Nov. 17, 1959 A. G. FOX 2,913,678

NONRECIPROCAL CIRCUIT ELEMENT

Filed Aug. 6, 1956 3 Sheets-Sheet 1

FIG. 1

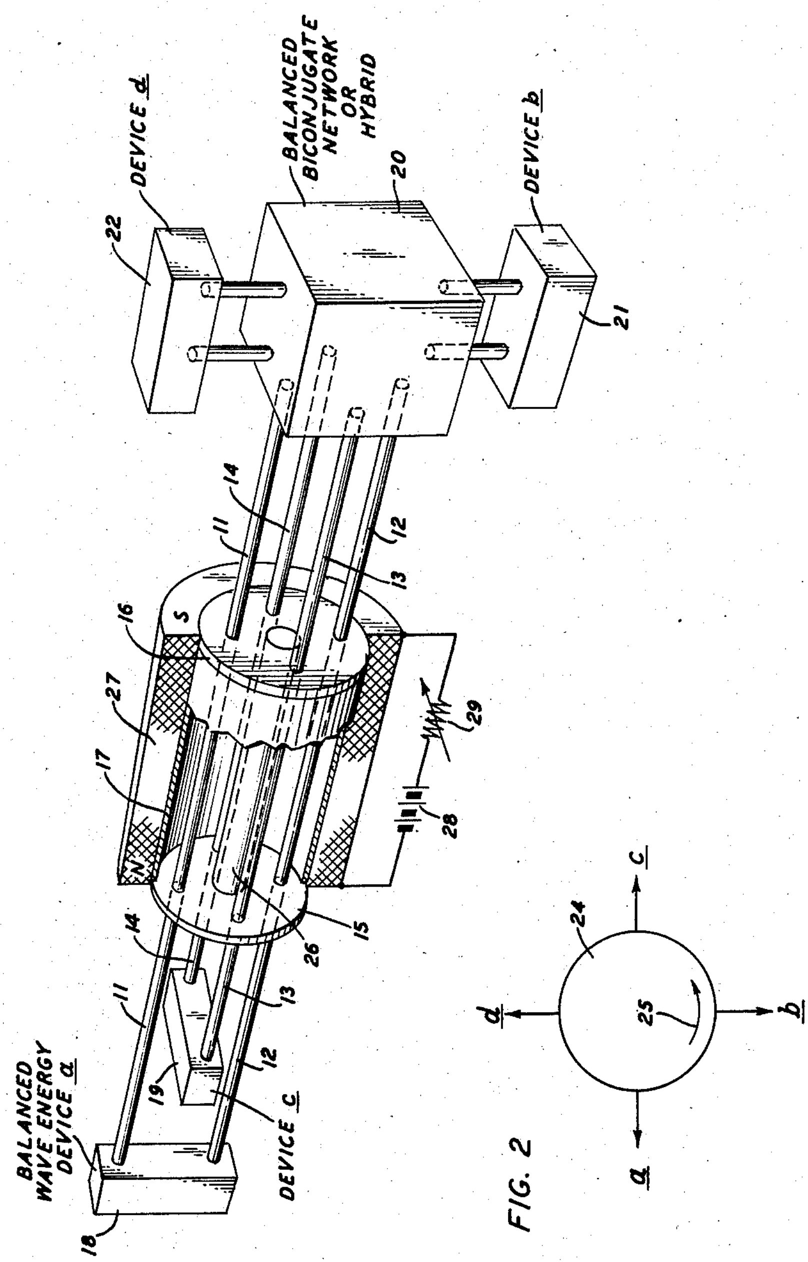



FIG. 2

INVENTOR
A. G. FOX
BY Roy M. Porter, Jr.

ATTORNEY

Nov. 17, 1959 A. G. FOX 2,913,678

NONRECIPROCAL CIRCUIT ELEMENT

Filed Aug. 6, 1956 3 Sheets-Sheet 2

FIG. 3

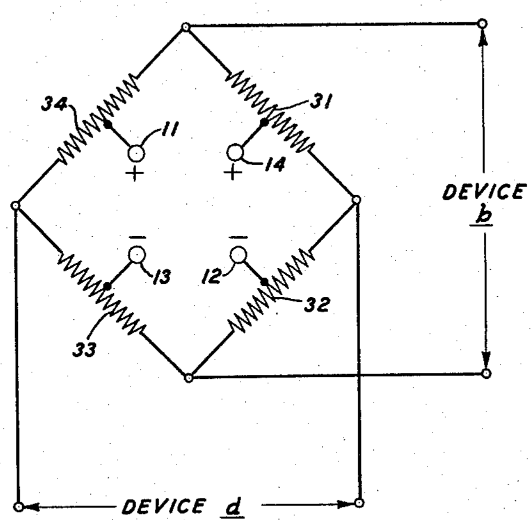
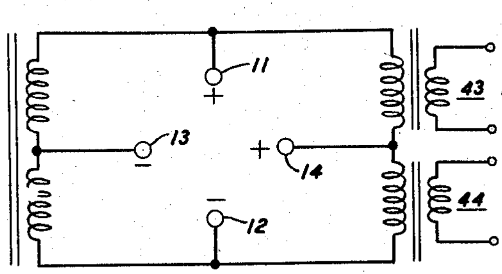



FIG. 4




INVENTOR
A. G. FOX
BY Roy M. Porter, Jr.
ATTORNEY

NONRECIPROCAL CIRCUIT ELEMENT

Filed Aug. 6, 1956 3 Sheets-Sheet 3

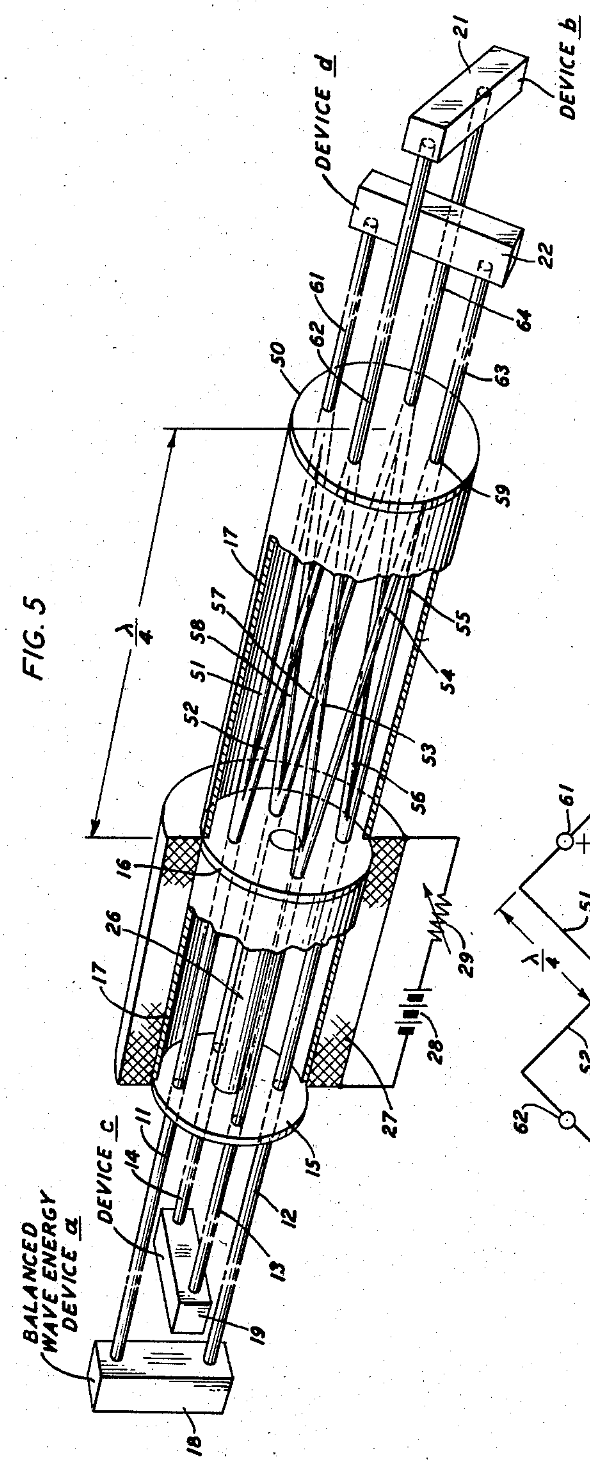



FIG. 5

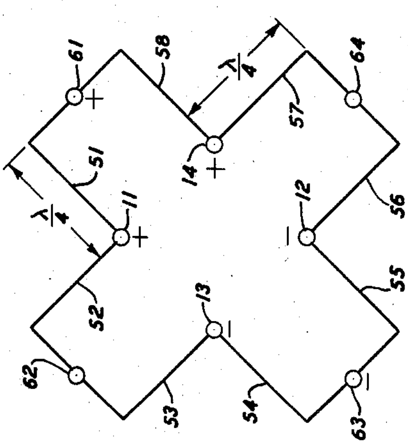



FIG. 6

INVENTOR
A. G. FOX
BY Roy M. Porter Jr.

ATTORNEY

2,913,678
Patented Nov. 17, 1959



2,913,678

# NONRECIPROCAL CIRCUIT ELEMENT

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

Application August 6, 1956, Serial No. 602,100

6 Claims. (Cl. 333—9)

This invention relates to nonreciprocal transmission circuits for electromagnetic wave energy, and more particularly to multibranch networks for establishing nonreciprocal connections for electromagnetic wave energy between a plurality of electromagnetic wave devices.

It is an object of the invention to couple electromagnetic wave energy from one balanced transmission line pair exclusively to a second transmission line pair for one direction of transmission therebetween and to a different transmission line pair for the opposite direction of transmission.

In the copending applications of J. H. Rowen, Serial No. 544,783 filed November 3, 1955, and Serial No. 485,280, filed January 31, 1955, and the application of A. M. Clogston, Serial No. 485,281, filed January 31, 1955, there are disclosed structures and techniques for utilizing one or more of the several nonreciprocal effects produced by polarized elements of gyromagnetic material such as ferrite at frequencies of wave energy below a few thousand megacycles. These structures comprise two branch coaxial or balanced transmission line networks capable of introducing either a nonreciprocal attenuation or a nonreciprocal phase shift to wave energy in the frequency ranges in which coaxial and balanced transmission lines are used. These frequency ranges include those designated very high frequency and ultrahigh frequency.

In accordance with the present invention these techniques are extended to a four-branch coupling circuit known as a circulator. A description of the wave guide or microwave counterpart of this circulator together with its principles of operation and its uses is to be found in an article entitled "Behavior and Applications of Ferrites in the Microwave Range" by A. G. Fox, S. E. Miller and M. T. Weiss, Bell System Technical Journal, January 1955, pages 5 through 103. The present invention fills the need for a similar circuit component for use at frequencies below the microwave range where wave guide techniques and apparatus are not applicable.

In a particular embodiment of the present invention four conductors are arranged in diametrically opposite pairs with a longitudinally biased gyromagnetic element centrally disposed with respect to said conductors. Wave energy components applied from a connected electromagnetic wave device to one end of a first of the pairs will be transferred to the second of the pairs by the precessing electrons within the gyromagnetic material. As the energy propagates toward the other end of the structure, one-half of the applied energy will eventually be transferred to the second pair in a given phase. The other ends of the pairs are terminated respectively in two of the branches of a suitable four-branch biconjugate or hybrid network so that the equal components are recombined in one of the remaining branches of the hybrid for delivery to a second connected device. Comparing the transfer of energy between the pairs by the electron precession for opposite directions of propagation, it will be seen to be nonreciprocal in phase so that if wave energy is initially applied from a third device to the second pair of conductors, one-half of it will be transferred to the first pair in such a phase that when the halves are recombined in the hybrid, they appear in phase in the fourth branch thereof for delivery to a fourth connected device. The resulting coupling is characteristic of the circulator circuit for which numerous uses and applications as a component are well known in the art.



Features of the invention reside in the forms of biconjugate or hybrid network employed by the invention which are particularly suited for use with diametrically disposed conductor pairs.

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

In the drawings:

Fig. 1 is a view of a circulator in accordance with the invention, partially in perspective and partially in schematic, interposed schematically between four balanced wave energy devices to be interconnected;

Fig. 2 is a schematic representation of the coupling characteristic exhibited by the circulator of Fig. 1;

Figs. 3 and 4 are schematic representations of typical biconjugate networks which can be employed in the combination of Fig. 1;

Fig. 5 is a perspective view of another embodiment in accordance with the invention employing a particular biconjugate network; and

Fig. 6 is a schematic representation of the biconjugate network portion of the embodiment of Fig. 5.

Referring more particularly to Fig. 1, an illustrative embodiment of a circulator circuit in accordance with the invention is shown. This circuit comprises four similar, elongated conductors or wires **11** through **14** that extend parallel to each other longitudinally and are located transversely at equally spaced points around the circumference of the circle. The radius of each conductor should be small compared to the distance between the nearest conductor centers. Thin transversely extending dielectric spacers **15** and **16** are longitudinally spaced to support the conductors relative to each other in this relationship. Support is also provided by a rigid cylindrical shield **17** which may be made of conductive, nonconductive or electrically dissipative material. Shield **17** protects conductors **11** through **14** from outside mechanical and electrical influences but otherwise plays no substantial part in the electrical operation of this embodiment.

The left hand extensions of diametrically opposed conductors **11** and **12** comprising one pair are connected to a balanced electromagnetic wave device *a* represented schematically by **18**. This device may be a source of wave energy, a load circuit or other wave energy utilizing device, or a coupling transducer which in turn couples to a source or a load depending upon the particular application. The connection from device **18** to a pair **11—12** is such that coupling is provided to and from wave energy of maximum voltage intensity lying in the plane of the pair. A similar device *c*, represented schematically by **19** is connected to the pair comprising conductors **13** and **14**. The right hand ends of pair **11—12** and a pair **13—14** are connected to a hybrid network schematically represented by **20** capable of deriving voltages representing the vector sum of the voltages supported by the pairs in one output and the vector difference of said voltages in a second output.

More particularly, a network **20** is a balanced eight terminal or four-branch biconjugate network or hybrid of which many forms, both tuned and untuned, are known to the art. These networks all have the property that energy applied to one branch thereof will not appear in a second branch thereof, but will be divided into equal inphase portions in the third and fourth branches. Energy applied to the second branch will not appear in the first, but will be divided into equal out-of-phase portions in the third and fourth branches. Thus if equal components that are "inphase" according to the above characterization are applied by way of pairs **11—12** and **13—14** to network **20**, the components will combine in the third branch of network **20** for delivery to device *b* represented by **21**. However, if equal components having a relative phase 180 degrees different from the preceding inphase condition are applied by way of pairs **11—12**, **13—14**, the components will combine in the fourth branch of network **20** for delivery to device *d* represented by **22**.

In the region between the left and right ends of the pairs thus arranged, a nonreciprocal coupling is provided by an elongated cylinder or pencil-shaped element **26** of gyromagnetic material similarly disposed with respect to conductors **11** through **14** and extending longitudinally along the center of the circle defined by the transverse locations of the conductors. Element **26** may be supported in this position by extending it through centrally located apertures in spacers **15** and **16**.

The material of element **26** is of the type having electrical and magnetic properties of the type described by the mathematical analysis of D. Polder in Philosophical Magazine, January 1949, volume 40, pages 99 through 115. More specifically, element **26** may be made of any of the several ferromagnetic materials combined in a spinel structure. For example, it may comprise iron oxide with a small quantity of one or more bivalent metals such as nickel, magnesium, zinc, manganese, aluminum, or other similar material in which the other metals combine with the iron oxide in a spinel structure. This material is known as a ferromagnetic spinel or as ferrite. Frequently these materials are first powdered and then molded with a small percentage of plastic material according to the process described in the publication of C. L. Hogan, "The Microwave Gyrator" in the Bell System Technical Journal, January 1952. One specific material which is particularly suitable at the lower frequencies contemplated by the present invention is magnesium-manganese-aluminum ferrite which has been found to exhibit a ferromagnetic resonance effect at a lower frequency range than prior considered ferrites.

Element **26** is biased by a polarizing magnetic field applied parallel to conductors **11** through **14**. This field may be supplied by a solenoid **27** mounted upon the outside of shield **17** and supplied by an energizing current from source **28** through rheostat **29**. It should be noted, however, that element **26** may be magnetized by a solenoid of other suitable physical design, by a permanent magnet structure, or the material of element **26** may be permanently magnetized.

The coupling produced by element **26** can be explained by the recognition that the gyromagnetic material of element **26** contains unpaired electron spins which tend to line up with the applied field. These spins have an associated magnetic moment which can be made to precess about the line of the biasing magnetic field, keeping an essentially constant moment component in the direction of the applied biasing field and at the same time providing a moment component which may rotate in a plane normal to the field direction. Thus when a reciprocating high frequency magnetic field of electromagnetic wave energy is impressed upon the moment, the moment will commence to precess in one angular sense.

The combined effect of many such electrons and their associated moments produces in the gyromagnetic material not only a flux representing the impressed magnetic field but also a flux representing a reciprocating field at right angles in space to the applied field and displaced in time from the applied field by a phase determined by the direction of precession of the electrons and independent of the direction of propagation of a wave along the lines. The amplitude of the coupled wave depends upon the parameters of the ferrite and may also be controlled by the strength of the biasing magnetic field.

Thus, when an electromagnetic wave is applied from device *a* to pair **11—12**, an electric field will be set up between the conductors with a magnetic field concentric with each conductor and having a maximum concentration extending between the conductors in a plane normal to the plane of the conductors. When this field encounters element **26** an induced magnetic field will be produced normal to the exciting field which in turn produces an electric field extending between pair **13—14**. Initially, this induced field will be small but as the distance from the excited end is increased, the field becomes increasingly larger. At an appropriate electrical distance to the right, depending in a given structure upon its physical length and the biasing field strength, the induced field contains one-half of the energy. For the biasing field polarity indicated on the drawing, the phase of this induced energy relative to the remaining portion of the excited energy on pair **11—12** is such that when conductor **11** is positive with respect to conductor **12**, conductor **13** is positive with respect to conductor **14**. Defining this relation as "inphase," the two components will appear in one of the outputs of network **20**, defined as the "inphase" output, for delivery to device *b*. If a voltage wave had been initially applied to pair **13—14**, however, as from device *c*, the constant direction of electron precession within element **26** will induce on pair **11—12** an "out-of-phase" voltage making conductor **12** positive with respect to conductor **11** when conductor **13** is positive with respect to conductor **14**. These two components will then appear in the other output of network **20**, defined as the "out-of-phase" output, for delivery to device *d*.

The coupling thus far established is schematically represented on Fig. 2 by the radial arrows *a*, *b*, *c* and *d* associated with the ring **24** and arrow **25** diametrically indicating the coupling from *a* to *b* and *c* to *d*.

If energy were applied from device *b* acting now as a source of wave energy, it will be divided by network **20** into equal inphase components upon pairs **11—12** and **13—14** for propagation to the left. Since the transfer of energy between the pairs is antireciprocal, i.e. it continues in the same sense regardless of the direction of propagation, the components supported between pair **11—12** will be transferred to pair **13—14** as the wave propagates to the left for delivery to device *c*. This transmission is indicated schematically on Fig. 2 by the arrow **25** which indicates coupling between *b* and *c*. Similarly, if energy is introduced initially from device *d*, it will appear at the left hand end **11—12** for delivery to device *a*. This coupling is similarly indicated on Fig. 2 by the schematic coupling between branches *d* and *a*. Thus each branch is coupled around the circle **24** to only one other terminal for a given direction of transmission but to a different terminal for the opposite direction of transmission. This is the characteristic typical of the group of coupling circuits known as circulators.

Referring to Fig. 3, a biconjugated network of resistances is illustrated that may be employed for network **20** of Fig. 1. As illustrated, this network comprises four, equal center tapped resistances **31** through **34** arranged in a bridge. The center tap of resistance **34** would be connected to conductor **11**, as illustrated, and the center tap of resistance **31**, **32** and **33** would similarly be connected to conductors **14**, **12** and **13** respectively. The circuit supplying device *b* is connected between the common junction of resistances **31** and **34** and the common junction of resistances **32** and **33**. Similarly the circuit supplying device *d* is connected between the junction of resistances **33** and **34** and resistances **31** and **32**. Thus, when equal voltages are applied across pair **11—12** with conductor **11** positive and across pair **13—14** with conductor **14** positive as represented by the symbols associated on the drawing with the conductors, the individual contributions are additive for device *b* and cancel at device *d*. If either one of the voltages represented is reversed in phase, the sum will appear at device *d* and cancel at device *b*. The advantages of such a network are its simplicity and broad band while its disadvantage lies in the power lost through dissipation in the resistance.

A biconjugate network having negligible dissipation and suitable for use at relatively low frequencies is shown in Fig. 4 and comprises a center tapped inductance or autotransformer **41** connected between conductors **11** and **12** with the center tap **42** connected to conductor **13**, a transformer **43** having its primary connected between conductors **11** and **14**, and a transformer **44** having its primary connected between conductors **14** and **12**. If equal voltages are applied across pair **11—12** with conductor **11** positve and pair **13—14** with conductor **14** positive as represented by the symbols associated with the conductors, the contributions are additive in the secondary of transformer **44** for delivery to device *b* and are in cancelling relationship in the secondary of transformer **43**. On the other hand, if either voltage applied to the conductor pairs is reversed in phase, wave energy is delivered to device *d* and not to device *b*. It should be understood that Figs. 3 and 4 are illustrative of only two suitable biconjugate circuits which are adaptable to the principles of the invention. The adaptation of other circuits will readily occur to one skilled in the art.

Fig. 5 illustrates a novel form of biconjugate network that is particularly well suited for use in the present invention at higher frequencies. This circuit is specifically disclosed and claimed in my copending application Serial No. 602,101, filed August 6, 1956. Essentially this network comprises four quarter wave shorted sections of transmission line connected between adjacent ones of conductors **11** through **14** with the shorted point of each line being made available as one output terminal. As shown on Fig. 5, supporting shield **17** of a structure substantially identical to that disclosed in Fig. 1, extends to the right an odd multiple of one-quarter wave lengths of the means operating frequency. The right hand end of shield **17** is closed by dielectric spacer **50** similar to spacers **15** and **16**. Shield **17** and spacer **50** provide support for the right hand ends of eight conductive elements **51** through **58** which each extend, in the manner to be described, from the right hand end of one of conductors **11** through **14** through one of the four apertures **59** provided in spacer **50** to receive the conductors. Each of apertures **59** is displaced about the longitudinal axis of the structure 45 degrees from or midway between the two circumferentially adjacent apertures in spacer **16**. Four conductive elements **61** through **64** emerge to the right of spacer **50** and form the two orthoganally related conductor pairs or output branches which are in turn connected to devices *b* and *d*. More particularly, each conductor of the first group **11** through **14** is joined with or forks with two conductors of the group **51** through **58** each of which in turn is connected to one of the circumferentially adjacent output conductors. For example, conductor **13** of pair **13—14** is connected by conductor **53** to conductor **62** of pair **62—64** and by conductor **54** to conductor **63** of pair **63—61**. Similarly, conductor **14** of pair **13—14** is connected by conductor **57** to conductor **64** of pair **62—64** and by conductor **58** to conductor **61** of pair **63—61**. In like manner the conductors **11** and **12** of pair **11—12** are connected by conductors **51** and **52**, and by conductors **55** and **56** to the conductors of the output pairs.

The diameters of conductors **51** through **58** are preferably smaller than the diameters of conductors **11** through **14** and **61** through **64** with the diameters relatively proportioned according to principles familiar to the art so that an impedance match is obtained between a single conductor, such as **13**, at the point where it forms a junction with a double conductor such as **53** and **54**.

Electrically, conductors **51** through **58** appear as schematically represented in Fig. 6 and constitute means for coupling to and from a resultant of the total energy supported by pair **11—12** and pair **13—14** that lies at 45 degrees to the plane of either of the pairs. Thus, if equal voltages are applied across pair **11—12** with conductor **11** positive and across pair **13—14** with conductor **14** positive, as represented on Fig. 6 by the symbols on the conductors, a voltage appears across pair **61—63** with conductor **61** positive and conductor **63** negative, representing the resultant of the two original voltages. No voltage appears between conductors **62** and **64** which are at the same potential. The nature of the quarter wave line **56—57** is such that it presents a high impedance between conductors **12** and **14** and line **53—52** between conductors **13** and **11**. If either one of the voltages on pair **11—12** or pair **13—14** is reversed, the resultant will appear between conductors **62** and **64** with no voltage between **63** and **61**.

In all cases it is understood that the above-described arrangements are illustrative of a small number of the many specific embodiments which can represent applications of the principles of the invention. Numerous and varied other 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 nonreciprocal component comprising a plurality of elongated conductors being disposed symmetrically relative to each other in diametrically opposite pairs with each conductor of one pair having adjacent to it conductors of the other pair, an elongated element of polarized gyromagnetic material centrally disposed with respect to said conductors, said conductors and said element being parallel to each other between their longitudinal ends, means for coupling electromagnetic wave energy supported between the conductors of one of said pairs to and from one end of said pair, means for coupling electromagnetic wave energy supported between the conductors of the other of said pairs to and from one end of said other pair, and a four-branch biconjugate network having two of its branches connected respectively to the other ends of each of said pairs with the remaining two of said branches comprising means for coupling electromagnetic wave energy to and from said network.

2. The combination according to claim 1 wherein said biconjugate network comprises a bridge of four center tapped resistances in which connections between opposite center taps comprises two of said branches and in which connection between opposite junctions comprises the remaining two of said branches.

3. The combination according to claim 1 wherein said biconjugate network comprises quarter wave shorted stubs connected between adjacent conductors, said remaining branches comprising the connections between the shorted point of oppositely disposed stubs.

4. A nonreciprocal coupling element comprising first and second pairs of transmission lines each comprising two elongated conductors spaced from and extending longitudinally parallel to and conductively isolated from each other along a major portion of their lengths, means for coupling said lines with a nonreciprocal coupling comprising a polarized element of gyromagnetic material extending in a space occupied in common by the magnetic fields of voltage waves conducted between said lines, and a four-branch biconjugate network having two branches thereof connected one each across said first and second pairs at one of their ends.

5. The combination according to claim 4 including an electromagnetic wave device connected across the other

ends of each of said pairs and an electromagnetic wave device connected across each of the remaining branches of said biconjugate network.

6. A nonreciprocal component comprising a plurality elongated conductors being disposed symmetrically around the circumference of a circle with one conductor diametrically opposite each conductor and two conductors circumferentially adjacent each conductor, an elongated element of polarized gyromagnetic material centrally disposed with respect to said conductors, said conductors and said element being parallel to each other between their longitudinal ends, means for coupling electromagnetic wave energy supported between one pair of opposite conductors to and from one end of said pair, means for coupling electromagnetic wave energy supported between another pair of opposite conductors to and from one end of said pair, and means for bridging the other ends of adjacent conductors to derive a voltage representing the vector sum of the voltages supported by the two pairs for delivery to one circuit and to derive a voltage representing the vector difference of said voltages for delivery to a second circuit.

**References Cited** in the file of this patent

UNITED STATES PATENTS

| | | |
|---|---|---|
| 2,788,396 | Abraham | Apr. 9, 1957 |
| 2,849,683 | Miller | Aug. 26, 1958 |

FOREIGN PATENTS

| | | |
|---|---|---|
| 644,768 | Great Britain | Oct. 18, 1950 |
| 1,111,860 | France | Nov. 2, 1955 |
| 938,021 | Germany | Jan. 19, 1956 |
| 541,439 | Italy | Mar. 29, 1956 |