United States Patent

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[54] **BROADBAND CIRCULATOR WHEREIN DIFFERENTIAL PHASE SHIFT VARIES WITH FREQUENCY IN PREDETERMINED MANNER**

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[52] **U.S. Cl.** **333/1.1,** 333/24.1

[51] **Int. Cl.** **H01p 1/32,** H01p 5/12

[58] **Field of Search** 333/1.1, 24.1

[56] **References Cited**

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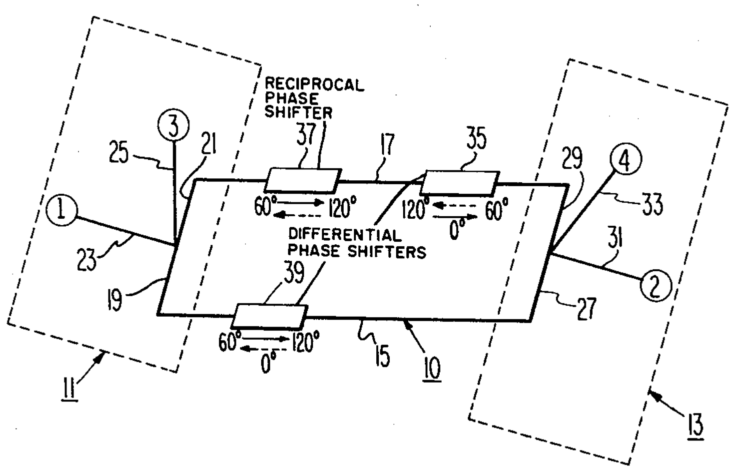
[57] **ABSTRACT**

A circulator includes a pair of magic tees and a pair of coupling paths therebetween. Each of the coupling paths includes a differential phase shifter. The differential phase shifter in a first path is arranged to provide a differential phase shift that increases with increase in frequency. The second differential phase shifter in the second path is arranged to provide a differential phase shift that decreases with increase in frequency. A reciprocal phase shifter is in the first path in series with the first differential phase shifter.

8 Claims, 5 Drawing Figures



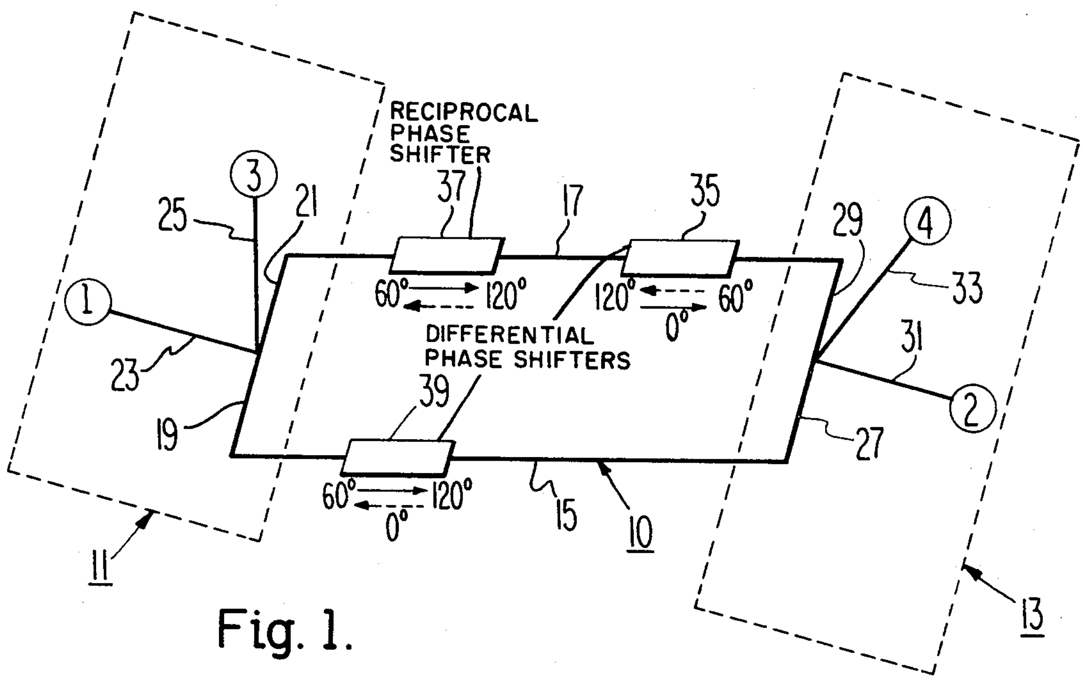
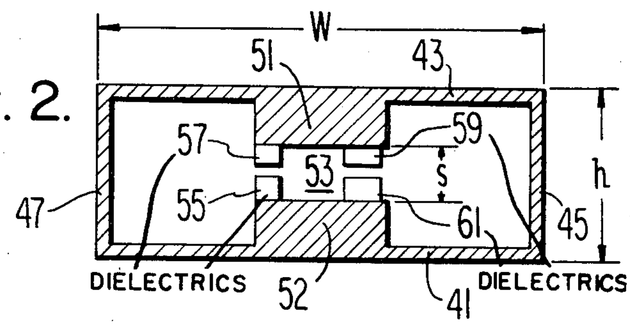


Fig. 1.

Fig. 2.



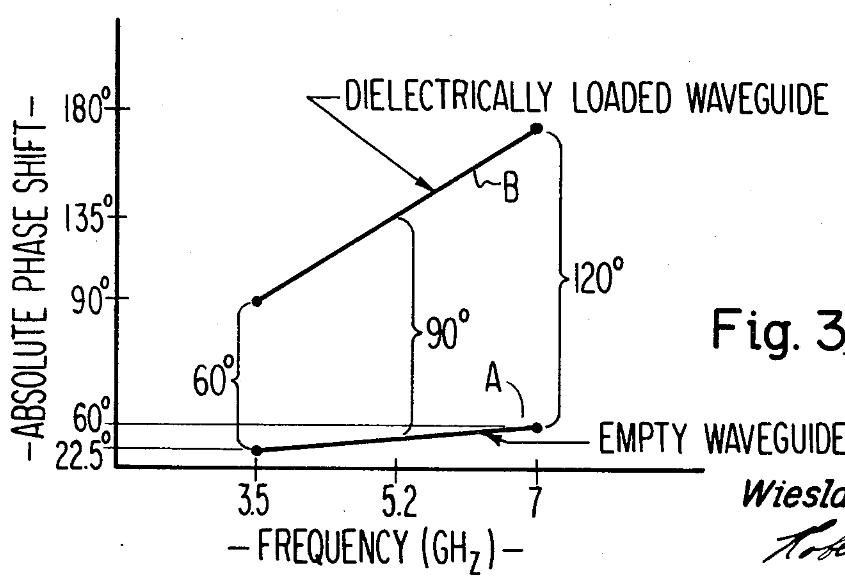


Fig. 3.

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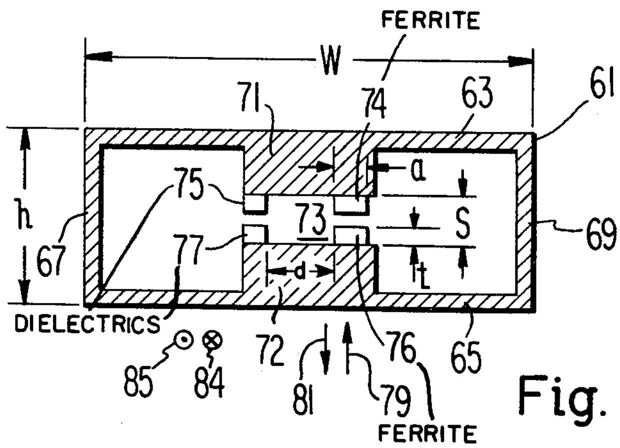

Fig. 4.

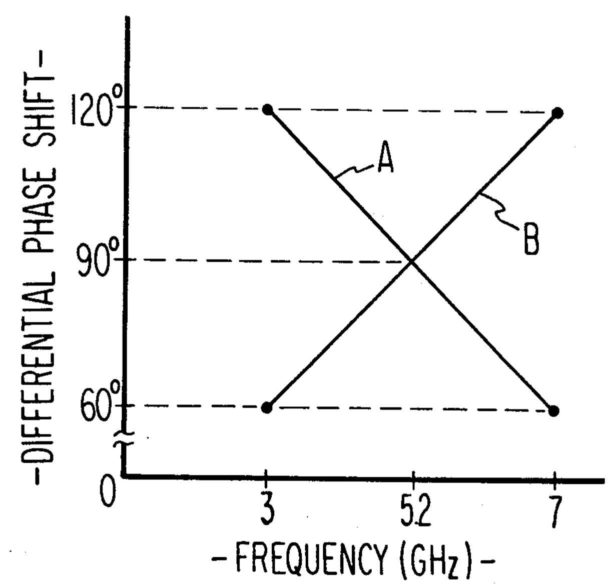

Fig. 5.

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BROADBAND CIRCULATOR WHEREIN DIFFERENTIAL PHASE SHIFT VARIES WITH FREQUENCY IN PREDETERMINED MANNER

The invention herein described was made in the course of or under a contract or subcontract thereunder with the Department of the Navy.

This invention relates to circulators and more particularly to a broadband circulator using differential phase shifters.

Circulators employing a nonreciprocal 180° ferrite phase shifter in one coupling path between a pair of hybrid couplers and a fixed section of dielectric in a parallel path between the hybrids are known. See FIG. 12–37 on page 590 of a book entitled "Microwave Ferrites and Ferrimagnetics" by Lax and Button, a McGraw-Hill Publication.

Also, it is known to provide a circulator where in a first of the paths between a pair of hybrid couplers there is provided a first 90° differential phase shifter in series with an extra line or reciprocal phase shifter section which provides an additional 90° nonreciprocal phase shift. In a second parallel path there is provided a second 90° differential phase shifter. The first 90° differential phase shifter in the first path provides an additional 90° phase shift for signals propagating in one direction in the first path relative to signals propagating in the same one direction in the second path. The first 90° differential phase shifter in combination with the 90° reciprocal phase shifter provides for signals propagating in the one direction 180° relative phase shift between the two paths. For signals propagating in a direction opposite the one direction, the second 90° differential phase shifter provides an additional 90° phase shift in the second path and the reciprocal phase shifter provides an additional 90° phase shift in the first path. Thus for signals propagating in the opposite direction through the two transmission paths, there is no difference in relative phase shift. This latter circulator using 90° differential phase shifters in contrast to the 180° nonreciprocal phase shifter described previously is dimensionally smaller and lighter and is less costly.

Broadband operation of this latter type of circulator device using 90° differential phase shifters was heretofore not possible because the extra length of line or reciprocal phase shifter section providing the reciprocal 90° phase shift does not maintain an additional 90° phase shift over a wide band of frequencies. Such an extra section of line or reciprocal phase shifter provides an increasing phase shift with frequency.

It is an object of this invention to provide an improved broadband circulator of the type that uses differential phase shifters, that is small, light and less costly.

Briefly, this and other objects of the present invention are provided by an improved broadband circulator of the type including a pair of transmission lines with a first means coupled to each end of the two transmission lines for providing at each end power splitting of signals applied thereto. A first of the transmission lines includes a first differential phase shifter and a reciprocal phase shifter. The second of the lines includes a second differential phase shifter. The reciprocal phase shifter however over a wide range of frequencies produces changes in phase shift with changes in frequency. An improved broadband circulator is provided by arranging the second differential phase shifter to provide a differential phase shift which increases with frequency and wherein the first differential phase shifter provides a differential phase shift that decreases with frequency. The amount of increase and decrease of differential phase shift with frequency is determined relative to the change in phase shift with frequency by the reciprocal phase shifter to provide no difference in the relative phase shift of signals propagating in one direction along the transmission lines and to provide a 180° difference in the relative phase shift of signals propagating in the opposite direction along the transmission lines.

For a better understanding of the invention, reference is made to the following description taken with the accompanying drawings in which:

FIG. 1 is a schematic diagram of a broadband circulator in accordance with the present invention,

FIG. 2 is a cross sectional view of a dielectrically loaded double ridge waveguide transmission line of the type used in accordance with one embodiment of the present invention,

FIG. 3 is a plot of absolute phase shift vs. frequency for the dielectrically loaded waveguide shown in FIG. 2,

FIG. 4 is a cross sectional view of a differential phase shifter in accordance with an embodiment of the present invention, and

FIG. 5 is a plot of differential phase shift vs. frequency for the differential phase shifters used in accordance with an embodiment of the present invention.

Referring to FIG. 1, there is illustrated a broadband circulator 10 in accordance with an embodiment of the present invention. The broadband circulator 10 comprises two magic tee hybrids 11 and 13 and two transmission line paths 15 and 17 therebetween. The magic tee hybrid 11 is made up of colinear arms 19 and 21, shunt H arm 23 and series E arm 25 joined at a common region. The magic tee hybrid 13 is likewise made up of colinear arms 27 and 29, shunt H arm 31 and series E arm 33. Transmission path 15 is coupled between colinear arm 19 of hybrid 11 and colinear arm 27 of hybrid 13. Transmission path 17 is coupled between colinear arm 21 of hybrid 11 and colinear arm 29 of hybrid 13. At the free end of H arm 23 is located port 1, at the free end of E arm 25 is located port 3. At the free end of H arm 31 is located port 2 and at the free end of E arm 33 is located port 4.

Along the transmission path 17, there is provided a differential phase shifter 35 in series with an additional length of line or reciprocal phase shifter 37. The additional length of line or reciprocal phase shifter 37 provides an additional phase shift to signals traveling in either direction along transmission path 17. Differential phase shifter 35 provides at the center operating frequency of the circulator 10, 90° more phase shift for signals propagating along transmission path 17 in the direction from right to left in FIG. 1 than for signals propagating in the opposite direction along transmission path 17 or for signals propagating in the right to left direction but along transmission path 15. A differential phase shifter 39 is provided along transmission path 15. The differential phase shifter 39 provides at the center operating frequency of the circulator 10, 90° more phase shift for signals propagating along transmission path 15 from left to right in FIG. 1 than for signals propagating in the opposite direction (right to left) along transmission path 15 or for signals propagating in the same direction (left to right) but along transmission path 17.

In one embodiment of the present invention, the entire circulator systems 10 uses double ridged waveguide. The magic tee hybrids 11 and 13 are of double ridged waveguide and the transmission paths or lines 15 and 17 are of equal physical length and are of double ridged waveguide.

Referring to FIG. 2, there is illustrated a cross section of a double ridged waveguide which in this case may be the additional length of line or reciprocal phase shifter 37. The waveguide comprises broad walls 41 and 43 and narrow walls 45 and 47. Along the broad walls 41 and 43 are ridges 52 and 51 which extend the longitudinal length of the waveguide. In the operation of double ridged waveguide, the electromagnetic field when applied to the waveguide, is primarily between the ridges 51 and 52. By the placement of these ridges 51 and 52 along the waveguide, the cutoff frequency for the dominant TE_{10} mode is lowered, and consequently, the waveguide is more broadband. Also, associated with double ridged waveguide systems is the relatively high power handling capability compared to single ridged waveguides. Therefore, by the use of a double ridge waveguide, a relatively high power and broad bandwidth circulator system is provided.

The magic tee hybrids may be double ridged waveguides as described in Ser. No. 55,057 filed July 15, 1970, by Wieslaw W. Siekanowicz and Robert W. Paglione. In this arrangement, the lower ridges of the colinear side arms and the H arm are connected to each other at the junction thereof. The upper ridges of each of the colinear side arms are connected to the nearest ridge of the E arm. The upper ridge of the H arm is connected by a first conductive rod to one of the colinear arms and by a second rod to the other colinear arm. Conventional rectangular waveguide magic tees may be used at the sacrifice of some bandwidth.

The transmission lines or paths **15** and **17** are of equal physical length double ridged waveguide sections. The additional electrical length of transmission line **17** is provided by the reciprocal phase shifter section **37** having pairs of dielectric members **55, 57, 59** and **61** as shown in FIG. **2** located in the gap **53** between the ridges **51** and **52**. This dielectrically loaded section of double ridged waveguide is referred to in the schematic of FIG. **1** as the reciprocal phase shifter **37**.

The dielectric member **55** extends from one cross sectional end of ridge **52** into the gap **53** and the dielectric member **57** extends from one cross sectional end of the ridge **51** into the gap **53**. The dielectric members **55** and **57** extend the longitudinal length of the waveguide section of the reciprocal phase shifter **37**. The dielectric constant ϵ of the dielectric material is relatively high, on the order of **30**, for example. By the placement of the high dielectric constant material members **55** and **57** as shown and described, the electromagnetic wave energy is primarily confined within the region of the dielectric members **55** and **57** and the gap therebetween. The dielectric members **59** and **61** at the opposite end of the ridges **51** and **52**, respectively, also extend into the gap **53**. A reciprocal phase shifter section **37**, as described above, was constructed and had the following values:

Width W from narrow wall **47** to narrow wall **45** is 1.490 inch,
Height h from broad wall **43** to broad wall **41** is 0.688 inch,
Ridge spacing S is 0.290 inch,
Members **55** and **57** are 0.090 by 0.090 inch, extend length of section **37**, the dielectric constant is 30, (TiO_2 material),
Members **59** and **61** are 0.150 by 0.090 inch, extend length of section **37**, the dielectric constant is 16 (TiO_2 material); and
Length of additional line **37** is 0.250 inch.

Referring to FIG. **3**, there is illustrated the absolute phase shift for the reciprocal phase shifter section **37** described above with signals applied thereto between 3.5 to 7 GHz (Gigahertz). Plot A of FIG. **3** is a plot of the phase shift vs. frequency for a double ridge waveguide section like that described above without the dielectric loading. Plot B is a plot of phase shift vs. frequency for the dielectrically loaded double ridge waveguide described above. At about the center operating frequency of the circulator (5.2 GHz), this reciprocal phase shifter section **37** provides about 90° additional phase shift as compared to a nondielectrically loaded or empty waveguide of the same dimension. As illustrated by plot B, however, over the frequency range of 3.5 to 7 GHz (Gigahertz), this amount of additional phase shift provided by the dielectric loading of section **37** ranges from 60° at 3.5 GHz to 120° at 7 GHz. This change in the amount of additional phase shift makes this type of circulator normally unsuitable for broadband operation, for such prior systems are dependent on this additional phase shift being constant at 90°.

In accordance with applicant's teaching herein, a broadband circulator **10** is provided by arranging the differential phase shifter **35** to provide a differential phase shift that decreases a given amount with increase in frequency and by arranging the differential phase shifter **39** to provide a differential phase shift that increases a given amount with increase in frequency. The amount of increase and decrease of phase shift with changes in frequency of the phase shifters is determined relative to the change in phase shift with frequency by the reciprocal phase shifter **37** to provide over a wide band of frequencies, no difference in the relative phase shift of signals propagating in one direction along the two paths **15** and **17** and to provide a 180° relative phase difference for signals propagating in the opposite direction along the transmission paths **15** and **17**.

Referring to FIG. **4**, there is illustrated in cross section a differential phase shifter **35** using a double ridged waveguide **61**. The waveguide **61** comprises broad walls **63** and **65** and narrow walls **67** and **69**. Along the broad walls **63** and **65**, midway between the narrow walls **67** and **69**, are ridges **71** and **72** which extend the longitudinal length of the waveguide section **35**. Because of ridges along the waveguide, the cutoff frequency for the dominant TE_{10} mode is lowered, and consequently, the waveguide is more broadband. In a double ridged waveguide, the electromagnetic field when applied to the waveguide is primarily between the ridges. A pair of dielectric members **75** and **77** are placed in the gap **73** between the ridges **71** and **72**, with member **75** extending from one end of ridge **71** and member **77** extending from ridge **72**. As in the case of the dielectrically loaded phase shifter section **37**, members **75** and **77** are of relatively high dielectric constant material to confine the electromagnetic wave when applied thereto, primarily within the dielectric members **75** and **77** and the gap therebetween. Waveguide **61** has members **74** and **76** of "gyromagnetic" material therein such as ferrite material. Member **74** extends from ridge **71** into gap **73** and member **76** extends from ridge **72** into gap **73**. Upon the application of a sufficient d.c. magnetic field in the direction of arrow **79**, the phase shifter **35** provides at the center operating frequency of the circulator (5.2 GHz for the example) about 90° differential shift for signals propagating in the direction of arrow **84** (into the paper) along waveguide **61** relative to signals in the direction of arrow **85** (out of the paper).

The term "gyromagnetic" material refers to ferrimagnetic, ferromagnetic and antiferromagnetic material, which materials exhibit a phenomenon associated with the motion of dipoles in these materials, which in the presence of a d.c. magnetic field is similar in many respects to the classical gyroscope. These materials and their properties are discussed by the above-mentioned book of Lax and Button in chapters 1 through 6. The book is entitled "Microwave Ferrites and Ferromagnetics" and was published in 1962 by McGraw-Hill.

A differential phase shifter **35** was constructed and this phase shifter had the following dimensions:

Width W is 1.490 inches,
Height h is 0.688 inches,
Ridge spacing s is 0.290 inch,
Members **75** and **77** are 0.090, 0.090 inch and extend the length of the phase shifter section **35** (TiO_2 material), dielectric constant **30**,
Gyromagnetic members **74** and **75** have a thickness t of 0.090 inch and a width a of 0.150 inch and extend the length of the phase shifter, (G1005 material sold by Trans-Teck of Gatherberg, Md.),
Gyromagnetic members **74** and **76** are spaced a distance d of 0.150 inch from dielectric members **75** and **77**, and
The length of the phase shifter section **35** is 3 inches.

The differential phase shifter **35** described above, when biased by a d.c. magnetic field in a direction of arrow **79** provided an additional phase shift for signals propagating in the direction of arrow **84** relative to the opposite direction (nonreciprocal). The amount of phase shift for signals propagating in the direction into the paper of arrow **84** is also in addition to that of the simple dielectrically loading of the waveguide due to the dielectric members **75** and **77** and the dielectric effects of the gyromagnetic members **74** and **76**. Associated with electromagnetic waves propagating at opposite directions arrow **85** is a counter rotating magnetic field vector presented to the gyromagnetic members, and consequently, a different permeability. For a d.c. magnetic field of about 750 Gauss, for the above-described arrangement, the electromagnetic waves propagating in a direction of arrow **85** undergo essentially the phase shift as that of the simple dielectric loading effect due to the dielectric members and the gyromagnetic members.

This additional amount of phase shift associated with signal propagation for one direction as compared to that of the simple dielectric loading provided by the members **75, 77, 74** and **76** associated with signal propagation in the opposite direction is termed the differential phase shift. Referring to FIG. 5, plot A illustrates the differential phase shift with frequency for the differential phase shifter **35** described above with the bias field of 750 Gauss in the direction of arrow **79**. As can be seen, the amount of differential phase shift decreases with increase in frequency for signals propagating in the direction of arrow **84**. The differential phase shift at 3.5 Ghz is 120°, at about 5.25 GHz is 90° and at 7 GHz is 60°.

The differential phase shifter **39** is similar in construction to that described above in connection with FIG. 4. All of the above described dimensions in connection with the differential phase shifter **35** apply to the differential phase shifter **39** except for the thickness of the gyromagnetic material t is about 0.070 inch and the spacing d is only about 0.100 inch. The d.c. magnetic field applied to the phase shifter **39** is again 750 Gauss but is applied in an opposite direction or arrow **81** so as to reverse the operating direction of the differential phase shift. Referring to FIG. 5, plot B illustrates changes in differential phase shift with frequency for differential phase shifter **39**. As can be seen, the amount of differential shift increases with increasing frequency for signals propagating in the direction of arrow **85** out of the paper in FIG. 4. The differential phase shift at 3.5 GHz is 60°, at 5.25 GHz is 90° and at 7 GHz is 120°. By decreasing the spacing d from 0.150–0.100 inch, the differential phase shift was changed from one which decreases with increasing frequency to one that increases with increasing frequency. The thickness t of the gyromagnetic members in the differential phase shifter **39** was made smaller so as to equalize the absolute phase shift of both nonreciprocal differential phase shifters **35** and **39**. Changes in the spacing d change the amount of absolute phase shift. An alternate way of equalizing the absolute phase shift is to reduce the width a of the gyromagnetic material in the second phase shifter **39**.

Referring to FIG. 1, the broad band circulator system **10** operates as follows for signals at the low end or 3.5 GHz frequency end of the band. Signals coupled at port **1** are coupled along the H arm of magic tee **11** and divide equally and in phase to the colinear arms **19** and **21** of magic tee **11**. The signals coupled to colinear arm **19** and traveling along transmission path **15** undergo 60° relative phase shift through differential phase shifter **39** to colinear arm **27** of magic tee **13**. The divided signal at colinear arm **21** is coupled along transmission path **17** wherein the signal undergoes 60° relative phase shift through differential phase shifter **37** with no additional relative phase shift through differential phase shifter **35**. Both signals are in phase at the colinear arms **27** and **29** and hence are coupled out of port **2** in the H arm **31** of magic tee **13**.

Signals coupled to port **2** are equally divided and are coupled in phase to the colinear arms **27** and **29**. The signals propagating from the colinear arm **27** to colinear arm **19** along path **15** undergoes no relative phase shift through differential phase shifter **39**. Signals propagating from colinear arm **29** undergo 120° relative phase shift through differential phase shifter **35** and 60° additional relative phase shift through reciprocal phase shifter **37** to the colinear arm **21**. Since the signals at the colinear arms **19** and **21** of magic tee **11** are 180° out of phase, the signals coupled originally at port **2** exit at port **3** in the series E arm **25** of the magic tee **11**.

Low frequency signals coupled at port **3** are equally divided and coupled 180° out of phase to the colinear arms **21** and **19**. Signals propagating from the colinear arm **19** undergo a 60° relative phase shift through phase shifter **39** to the colinear arm **27** of magic tee **13**. Signals propagating from colinear arm **21** undergo a relative phase shift of 60° through reciprocal phase shifter **37** and no additional relative phase shift through differential phase shifter **35** to provide at colinear arm **29** a total relative phase shift of 60°. Since the signals at the colinear arms **19** and **21** are 180° out of phase and have no change in their relative phase through the transmission lines **16** and **17**, the signals at the colinear arms **29** and **27** remain 180° out of phase and are coupled out of port **4** through the series E arm **33**.

In the operation of the broadband circulator described above, when operating at the 7 GHz or high end of the operating frequency band of the circulator system **10**, signals coupled to port **1** are divided equally and in phase to the colinear arms **19** and **21**. Signals at colinear arm **19** are coupled to transmission line **15** and undergo 120° relative phase shift through differential phase shifter **39** to colinear arm **27**. Signals from colinear arm **21** are coupled along transmission path **17** and undergo 120° relative phase shift through reciprocal phase shifter **37** and no additional relative phase shift through phase shift **35** to provide at the colinear arm **29** a relative phase shift of 120°. Since the signals at colinear arms **27** and **29** are in phase, signals are coupled through H arm **31** to port **2**.

Signals coupled at port **2** are divided equally and are coupled in phase to colinear arms **27** and **29** of hybrid **13**. Signals propagating from colinear arm **27** undergo no relative phase shift through phase shifter **39** to colinear arm **19**. Signals propagating from colinear arm **29** undergo 60° relative phase shift through the phase shifter **35** and 120° additional relative phase shift through the reciprocal phase shifter **37** to colinear arm **21**. Since the signals at colinear arms **19** and **21** are 180° out of phase, these signals are coupled out of the E arm **25** to port **3**.

Signals coupled within the high end of the frequency band at port **3** are divided equally and are coupled 180° out of phase to colinear arms **19** and **21**. Signals propagating from colinear arm **19** undergo a relative phase shift of 120° through phase shifter **39** to colinear arm **27**. Signals propagating from colinear arm **21** undergo a relative phase shift of 120° through the reciprocal phase shifter **37** and no additional relative phase shift through phase shifter **35** to colinear arm **29**. Since the signals at colinear arms **27** and **29** are 180° out of phase, they are coupled out of the E arm **33** to the port **4** of hybrid **13**.

Signals coupled at port **4** are divided equally and are coupled at 180° out of phase with respect to each other to the colinear arms **27** and **29**. The signals propagating along path **15** to the colinear arm **19** undergo no relative phase shift. Signals propagating along transmission line **17** undergo 180° relative phase shift through reciprocal phase shifter **37** and phase shifter **35** to provide at colinear arms **19** and **21** no difference in relative phase shift and coupling out of the H arm **23** to port **1**.

While in the above-described arrangement, opposite slopes of differential phase shift with frequency were provided by changing the spacing of the gyromagnetic material relative to dielectric material, the same change in slope may be provided by changing the spacing the gyromagnetic material is from one of the narrow walls of a conventional rectangular waveguide. Since the narrow wall is a point of low electric field and the dielectric represents an area of high electric field, the effects when changing the distance are reversed. In the example described above, by placing the gyromagnetic material closer to the dielectric members in the above example, the differential phase shift was made to increase with increase in frequency. The same effect will be provided by changing the spacing so that the gyromagnetic material is placed further from the narrow wall of the waveguide.

In the above example, the hybrid couplers were magic tees. The same circulation effect can be provided by replacing the magic tee hybrids with other hybrids such as the short-slot hybrid. For an example of a circulator system using short-slot couplers, see FIGS. 12–37 and the accompanying description in Lax and Button cited above.

What is claimed is:

1. In a circulator of the type including: a first transmission path including a reciprocal phase shifter and a first differential phase shifter, a second transmission path including a second differential phase shifter, hybrid means coupled to each end of the two transmission paths for providing at each end power splitting of signals applied thereto, said first differential phase shifter responsive to signals applied thereto for providing additional phase shift to signals propagating in a first direction

along said first transmission path and said second differential phase shifter responsive to signals applied thereto for providing additional phase shift to signals propagating in a second direction opposite said first direction, said reciprocal phase shifter inherently providing in response to signals over a wide range of frequencies changes in the amount of phase shift, the improvement comprising:

said first differential phase shifter being arranged to provide a differential phase shift that decreases a given amount with increase in frequency, and

said second differential phase shifter being arranged to provide a differential phase shift that increases a given amount with increase in frequency, and

said given amount of said increase and decrease being determined relative to said changes in the amount of phase shift provided by said reciprocal phase shifter to provide no difference in the relative phase shift of signals propagating in one direction along said paths and to provide 180° difference in the relative phase shift of signals propagating in the opposite direction along said transmission paths.

2. The combination claimed in claim **1** wherein each of said differential phase shifters includes a body of gyromagnetic material and wherein said second differential phase shifter has the body of gyromagnetic material closer to the high electric field region of said transmission path than said first differential phase shifter.

3. The combination claimed in claim **2** wherein said differential phase shifters and said reciprocal phase shifters are each constructed of double ridged waveguide sections.

4. The combination claimed in claim **3** wherein said double ridged waveguide sections are dielectrically loaded by a body of dielectric material located adjacent to both of the ridges of said double ridged waveguide.

5. The combination claimed in claim **4** wherein said differential phase shifters each have at least one body of gyromagnetic material positioned adjacent to both of the ridges of said double ridged waveguide and spaced from an associated dielectric body.

6. The combination claimed in claim **5** wherein the body of gyromagnetic material in said second differential phase shifter is more closely spaced from the associated dielectric body than the body of gyromagnetic material in the first differential phase shifter.

7. The combination claimed in claim **6** wherein the gyromagnetic body of said second differential phase shifter is made relatively thin compared to the gyromagnetic body of said first differential phase shifter to equalize the amount of absolute phase shift of said differential phase shifters.

8. The combination claimed in claim **7** wherein the width of the gyromagnetic body of said second differential phase shifter is made relatively narrow compared to the width of the gyromagnetic body of the first differential phase shifter to equalize the absolute phase shift of the differential phase shifters.

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