

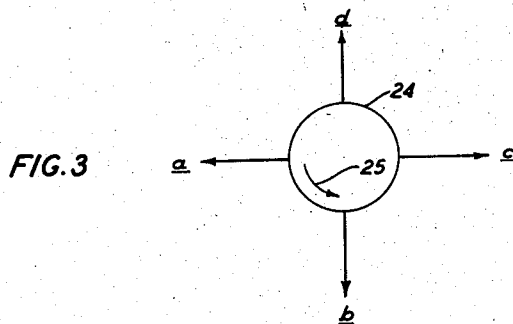
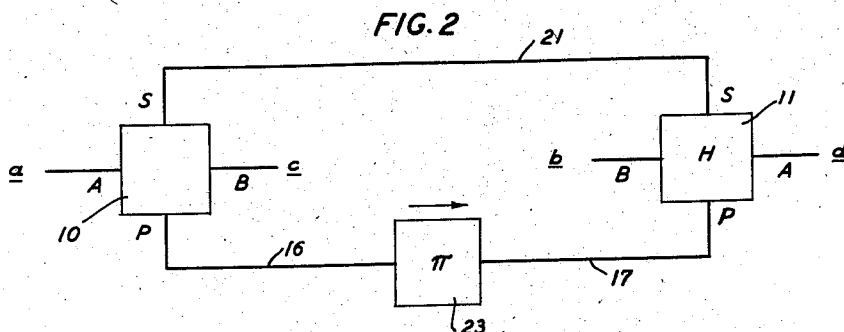
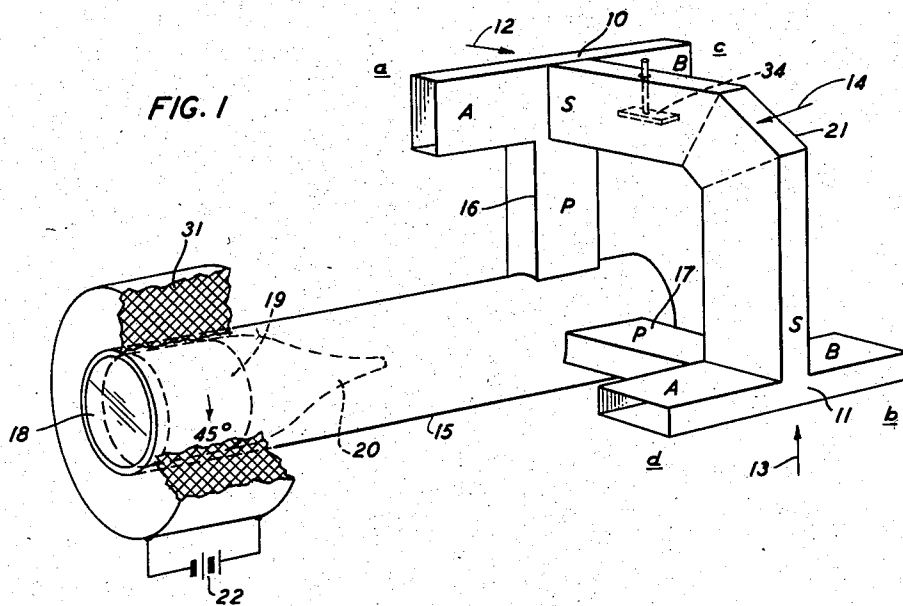
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A. G. FOX

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GYRATING WAVE TRANSMISSION NETWORKS

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INVENTOR
A. G. FOX
BY *Ray M. Porter, Jr.*
ATTORNEY

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GYRATING WAVE TRANSMISSION NETWORKS

Arthur G. Fox, Rumson, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Original application May 16, 1952, Serial No. 288,288, now Patent No. 2,832,054, dated April 22, 1958. Divided and this application October 1, 1954, Serial No. 459,780

6 Claims. (Cl. 333-9)

This invention is a division of my copending application, Serial No. 288,288, filed May 16, 1952, which issued as United States Patent 2,832,054 on April 22, 1958, and relates to electrical transmission systems and, more particularly, to multibranch circuits having non-reciprocal transmission properties.

It is an object of the invention to establish non-reciprocal electrical connections between a plurality of branches of a multibranch network.

In the copending application of C. L. Hogan, Serial No. 252,432, filed October 22, 1951, now United States Patent No. 2,748,353, issued May 29, 1956, there is disclosed and claimed one embodiment, and in the copending application of S. E. Miller, Serial No. 263,600, filed December 27, 1951, now United States Patent No. 2,748,352, issued May 29, 1956, there is disclosed and claimed another embodiment of a non-reciprocal multibranch network. These networks are therein designated "circulator circuits" and have electrical properties such that electrical energy appearing in one branch thereof is coupled to only one other branch for a given direction of transmission, but to another branch for the opposite direction of transmission. Specific useful and novel applications for the unusual properties of these circulator networks are disclosed and claimed in the above mentioned applications and in the copending application of W. W. Mumford, Serial No. 263,656, filed December 27, 1951, now United States Patent No. 2,769,960, issued November 6, 1956.

It is a more specific object of the present invention to provide new and improved types of circulator circuits.

In the particular form of circulator as disclosed in said Hogan application, for example, one element or component of the circulator comprises means for introducing a non-reciprocal phase inversion to electrical energy. This element or component is now denominated a "gyrator" and further detailed examination of its general properties will be found hereinafter.

Special features of the present invention reside in a new and improved form of gyrator. Further features of the invention reside in the circulator circuit built upon the gyrator.

These and other objects and features of the invention, the nature of the present invention and its advantages, will appear more fully upon consideration of the various specific illustrative embodiments shown in the accompanying drawings and the following detailed description of these embodiments.

In the drawings:

Fig. 1 is a perspective view of a non-reciprocal multibranch network or circulator, in accordance with the invention;

Fig. 2, given for the purpose of explanation, is a schematic representation of the circulator of Fig. 1; and

Fig. 3, given for the purpose of explanation, is a diagrammatic representation of the coupling characteristics of the circulator of Fig. 1.

In more detail, Fig. 1 illustrates a four branch micro-

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wave circulator network having four branches or terminals *a*, *b*, *c* and *d*. The circulator comprises a gyrator portion and a hybrid portion. The hybrid portion in turn comprises a pair of microwave hybrid structures 10 and 11 to be further considered in detail hereinafter. The gyrator portion comprises a section of circular wave guide 15 which is joined near its right-hand end by a pair of rectangular wave guides 16 and 17 coupled to guide 15 in shunt or H-plane junctions at points displaced from each other around the periphery of guide 15 by 90 degrees. Rectangular wave guides 16 and 17 will accept and support only plane waves in which the component of the electric vector, which determines the plane of polarization of the wave, is consistent with the dominant TE_{10} mode in rectangular wave guide. Likewise, the dimension of guide 15 is preferably chosen so that only the various wave polarizations of dominant TE_{11} mode in it can be propagated. In view of the physical orientation of guides 16 and 17, and by virtue of the shunt plane junctions, the TE_{10} mode in guide 16 is coupled to a horizontally polarized TE_{11} mode in circular guide 15, which is perpendicular therein to the vertically polarized TE_{11} mode introduced by guide 17. Thus, guides 16 and 17 comprise a pair of polarization-selective connecting terminals by which wave energy in two orthogonal TE_{11} mode polarizations may be coupled to and from one end of guide 15. Furthermore, these guides comprise a pair of conjugately related terminals or branches of guide 15 inasmuch as a wave launched in one will not appear in the other.

The left-hand end of guide 15 is closed by a smooth reflecting surface or plate 18 of highly conductive material. The right-hand end of guide 15 may be similarly closed. Interposed between surface 18 and guides 16 and 17 and in the path of wave energy passing therebetween in guide 15 is suitable means of the type which produces an antireciprocal rotation of the plane of polarization of these electromagnetic waves, for example, a Faraday-effect element having such properties that an incident wave impressed upon a first side of the element emerges on the second side polarized at a different angle from the original wave and an incident wave impressed upon the second side emerges upon the first side with an additional rotation of the same angle. Thus, the polarization of a wave passing through the element first in one direction and then in the other undergoes two successive space rotations in the same sense, thereby doubling the rotation undergone in a single passage. As illustrated by way of example in the drawing, this means comprises a Faraday-effect element 19 with an accompanying conical transition member 20 which may be of polystyrene or ferrite and is provided to cut down reflections from the face of element 19. As a specific embodiment, element 19 may be a block of magnetic material, for example nickel-zinc ferrite prepared in the manner disclosed in said copending application of C. L. Hogan, having a thickness of the order of magnitude of a wavelength. This material has been found to operate satisfactorily as a directionally selective Faraday-effect rotator for polarized electromagnetic waves to an extent up to 90 degrees or more when placed in the presence of a longitudinal magnetizing field of strength which is readily produced in practice and in such thickness is capable of transmitting electromagnetic waves, for example in the centimeter range, with very little attenuation. Suitable means for producing the necessary longitudinal magnetic field surrounds element 19 which means may be, for the purpose of illustration, a solenoid 31 mounted upon the outside of guide 15 and supplied by a source 22 of energizing current. It should be noted, however, that element 19 may be permanently magnetized or element 31 can be a permanently mag-

netized structure. The angle of rotation of polarized electromagnetic waves in such magnetic material is approximately directly proportional to the thickness of the material traversed by the waves and to the intensity of the magnetization to which the material is subjected, whereby it is possible to adjust the amount of rotation by varying or properly choosing the thickness of the material comprising element 19 and the intensity of magnetization supplied by solenoid 31. In the present embodiment, the thickness of element 19 and the potential from source 22 are adjusted to give a 45 degree rotation of the plane of polarization for a single passage of electromagnetic energy.

In the simplified view of the phenomenon involved as offered in said Hogan application, a plane polarized wave incident upon the magnetic material in the presence of the magnetic field, produces two sets of secondary waves in the material, each set of secondary waves being circularly polarized. The two sets of secondary waves are circularly polarized in opposite senses and they travel through the medium at unequal speeds. Upon emergence from the material the secondary waves in combination set up a plane polarized wave, which is in general polarized at a different angle from the original wave. It should be noted that the Faraday rotation depends for its direction upon the direction of the magnetic field. Thus, if the direction of the magnetic field is reversed, the direction of the Faraday rotation is also reversed in space while retaining its original relationship to the direction of the field.

The apparatus thus far described, comprising the polarization-selective terminals 16 and 17 with the guide 15 and the element 19 interconnecting them, possesses the property of introducing a phase delay to energy transmitted in the direction from terminal 16 to terminal 17 which is 180 degrees different than the phase delay of energy transmitted in the opposite direction therebetween. In other words, the structure possesses a directional phase shift of 180 degrees, the principal characteristic defining the property of gyrators. This directional phase shift may be readily seen by assuming that an initial electromagnetic wave is introduced in terminal 16 polarized parallel to and in the same sense as arrow 12 on the drawing. The horizontally polarized wave introduced by terminal 16 into guide 15 travels to the left, and past transition member 20, to element 19. Element 19 rotates the polarization of this wave 45 degrees in the direction indicated by the arrow on element 19 in the drawing. The rotated wave emerging from the left-hand face of element 19 is reflected by surface 18 and undergoes a successive rotation of 45 degrees on repassage through element 19 to emerge from the right-hand face of element 19 with a total polarization rotation of 90 degrees from its initial polarization. This wave, being vertically polarized, is in the preferred direction for transmission through terminal 17 and has a polarization vector which is directed downward, that is, in the opposite direction from vector 13 shown on the drawing. If now we consider transmission in the reverse direction where a wave is introduced in terminal 17 with a polarization vector which is vertical and in the same sense as vector 13, this wave will be transmitted through element 19 to the reflector 18 and back again with a total rotation of 90 degrees in the same sense as before. The returning wave being horizontally polarized is now in the preferred direction for transmission through terminal 16 and its polarization vector is in the same direction as the arrow 12. It may be seen therefore that for transmission from terminal 17 to terminal 16 the polarization vectors of the input and output waves are parallel with the arrows 13 and 12, respectively, but that for transmission in the opposite direction from terminal 16 to terminal 17, an input polarization vector parallel with arrow 12 will produce an output polarization vector in opposition to arrow 13. This means that the total

phase delay in transmission differs by 180 degrees depending upon the direction of transmission between terminal 16 and terminal 17.

The hybrid portion of the circulator of Fig. 1 comprises a first hybrid junction 10 and a second hybrid junction 11 which may be wave-guide hybrid junctions of the types illustrated and described, for example, in the Proceedings of the Institute of Radio Engineers, vol. 35, November 1947, pages 1294-1306, or of the type illustrated and described with reference to Figs. 4, 5 and 6 in United States Patent 2,510,288, granted June 6, 1950, to W. D. Lewis. Whatever form of hybrid structure is employed, it should have four arms or branches, associated in two pairs, each arm of a pair being conjugately related to the other arm of the same pair. For convenience here, the notation adopted in the above mentioned patent will be employed throughout the following description of hybrid junctions in which the arms of one pair will be designated P and S, respectively, and the arms of the other pair will be designated A and B, respectively. The inherent properties of hybrid junctions are well known, in which wave energy introduced into the structure from or by way of either arm of one pair will produce no energy leaving the structure by way of the other arm of that pair, but the energy introduced will divide equally between the other pair of arms of the structure.

Further, the waves representing the halves of the energy in each of the arms A and B will be in phase if the energy is introduced by arm P and will be 180 degrees out of phase if introduced by way of arm S. Assuming that for both hybrid junctions, wave energy introduced by way of arm A will appear in phase in arms P and S, then wave energy introduced by way of arm B will appear 180 degrees out of phase in arms P and S.

If equal wave energies are introduced in phase into the hybrid junction by way of arms P and S, they will combine in arm A, no wave energy being transmitted to arm B. If equal wave energies 180 degrees out of phase are introduced into the hybrid junction by way of the two arms P and S, the energies will combine in arm B, no wave energy being transmitted to arm A. Any multiple of 360 degrees phase difference can be added to the in phase or out of phase conditions just described without affecting the arm in which the energies applied to arms P and S will combine. When equal energies are introduced into the P and S arms, changing the phase of the energy introduced into one only of the P or S arms by 180 degrees will cause the combined energy to appear in the opposite one of the arms A or B, in which it would have appeared without such a change.

As illustrated in Fig. 1 of the drawing the P arm of hybrid 10 is coincident with terminal 16 of the gyrator portion described above and the P arm of hybrid 11 is coincident with terminal 17 thereof. The S arms of each hybrid are suitably connected together, as for example, by an angled section of wave guide 21.

Having in mind the properties of the gyrator portion of the circulator and the properties of hybrids 10 and 11, each described above, the operation of the circulator circuit of Fig. 1 may be conveniently explained by means of its electrical schematic diagram shown in Fig. 2, taken together with the diagram of Fig. 3. Thus, Fig. 2 represents hybrids 10 and 11 having the S arms thereof connected together by 21 and the P arms thereof connected together by a gyrator element 23, i.e., means introducing a directional 180 degree phase shift or a phase inversion to that energy passing through element 23 in the direction of the arrow above it. Wave energy applied at terminal a to arm A of hybrid 10 divides in phase in arms S and P. The wave energy from arm P in 16 receives a phase inversion as indicated by the arrow on element 23 in the direction of transmission from 16 to 17, as has been described, thereby producing an out of phase relation between the energy applied to the P and S arms

of hybrid 11, which causes these components to combine in arm B of hybrid 11 and to appear at terminal *b*. Substantially free transmission is, therefore, afforded from terminal *a* to terminal *b* and this condition is indicated on Fig. 3 by the radial arrows labeled *a* and *b*, respectively, associated with a ring 24, and an arrow 25 diagrammatically indicating progression in the sense from *a* to *b*. Wave energy applied at terminal *b* to arm B of hybrid 11 appears relatively out of phase in the S and P arms thereof and remains out of phase in 21 and 17—16, since no inversion is introduced by element 23 for this direction of transmission. The two components are applied out of phase to the S and B arms of hybrid 10 and combine in the B arm thereof to appear at terminal *c*. This transmission is indicated by arrow 25 on Fig. 3 which tends to turn the arrow *b* in the direction of the arrow *c*. By similar analysis, energy applied to terminal *c* appears out of phase in 16 and 21, in phase in 17 and 21, combines in arm A of hybrid 11, and appears at terminal *d*. Energy applied at terminal *d* appears in phase in 17 and 21, in phase in 16 and 21, combines in arm A of hybrid 10 and appears at terminal *a*. This transmission is indicated on Fig. 3 by arrow 25 which successively tends to turn the arrow *c* in the direction of the arrow *d* and the arrow *d* in the direction of the arrow *a*.

Considering the above described transmission characteristics as they are indicated diagrammatically on Fig. 3, the applicability of the term "circulator" as a descriptive name for the non-reciprocal four branch network of Fig. 1 is apparent. Transmission of waves at *a* takes these waves in circular fashion to terminal *b*, transmission from *b* leads to terminal *c*, transmission from *c* leads to terminal *d*, and transmission from terminal *d* leads to terminal *a*. Thus, each terminal is coupled around the circle to only one other terminal for a given direction of transmission, but to another terminal for the opposite direction of transmission.

It should be noted that the electrical length from the point of symmetry at the junction of the arms of hybrid 10 to the corresponding point in hybrid 11, as measured through the path comprising the S arms thereof and section 21, should be related by substantially an even multiple of half wavelengths to the length of the path as measured through the P arm of one hybrid, the round trip through guide 15 to plate 18 and through the P arm of the other hybrid. Phase shift means may be inserted at a convenient point in either path, for example, such as a phase shifting vane 34, which may be of dielectric material, to adjust small differences in the electrical length of the paths.

If, however, these path lengths differ by odd multiples of one-half wavelength, operation as a circulator still obtains except that conduction will be found between the terminals in the successive order *a*, *d*, *c*, *b*. Reversing the direction of rotation produced by element 19 from that shown on the drawing will likewise cause conduction in the order *a*, *d*, *c*, *b*.

While particular arms of hybrids 10 and 11, labeled according to accepted standards, have been illustrated as connected in a particular order to facilitate explanation of the basic operation of the circulator, it should be noted that a connection of any two of the four arms of one hybrid to any two of the other in the manner described will render circulator action in which the order of conduction between the circulator terminals may be easily predicted in view of the foregoing explanation.

What is claimed is:

1. A gyrator for introducing a non-reciprocal phase inversion to electromagnetic wave energy comprising a

section of wave guide adapted to support electromagnetic wave energy in orthogonal polarizations, a pair of polarization-selective wave-guide connections at one end of said guide each adapted to couple to and from one of said orthogonal polarizations of wave energy in said one end, a polarization-indifferent reflecting termination comprising means for reflecting wave energy of arbitrary polarization substantially completely with equal amounts of phase shift spaced at the other end of said guide at a location electrically and physically equivalent for said arbitrarily polarized wave energy, and an antireciprocal rotator for said energy interposed in said guide between said ends and having an angle of rotation equal to 45 degrees.

2. The apparatus of claim 1, wherein said reflecting termination comprises a conductive sheet extending transversely across and completely closing said guide.

3. The gyrator of claim 1 in combination with a pair of hybrid junctions, each having four arms, one arm of each hybrid being connected to one arm of the other hybrid, and another arm of each hybrid being connected, respectively, to one of said connections.

4. Apparatus for introducing a non-reciprocal phase shift to electromagnetic wave energy comprising a section of circular wave guide, a first connection coupled to said guide to a preferred plane of wave energy polarization therein, a second connection coupled to said guide to another preferred plane of polarization therein, said other plane being related by a given angle to said first mentioned plane, reflecting means disposed in said guide at a location electrically and physically equivalent for all wave energy polarizations to reflect wave energy in both of two planes of polarization related to each other by an angle equal to said given angle, and an antireciprocal rotator for said energy interposed in said guide between said connections and said reflecting means, said rotator having an angle of rotation equal to one half said given angle.

5. The apparatus of claim 4, wherein said rotator produces an angle of rotation of 45 degrees and wherein said reflecting means comprises a conductive plate terminating said guide.

6. A non-reciprocal multibranch network comprising a section of wave guide adapted to support electromagnetic wave energy in orthogonal polarizations, a pair of polarization-selective wave guide connections at one end of said guide each adapted to couple to and from one of said orthogonal polarizations of wave energy in said one end, a polarization-indifferent reflecting termination for said wave energy at the other end of said guide, an antireciprocal rotator for said energy interposed in said guide between said ends and having an angle of rotation equal to 45 degrees, and a pair of hybrid junctions each having four arms with one arm of each hybrid being connected to one arm of the other hybrid and another arm of each hybrid being connected, respectively, to one of said connections.

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