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3,270,298

FOUR PORT CIRCULATOR HAVING MUTUALLY COUPLED RESONANT CAVITIES

Filed Oct. 31, 1963

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FIG. 1

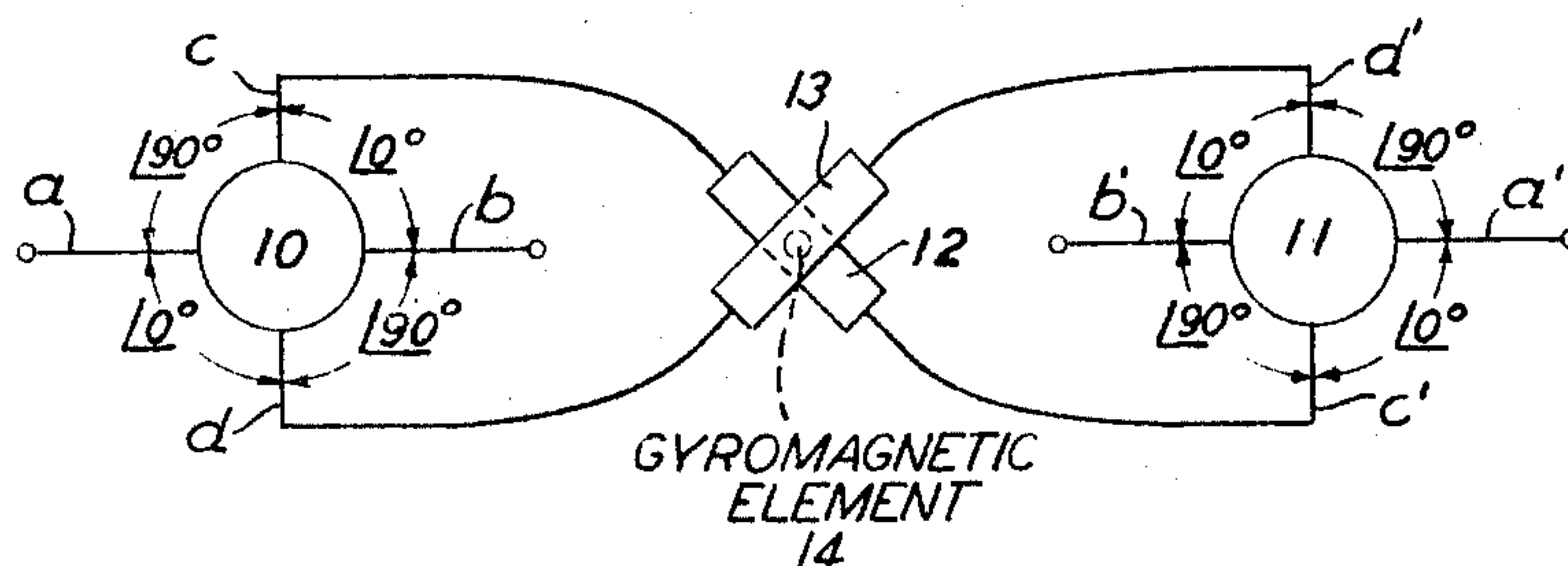


FIG. 1A

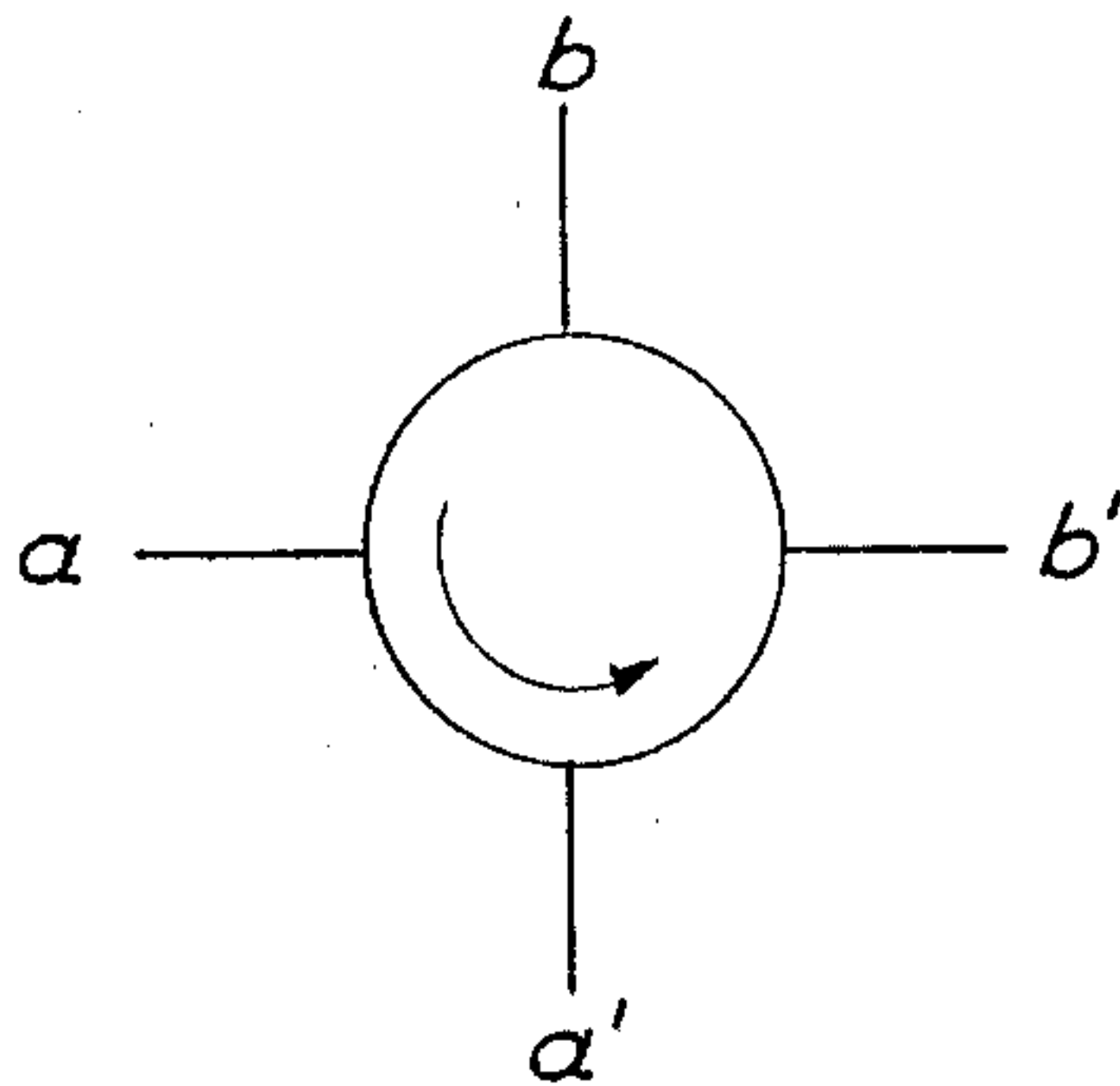
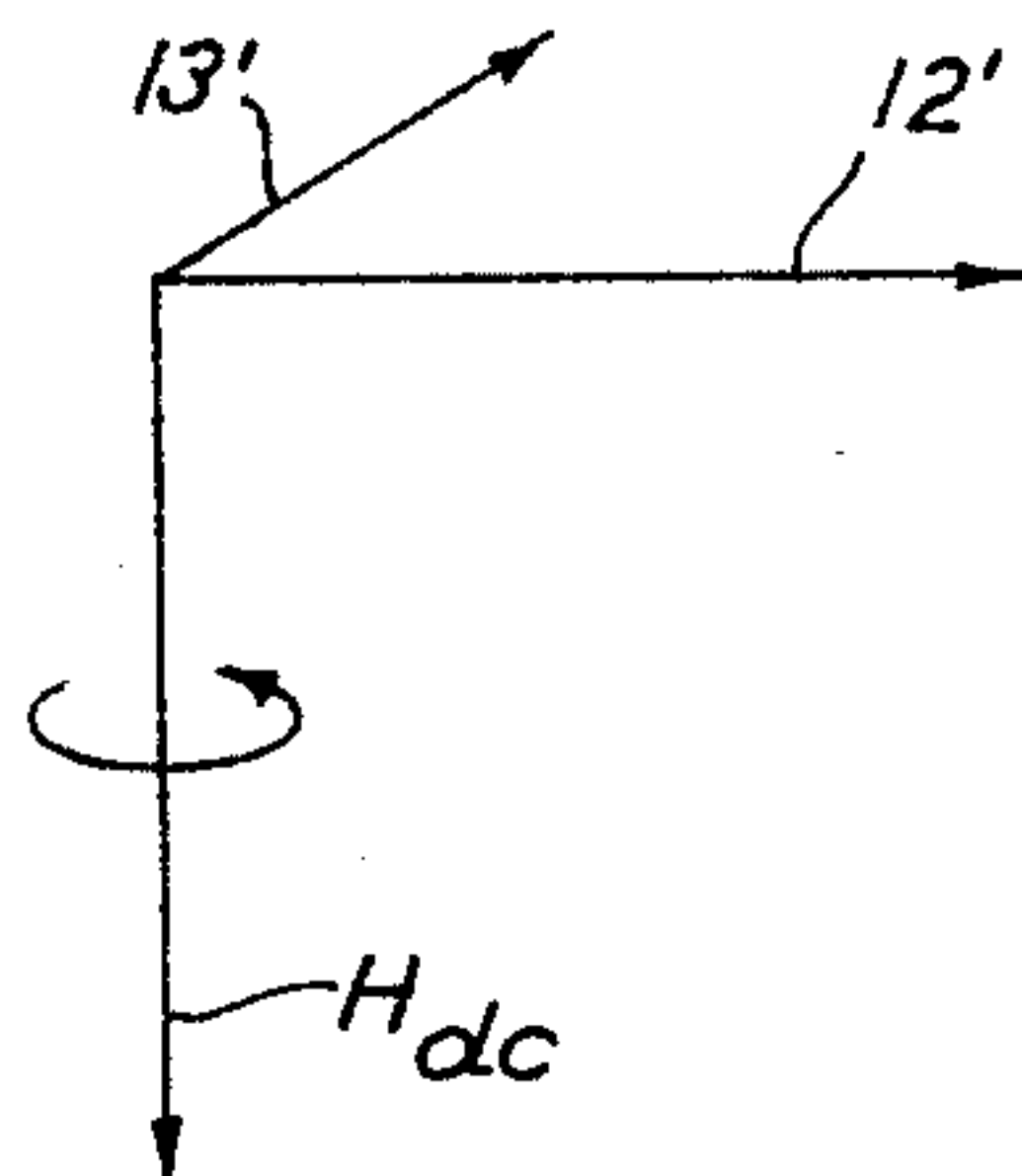


FIG. 2



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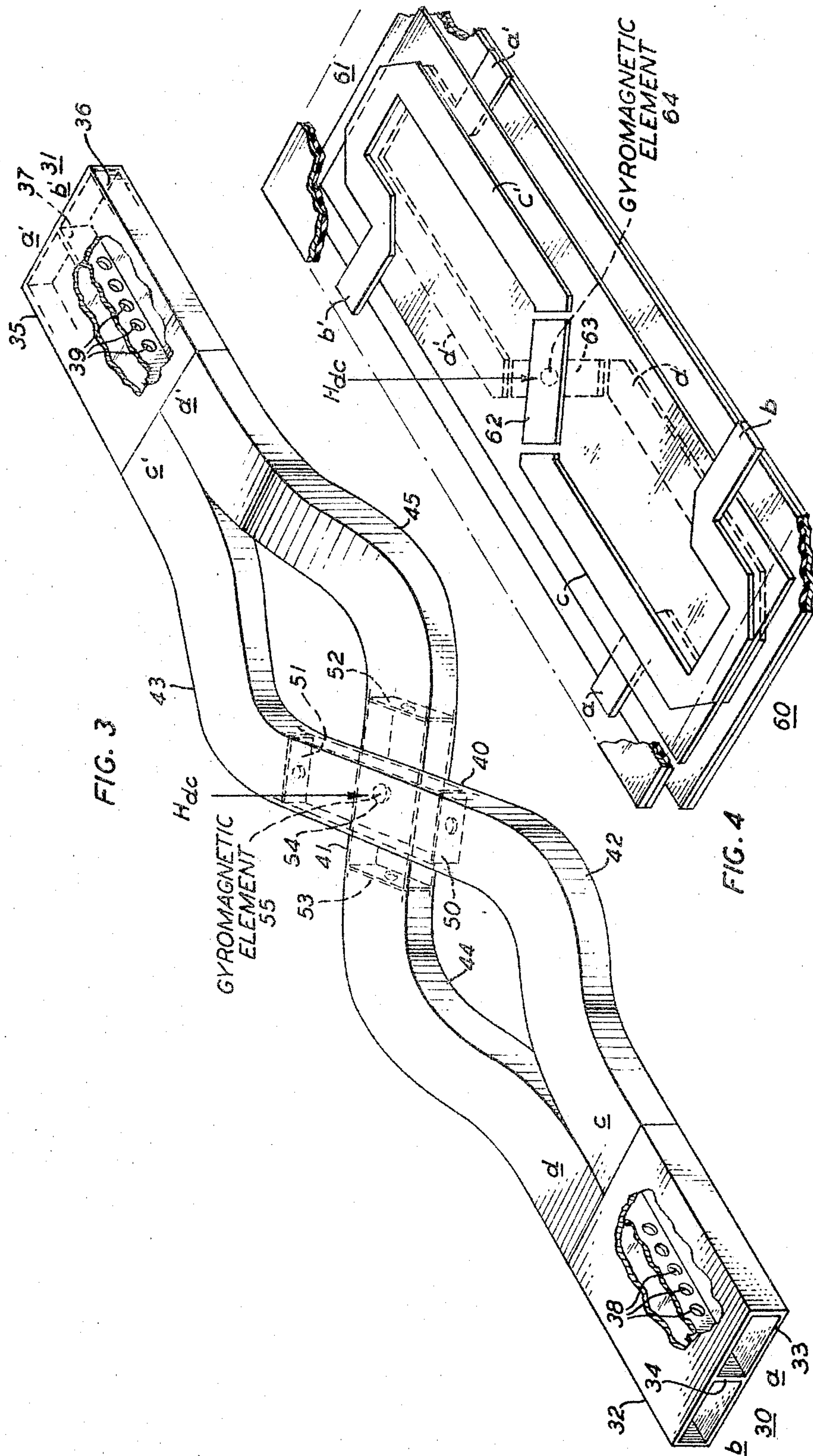
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7 Claims. (Cl. 333-1.1)

This invention relates to electromagnetic wave transmission systems and, in particular, to four port circulators for use in such systems.

The use of materials having gyromagnetic properties to obtain both reciprocal and nonreciprocal transmission effects in electromagnetic circuits is widely known and has found numerous applications in propagation structures of both the waveguide and the two-conductor transmission line types.

Included among these new transmission components that have been developed is the so-called "circulator." While structurally circulators may differ substantially from each other, they all have in common the electrical property of transmitting energy into and out of the various branches of the network in rotation. Thus, energy applied to a first branch of the circulator is coupled selectively to a second branch, whereas energy applied to the second branch is coupled selectively to a third branch. This process is continued until finally energy applied to a fourth branch is coupled selectively to the first branch, thus completing the rotational process.

In United States Patent 2,887,664, issued to C. L. Hogan on May 19, 1959, circulator action is obtained by utilizing the nonreciprocal polarization rotational effects produced by a longitudinally biased gyromagnetic material. In United States Patent 2,849,685, issued to M. T. Weiss on August 26, 1958, the nonreciprocal phase shift produced by a transversely biased gyromagnetic material is utilized to produce circulator action.

In accordance with the present invention, large nonreciprocal dissipation is utilized to produce low-loss nonreciprocal transmission effects and, in turn, to produce a four port circulator. More particularly, a resonantly biased gyromagnetic element is coupled to a pair of suitably oriented resonant cavities. Transmission through the cavities occurs in that direction of propagation consistent with low dissipation. For propagation in the opposite direction, the large lossy component introduced into the cavities by the resonantly biased gyromagnetic element results in a destruction of the resonant properties of the cavities and a virtually complete reflection of the incident wave energy.

In an illustrative embodiment of the invention utilizing the principles described above, two 3 db quadrature hybrids are employed. One pair of conjugate branches of one of the hybrids is connected to a pair of conjugate branches of the other hybrid by means of a pair of orthogonally oriented resonant cavities. The cavities are mutually coupled to a magnetically biased element of gyromagnetic material whose biasing field is adjusted to produce gyromagnetic resonance at the resonant frequency of the two cavities. Because of the 90 degree phase delay introduced by the quadrature hybrids and the orthogonal spatial orientation of the cavities, a region of circularly polarized magnetic field is established at the gyromagnetic element. The sense of rotation of the magnetic field is a function of the direction of propagation of the incident wave energy. For one direction of propagation, and one sense of rotation, energy is freely propagated through the resonant cavities, whereas for propagation in the opposite direction the sense of rotation is reversed, and the incident energy is reflected. The energy components

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so transmitted or reflected are recombined in the hybrids to produce circulator action.

The invention as described above can be embodied using hollow, conductively bounded waveguides, or two-conductor transmission lines, as will be described in greater detail hereinafter.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a block diagram of a circulator in accordance with the invention;

FIG. 1A shows the sequence of coupling between branches of the circulator of FIG. 1;

FIG. 2, given for purposes of explanation, shows the signal magnetic field components and the biasing field in the region of the gyromagnetic material;

FIG. 3 is an illustrative embodiment of the invention using rectangular waveguides; and

FIG. 4 is an illustrative embodiment of the invention using strip transmission lines.

Referring to FIG. 1, there is illustrated, in block diagram, a circulator in accordance with the invention. The circulator comprises a pair of 3 db quadrature hybrids 10 and 11, each of which has two pairs of conjugate branches. The pairs of conjugate branches associated with hybrid 10 are designated $a-b$ and $c-d$. The pairs of conjugate branches associated with hybrid 11 are designated $a'-b'$ and $c'-d'$.

The term "3 db quadrature hybrid" refers to that class of power dividing networks in which the power of the incident signal applied to one branch of one pair of conjugate branches divides equally between the other pair of conjugate branches and wherein the relative phases of the divided signals differ by 90 degrees. This includes a large variety of power dividing networks among which are the Riblet coupler (H. J. Riblet, "The Short-Slot Hybrid Junction," Proceedings of the Institute of Radio Engineers, vol. 40, No. 2, February 1952, pages 180 to 184), the multi-hole directional coupler (S. E. Miller, "Coupled Wave Theory and Waveguide Applications," Bell System Technical Journal, vol. 33, May 1954, pages 661 to 719), the semi-optical directional coupler (E. A. J. Marcatili, "A Circular Electric Hybrid Junction and Some Channel-Dropping Filters," Bell System Technical Journal, vol. 40, January 1961, pages 185 to 196), and the strip transmission line directional coupler (J. K. Shimizu, "Strip-line 3 db Directional Couplers," published in the 1957 Institute of Radio Engineers Wescon Convention Record, vol. 1, Part 1, pages 4 to 15).

In each of the above-mentioned power dividing networks there is a 90 degree relative phase shift between the output wave components. This is indicated by the $\angle 0^\circ$ and $\angle 90^\circ$ designations between adjacent branches of each of the hybrids 10 and 11.

To avoid unnecessary repetition, the terms "directional coupler" or "hybrid" when used hereinafter shall be understood to mean a "3 db quadrature hybrid" having the characteristics referred to above.

Referring again to FIG. 1, branch c of hybrid 10 is connected to branch c' of hybrid 11 by means of a first resonant member 12. Similarly, branch d of hybrid 10 is connected to branch d' of hybrid 11 by means of a second resonant member 13. Members 12 and 13, which are preferably identical, are spatially oriented with respect to each other to produce a region of orthogonally directed magnetic fields. A magnetically biased element of gyromagnetic material 14 is located within that region. Typically, resonant members 12 and 13 are transmission line cavities and are oriented at right angles to each other.

The term "gyromagnetic material" is employed here in its accepted sense as designating the class of magnetically polarizable materials having unpaired spin systems involving portions of the atoms thereof that are capable of being aligned by an external magnetic polarizing field and which exhibit a precessional motion at a frequency with the range contemplated by the invention under the combined influence of said polarizing field and an orthogonally directed varying magnetic field component. This precessional motion is characterized as having an angular momentum, and a magnetic moment. Typical of such materials are ionized gases, paramagnetic material and ferromagnetic materials, the latter including the spinels such as magnesium aluminum ferrite, aluminum zinc ferrite and the rare earth iron oxides having a garnet-like structure of the formula $A_3B_5O_{12}$ where O is oxygen, A is at least one element selected from the group consisting of yttrium and the rare earths having an atomic number between 62 and 71, inclusive, and B is iron optionally containing at least one element selected from the group consisting of gallium, aluminum, scandium, indium and chromium.

Both circuits 12 and 13 are tuned to resonance at the operating frequency. If a band of frequencies are involved, the circuits are tuned to resonance at the mid-band frequency. In addition, the gyromagnetic element is biased to gyromagnetic resonance at that same frequency by magnetic means not shown.

The operation of the circulator shown in FIG. 1 is based upon the nonreciprocal behavior of gyromagnetic materials. As is well known, magnetically polarized gyromagnetic materials exhibit distinctly different properties depending upon the nature of the applied magnetic fields. These properties are the result of the fact that the magnetic moment of the material tends to precess in a preferred sense and resists rotation in the opposite sense. As a consequence, circularly polarized magnetic fields influence the gyromagnetic material differently depending upon their sense of rotation. This is so since a circularly polarized magnetic field rotating in one direction is rotating in the easy angular direction of precession of the magnetic moment, whereas an oppositely rotating circularly polarized magnetic field is rotating in a sense inconsistent with the natural behavior of the magnetic moment of the gyromagnetic material. Therefore, when the effective magnetic field of the signal wave rotated in the same sense as the preferred direction of precession of the magnetic moment, it couples strongly to the gyromagnetic material. However, very little coupling takes place between the external magnetic field and the gyromagnetic material when the effective signal magnetic field is rotating in the opposite angular direction.

Referring again to FIG. 1, the gyromagnetic element 14 is coupled to cavity 12 in a region of the cavity having a substantial magnetic field component. It is also coupled to a corresponding region of cavity 13 having an equal magnetic field intensity. Since the cavities are oriented at right angles to each other, the magnetic field components produced by the two cavities are similarly orthogonally oriented.

In addition to the spacial orthogonality of the two fields, there is a time orthogonality produced by the power dividing networks 10 and 11. The combined effect of these two orthogonalities is to produce the equivalent of a circularly rotating magnetic field at the gyromagnetic material.

FIG. 2, given for purposes of explanation, shows the orientation and phase relationships of the magnetic field components at the gyromagnetic material.

Assuming that signal is applied to branch *a* of hybrid 10, half of the incident power is coupled to branch *c* and the remaining half to branch *d*. In addition, there is a 90 degree time phase difference between the two equal wave components. These waves excite cavities 12 and 13 ninety degrees out of time phase with respect to each other.

er. In addition, the magnetic field components are in space quadrature. This is illustrated in FIG. 2, which shows a first field component from cavity 12 indicated by arrow 12', and a second field component from cavity 13 indicated by arrow 13'. Because of the orientation of the cavities these components are perpendicular to each other. Also shown is the biasing field component H_{dc} which is applied in a direction perpendicular to the plane defined by components 12' and 13'.

Because the cavities are excited 90 degrees out of time phase, component 13' is a minimum when component 12' is a maximum. As component 13' increases in amplitude, component 12' decreases. As illustrated in FIG. 2, component 13' is pictured as increasing in the indicated direction while component 12' is decreasing. The effect of field components 12' and 13' varying in this manner is to produce the equivalent of a single, resultant field component which appears to rotate in space in the region occupied by the gyromagnetic element 14. With the biasing field H_{dc} directed as shown, a negative, or counter-clockwise rotation is produced when viewed along the direction of the biasing field. As this sense of rotation is opposite to the natural precessional sense of the material, little or no interaction takes place between the signal wave and the gyromagnetic material. Substantially all of the wave energy applied to cavities 12 and 13 continues to propagate through the cavities to hybrid 11, where the two components recombine and leave the circulator through branch *a'*.

For wave energy applied to branch *a'* of hybrid 11, the relative time phase difference between magnetic field components 12' and 13' is such that a positive, or clockwise sense of rotation is produced at the gyromagnetic material. This produces a strong interaction with the gyromagnetic material. Since the latter is biased to gyromagnetic resonance, a large lossy component is introduced into each of the cavities. The effect of this lossy component is to detune the cavities, thereby causing a large impedance mismatch at the inputs to the cavities which, in turn, causes substantially all of the incident wave energy to be reflected back towards hybrid 11. The two reflected wave components recombine and leave by way of branch *b'*.

Similarly, it can be shown that wave energy applied at branch *b'* leaves the network by way of branch *b* whereas wave energy applied at branch *b* leaves the network by way of branch *a*, thus providing typical circulator action. The sequence of coupling between branches is thus *a-a'-b'-b*, as shown in FIG. 1A.

FIGS. 3 and 4 are specific illustrative embodiments of the invention broadly described above. The embodiment of FIG. 3 illustrates the invention in a system using conductively bounded waveguides, whereas the embodiment of FIG. 4 illustrates the invention in a system using strip transmission lines.

Referring to FIG. 3, a pair of distributed hole directional couplers 30 and 31 are used as the 3 db quadrature hybrids. Each comprises a pair of rectangular waveguides of substantially equal cross-sectional dimensions aligned parallel to each other and sharing a common narrow wall. More specifically, directional coupler 30 is made up of waveguide sections 32 and 33 which share a common narrow wall 34. Directional coupler 31 is made up of waveguide sections 35 and 36 which share a common narrow wall 37.

Distributed along the common walls 34 and 37 are the coupling apertures 38 and 39, respectively. The size and distribution of the coupling apertures are designed in accordance with procedures well known in the art as are described in the above-mentioned article by S. E. Miller.

Each of the directional couplers has two pairs of conjugate branches *a-b*, *c-d* and *a'-b'*, *c'-d'*.

Branch *c* of coupler 30 and branch *c'* of coupler 31 are connected to cavity 40 by means of waveguide sections 42 and 43, respectively. Similarly, branch *d* of

coupler 30 and branch a' of coupler 31 are connected to cavity 41 by means of waveguide sections 44 and 45, respectively. Preferably sections 42, 43, 44 and 45 have the same electrical lengths.

Cavities 40 and 41 are sections of dominant mode rectangular waveguide, bounded at each end by means of transversely extending conductive members 50, 51, 52 and 53 each of which has a coupling aperture for coupling wave energy into and out of the respective cavities.

Cavities 40 and 41 cross each other such that a portion of the lower wide wall of cavity 40 is contiguous with a corresponding portion of the upper wide wall of cavity 41. In particular, the two cavities cross each other at right angles. That is, the longitudinal axis of cavity 40 is perpendicular to the longitudinal axis of cavity 41.

Extending through the contiguous wide walls of cavities 40 and 41 is an aperture 54 in which there is located an element of gyromagnetic material 55. The element 55 is shown as a sphere. However, it may assume any other convenient shape since its particular physical configuration is not critical to the operation of the invention.

A static magnetic biasing H_{dc} is applied perpendicular to the wide walls of the cavities and is adjusted to produce gyromagnetic resonance in element 55 at the operating frequency. If the device is to operate over a band of frequencies, gyromagnetic resonance is induced at the mid-band frequency.

The biasing field H_{dc} can be supplied by any suitable means (not shown), such as an electric solenoid, a permanent magnet, or the gyromagnetic material itself can be permanently magnetized.

Advantageously, the gyromagnetic material is located in a region of high magnetic field intensity. In the embodiment of FIG. 3, the cavities are made to have an electrical length of one wavelength, and the gyromagnetic material is located in the center of the cavities. In this position the gyromagnetic element is in a region of maximum transverse magnetic field intensity. Alternatively, the gyromagnetic material can be coupled to longitudinal magnetic field components.

As indicated above, the principles of the invention can be applied to other types of transmission media. Another application is illustrated in the embodiment of FIG. 4 which utilizes strip transmission lines. In this embodiment, a pair of directional couplers 60 and 61, of the type described in the above-mentioned article by J. K. Shimizu, are used as the quadrature power divided networks.

As before a pair of conjugate branches of each directional couplers $c-d$ and $c'-d'$ are connected to a pair of orthogonally oriented resonant cavities 62 and 63. Each cavity comprises a length of conductively insulated line whose electrical length is a multiple of half a wavelength at the operating frequency. An element of gyromagnetic material 64 is located between the cavities and means for magnetically biasing the element are provided. The mode of operation of this embodiment of the invention is the same as described hereinabove.

In all cases it is understood that the above-described arrangements are simply illustrative of but a small number of the many possible specific embodiments which can represent applications of the invention. For example, other types of 3 db quadrature hybrids and other cavity configurations can be used. In addition, two or more sets of cavities can be used to increase the isolation between noncoupled branches. Thus, numerous and other varied 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. A four port circulator comprising:
two 3 db quadrature hybrids each having two pairs of conjugate branches;

a pair of transmission line resonant members supportive of electromagnetic wave energy connecting one pair of conjugate branches of one of said hybrids to one pair of conjugate branches of the other of said hybrids;

said resonant members being physically oriented with respect to each other to produce when energized a region of orthogonally intersecting magnetic fields; and an element of magnetically biased gyromagnetic material located within said region.

2. The circulator according to claim 1 wherein said hybrids and said resonant members comprise sections of strip transmission line.

3. A four port circulator comprising:

two 3 db quadrature hybrids each having two pairs of conjugate branches;

a pair of transmission line resonant cavities tuned to the same resonant frequency connecting one pair of conjugate branches of one of said hybrids to one pair of conjugate branches of the other of said hybrids;

said cavities crossing each other at right angles at a region along their respective lengths;

and an element of gyromagnetic material magnetically biased to gyromagnetic resonance at said same frequency electromagnetically coupled to said crossed cavities.

4. The circulator according to claim 3 wherein said hybrids and said cavities comprise sections of conductively bounded waveguide.

5. The circulator according to claim 4 wherein each of said cavities comprises a length of conductively terminated waveguide;

and means for coupling into and out of each end of said cavities.

6. The circulator according to claim 5 wherein said element of gyromagnetic material is coupled to corresponding regions of said cavities at an electrical distance from said terminations equal to an integral multiple of half a wavelength at said resonant frequency.

7. In an electromagnetic wave transmission system, a four port circulator comprising:

two 3 db directional couplers each having two pairs of conjugate branches;

means for connecting the branches of one pair of conjugate branches of one directional coupler to the branches of one pair of conjugate branches of the other of said directional couplers comprising a pair of tuned transmission line members;

said members being supportive of electromagnetic wave energy having transversely directed magnetic field components;

said members being oriented with respect to each other with the transversely directed components of each being orthogonal to the transversely directed components of the other;

an element of gyromagnetic material positioned with respect to said members so as to couple to a region of said orthogonally directed field components;

and means for magnetically biasing said element to gyromagnetic resonance at the frequency of said members.

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