide with respect to wave energy propagating in said second path in the reverse direction by a value of $[x - (n-1)(180)]$ degrees.

2. A combination as defined in claim 1 wherein said apertures are of such a configuration that there is an unequal division of power at one of said directional coupling apertures.

3. In a stable nonreciprocal multibranch waveguide component, two waveguides having longitudinally extending axes, three spaced regions of coupling between said two waveguides, and an element of gyromagnetic material

coupled to one of said waveguides and confined in each of the intervals between each of said coupling regions, said elements being magnetically biased transversely to the axis of said one waveguide.

4. In combination, two substantially parallel rectangular waveguides having a common wall, three spaced broadband directional coupling slots in said common wall, and nonreciprocal phase shifting elements coupled to one of said waveguides in each of the intervals between said directional coupling slots.

5. In a nonreciprocal multibranch waveguide component, two substantially parallel rectangular waveguides having longitudinally extending axes, a plurality of spaced directional coupling means for transferring a fraction of the energy in one of said waveguides to the other waveguide, at least one of said coupling means transferring a fraction not greater than $\sin 22.5$ degrees and at least one paramagnetic element of low conductivity coupled to at least one of said guides in the interval between each pair of said directional coupling means, said element being magnetized transversely to the axes of said guides.

6. A waveguide component as set forth in claim 5 wherein there are at least three directional coupling means.

7. A waveguide component as set forth in claim 5 wherein there are two directional coupling means each of which is approximately 8.34 decibel couplers.

8. In combination, two waveguides having longitudinally extending axes, two spaced directional couplers interconnecting said waveguides, each of said couplers constituting means for transferring a minor fraction of the power in one of said waveguides to the other, said minor fraction being no greater than -8.34 decibels of the total power applied to said one waveguide, and nonreciprocal phase-shifting means coupled to at least one of said waveguides between said spaced couplers.

9. A nonreciprocal power-splitting waveguide component in accordance with claim 8 wherein each coupling structure is approximately an 8.34 decibel coupler and the entire unit divides the power input at one of the four terminals into two substantially equal parts.

10. A combination as set forth in claim 8 wherein said phase-shifting means is an element of ferromagnetic material of low conductivity magnetically biased transversely to the axis of said one waveguide.

11. A selective transmission system for propagating electromagnetic wave energy comprising first and second

four-branch power dividing networks, each of said branches having the branches thereof arranged in pairs with the branches comprising one pair being conjugate to each other and in coupling relation to the branches of the other pair, at least one of said networks being of directional coupler type introducing a 90-degree phase shift to wave energy coupled between said pairs, a first wave transmission path connecting a branch of one pair of branches of said first network to a branch of one pair of branches of said second network, a second wave transmission path separate from said first path connecting the other branch of said one pair of said first network to the other branch of said one pair of said second network, means including an element of gyromagnetic material interposed in both of said paths and magnetized transversely to the axes of said paths for shifting the phase of wave energy in said first path with respect to the phase shift introduced to wave energy in said second path by a phase angle for propagation in one direction along said paths of x degrees, said phase shift being non-reciprocal and capable at the same time of shifting the phase of wave energy propagating in a direction opposite to said one direction in said first path with respect to the phase shift introduced to wave energy propagating in said opposite direction in said second path by a value of $x-180$ degrees.

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