Nov. 21, 1961

H. SEIDEL

3,010,085

ISOLATORS IN LUMPED CONSTANT SYSTEMS

Filed Nov. 17, 1958

2 Sheets-Sheet 1

FIG. 1

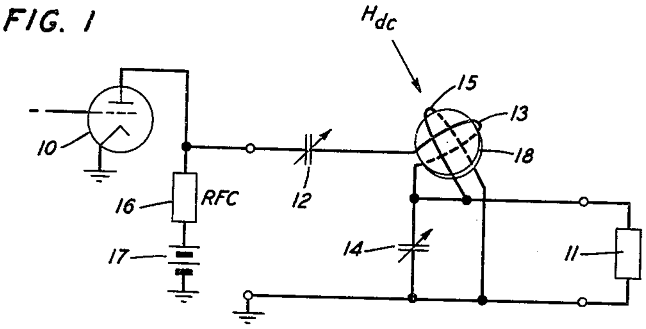


FIG. 3

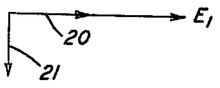


FIG. 2

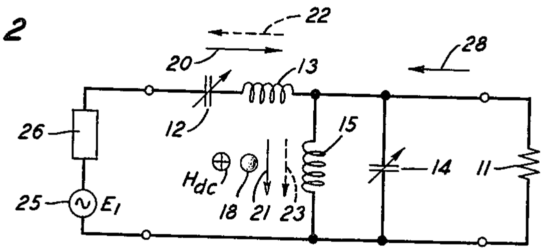


FIG. 4

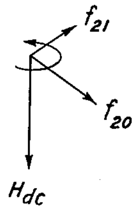


FIG. 5

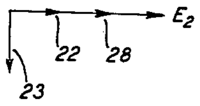


FIG. 6

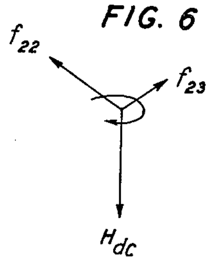


FIG. 8

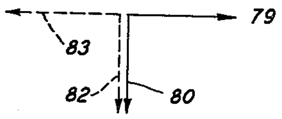
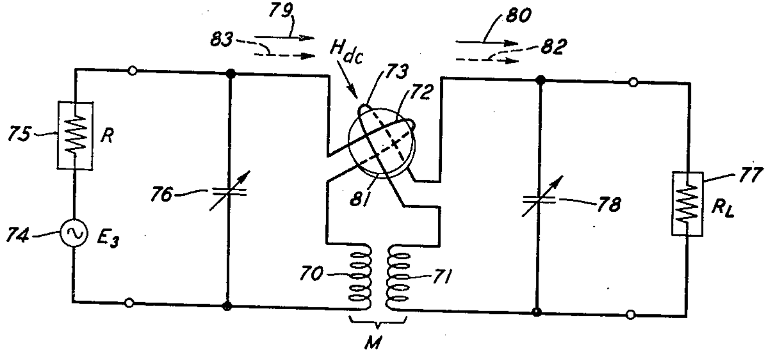


FIG. 7



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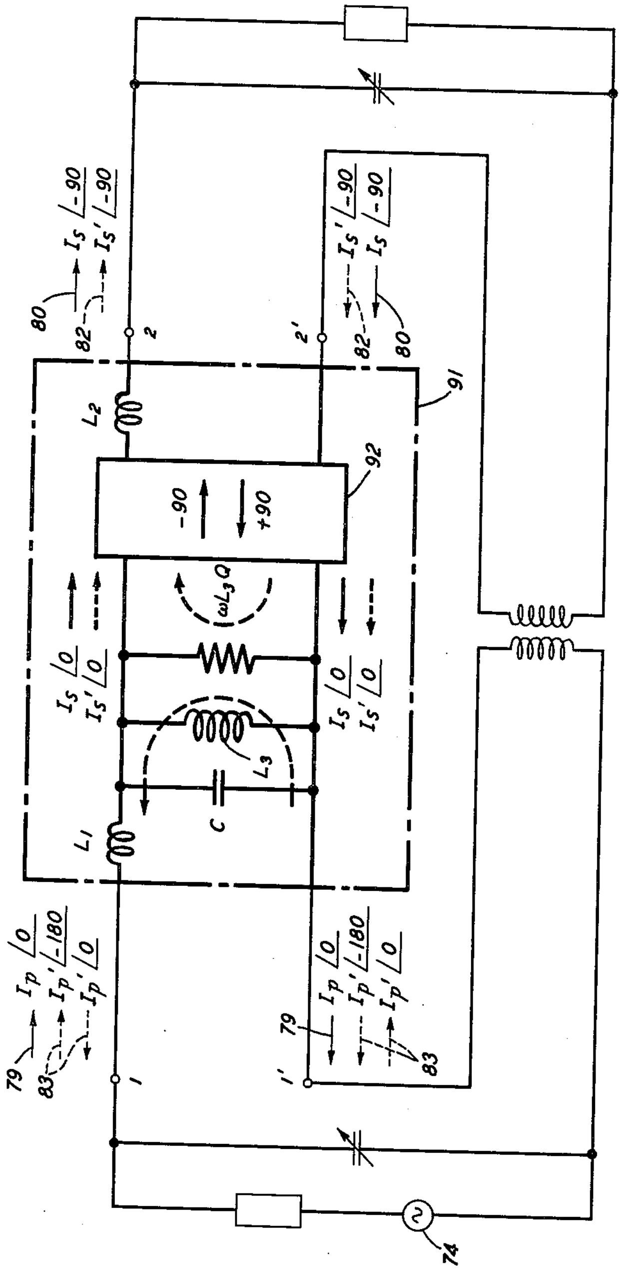
2 Sheets-Sheet 2

FIG. 9



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United States Patent Office

3,010,085

Patented Nov. 21, 1961

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ISOLATORS IN LUMPED CONSTANT SYSTEMS

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Filed Nov. 17, 1958, Ser. No. 774,389
3 Claims. (Cl. 333—24)

This invention relates to nonreciprocal transmission circuits for electromagnetic wave energy and more particularly to isolators in lumped constant systems.

The use of materials having gyromagnetic properties to obtain both reciprocal and nonreciprocal effects in microwave transmission circuits is widely known and has found numerous and varied application in propagation structures of both the waveguide and the transmission line types. A résumé of the early work done using distributed circuit elements is contained in technical papers too numerous to mention. It has become apparent, however, that the need for nonreciprocal circuit elements is at least as great in the lower frequency ranges in which lumped circuit elements are normally used.

Included among the new transmission components that have found widespread use in the microwave art and which would be very useful in the low frequency lumped constant circuits is the so-called "isolator." The isolator may be defined as a circuit element which is transparent to electromagnetic transmissions in one direction, designated the forward direction, whereas electromagnetic transmissions in the opposite or reverse direction are attenuated.

Included among the several types of isolators known to the prior art is the so-called "resonant isolator." The resonant isolator operates by virtue of the absorption of power by the magnetically biased gyromagnetic material from a circularly polarized radio frequency magnetic field. Nonreciprocal attenuation effects are produced as a consequence of the ability of the magnetically polarized gyromagnetic material to distinguish between oppositely rotating magnetic fields. Thus, energy is only absorbed for one sense of polarization.

It is therefore an object of this invention to induce circularly polarized magnetic radio frequency fields in a gyromagnetic material in a lumped constant electrical system.

It is a further object of this invention that the sense of said circularly polarized magnetic fields be reversed for opposite directions of transmission through said system.

In accordance with the invention, a circularly polarized wave is induced in a resonantly biased element of gyromagnetic material by simultaneously controlling the relative time phase and space phase of a pair of intersecting radio frequency magnetic field components. Reciprocal and nonreciprocal coupling means are provided between the input and output meshes of a lumped constant network. In accordance with the invention, the couplings and the associated components of the network are adjusted to establish a pair of radio frequency magnetic field components that have a relative time phase β, and a relative space phase α, such that $\beta=[(2n+1)\pi-\alpha]$, where n is an integer. The relative time phase of one of the induced fields is further adjusted to be either lagging or leading with respect to the other of said fields depending upon the direction of propagation through the network. As a consequence, the resulting magnetic field is a circularly polarized field having a sense of rotation which depends upon the direction of transmission through the network.

Nonreciprocal coupling between the meshes is provided by an element of resonantly biased gyromagnetic material disposed in the region of the rotating magnetic field. The gyromagnetic material is loosely coupled to the network. Because of the loose coupling the energy exchange process between the network and the gyromagnetic material may be thought of in terms of a perturbation phenomenon.

Isolator effects occur as a result of the nonreciprocal coupling produced by the gyromagnetic material in response to the action of the circularly polarized magnetic fields.

In a first embodiment of the invention, both the reciprocal and the nonreciprocal coupling between the input and output circuits utilize a common circuit component. In this embodiment, the mutual coupling between the input and output circuits is provided by an inductive coil which is also part of the nonreciprocal coupling mechanism. The latter comprises a pair of coils and an element of resonantly biased gyromagnetic material. The rotating field effect is obtained by winding the pair of coils on the gyromagnetic material so that their axes are normal to each other, and by energizing the coils 90° out of time phase.

In a second embodiment of the invention, the reciprocal and nonreciprocal couplings are independently performed by separate transformers. As in the first embodiment, the time and space relationships of the magnetic field components in the region of the gyromagnetic material are such as to produce a circularly polarized magnetic field having a sense of rotation which varies as a function of the direction of transmission through the system.

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 combined schematic and perspective view of the first embodiment of the invention;

FIG. 2 is a schematic diagram of the isolator illustrated in FIG. 1;

FIG. 3 shows, by way of illustration, the time relationships of the energizing currents for transmission in the forward direction;

FIG. 4 shows, by way of illustration, the space orientation of the polarizing direct-current field and the radio frequency field components for transmission in the forward direction;

FIG. 5 shows, by way of illustration, the time relationships of the energizing currents for transmission in the reverse direction;

FIG. 6 shows, by way of illustration, the space orientation of the polarizing direct-current field and the radio frequency field components for transmission in the reverse directions;

FIG. 7 is a schematic diagram of the second embodiment of the invention showing separate reciprocal and nonreciprocal coupling means;

FIG. 8 is a time vector diagram of the energizing currents in the second embodiment of the invention for transmission in the forward and reverse directions; and

FIG. 9 is a circuit diagram of the equivalent circuit of the nonreciprocal coupling means showing the current relationships for transmission in the forward and in the reverse directions.

Referring more particularly to FIG. 1, a combination electrical schematic and perspective view of a first illustrative embodiment of the present invention is shown connected and utilized to produce nonreciprocal attenuation at the lower radio frequencies normally encountered in lumped constant systems.

As shown in FIG. 1, the isolator is interposed between a source of radio frequency excitation represented, for example, by a vacuum tube **10**, and an output circuit represented by load impedance **11**. The isolator itself comprises a pair of resonant circuits arranged in two meshes. The first, or input mesh which connects to the source of excitation **10** comprises the series-connected resonant circuit including variable capacitor **12** and inductor **13**. (A high-impedance radio frequency choke **16** is connected across the input to the isolator merely to provide direct-current continuity from a source of direct-current potential **17** to vacuum tube **10**.) The second, or output mesh connects to the load **11**. The input and output meshes are mutually coupled by a combination of reciprocal and nonreciprocal coupling means. Reciprocal coupling is provided by the second resonant circuit which comprises the shunt-connected variable capacitor **14** and inductor **15**. Nonreciprocal coupling between the meshes is provided by means of inductor **13** and **15** and a disc **18** of gyromagnetic material. 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 significant precessional motion at a frequency within 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 materials 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. In the particular embodiment of the invention shown in FIG. 1, a disc of aluminum-substituted yttrium iron oxide is used.

In particular, the coils 13 and 15 are wound on a common core **18** of gyromagnetic material so that their axes, and consequently their magnetic fields, intersect at right angles to each other. So wound, there is substantially no direct coupling between the two coils as a result of their physical relationship to each other. In accordance with the invention, the core material is loosely coupled to the coils, the coupling being in the range of critical coupling or below. As such, the degree of coupling between the coils which results as a consequence of the presence of core **18** is small compared to the reciprocal coupling and for the purposes of the invention may be neglected.

The core **18** is in the shape of a disc with its faces parallel to the plane of the axes of cores 13 and 15. A static magnetic field H_{dc} is applied normal to the faces of the disc and is adjusted to produce gyromagnetic resonance at the frequency of interest.

The biasing field may be supplied by any suitable means (not shown) such as an electric solenoid, a permanent magnetic structure or, in some instances, the core **18** may be permanently magnetized.

To produce isolator action, conditions must be established whereby energy can be dissipated in one direction of transmission to a substantially smaller degree than in the reverse direction of transmission. In the isolators constructed in accordance with the invention, the phenomenon of gyromagnetic resonance is utilized to provide the necessary loss mechanism. At is well known, magnetically polarized gyromagnetic materials exhibit distinctly different properties depending upon the nature of the applied magnetic fields. These unusual properties which are produced can be explained by recognizing that

the gyromagnetic materials contain unpaired electron or nuclear spins which tend to align themselves with the polarizing field but which can be made to precess about an axis parallel to the direction of this field by the application of a high-frequency magnetic field. The magnetic moments associated with the spinning atomic particles, however, tend to precess in only one angular sense and will resist rotation in the opposite sense. It is therefore evident that oppositely circularly polarized waves influence the gyromagnetic material differently, depending upon their sense of rotation. This is so since a circularly polarized wave rotating in one direction will be rotating in the easy angular direction of precession of the magnetic moments whereas an oppositely rotating circular polarized wave will be rotating in a sense inconsistent with the natural behavior of the magnetic moments of the gyromagnetic material. As a consequence, when the high-frequency magnetic field is rotating in the same sense as the preferred direction for precession of the magnetic moments, it couples strongly to the gyromagnetic material. However, very little coupling takes place between the external magnetic field and the magnetic moments when the high-frequency magnetic intensity is rotating in the opposite angular direction.

While this difference in coupling, and consequent difference in permeability provided by oppositely rotating circularly polarized magnetic fields is not limited to any particular frequency or polarizing field strength, particularly useful effects are observed at gyromagnetic resonance when the frequency of the circularly polarized magnetic field is the same as the natural precessional frequency of the magnetic moments as determined by the strength of the polarizing field. Under these particular conditions, a large amount of power can be extracted from a magnetic field circularly polarized in the preferred sense and absorbed in the gyromagnetic material. However, very little power is absorbed from an oppositely circularly polarized component.

It is apparent, therefore, that a circularly polarized magnetic field must be generated whose sense of rotation is dependent upon the direction of propagation of the signal through the network.

FIG. 2 is an electrical schematic representation of the embodiment of the invention shown in FIG. 1, which is included to demonstrate how the necessary circularly polarized magnetic field conditions are realized. In this schematic representation, the corresponding reference numerals used in FIG. 1 are also used in FIG. 2 whenever possible.

If the operation of the circuit is thought of in terms of a perturbation phenomenon, the device may be considered as comprising an input and an output branch coupled by means of a pair of electrically independent coupling paths. The first coupling path includes a reciprocal coupling means for exciting coils **13** and **15** ninety degrees out of time phase. The second coupling path includes the nonreciprocal loss mechanism and comprises the gyromagnetic material **18** and coils **13** and **15**. For the sake of simplicity, in FIG. 2, certain changes and omissions have been made. For example, the vacuum tube **10** has been replaced by a generator **25** and its equivalent internal resistance **26**. The effects produced by the slight mutual coupling between coils **13** and **15**, due to the presence of the gyromagnetic core material **18**, has been omitted as has been the radio frequency choke **16**. Similarly, the load **11** is shown as a resistive impedance since any reactive component of the load may be tuned by means of capacitor **14**.

Before proceeding with a detailed discussion of the operation of the isolator, it is well to define, in a general way, the function of the several portions of the network shown in the embodiment of FIG. 1. Briefly, it is a function of the reciprocal coupling path to couple the input mesh to the output mesh and in cooperation with the other components in the network (such as the tuning capacitors) to establish the required time phase relationship between the currents in the second, or nonreciprocal coupling path. It is then the function of the nonreciprocal coupling acting upon the gyromagnetic material to produce the nonreciprocal loss effects characteristic of an isolator. If the coupling between the circuits and the gyromagnetic material is loose, as has been previously indicated, the operation of the circuit may be thought of in terms of a perturbation phenomenon and, as a first approximation, the interaction between the coupling paths may be neglected. Thus, in the following discussion, the two coupling functions are considered separately and independently.

Let us now consider the operation of the system. Under the influence of generator **25**, a current **20** is caused to flow. With both tuned circuits adjusted to resonance, this current is in time phase with the applied voltage E_1, as shown in the time vector diagram in FIG. 3. The component of current **21** flowing in inductor **15**, however, is in time quadrature with current **20** and is so shown in FIG. 3. The effect of these two currents is to produce the two magnetic field components f_{20} and f_{21} shown in the space vector diagram of FIG. 4. Because of the spatial orientation of the coils, these field components are in space quadrature as well as time quadrature and are so shown.

Because of the ninety degree times difference between current **20** and current **21**, as current **20** in coil **13** passes through its maximum amplitude and starts to decrease towards zero, current **21** in coil **15** is passing through zero and is starting to increase towards its maximum value. Correspondingly, the magnetic fields f_{20} and f_{21}, produced by the currents **20** and **21** respectively, are likewise varying in amplitude in a similar manner. The effect of having the field components f_{20} and f_{21} varying in this manner is to produce a single resultant field vector which appears to rotate in space in the region of the gyromagnetic material **18**. With the polarizing field H_{dc} directed normal to the plane of field components f_{20} and f_{21} as shown in FIG. 4, a negatively or counterclockwise rotation of the resultant magnetic field is produced when viewed along the direction of the biasing field. This sense of circularly polarized magnetic field, however, is opposite to the natural precessional sense of the magnetic moments in the gyromagnetic material and little or no interaction takes place between the electrical energy and the core material and consequently substantially all the energy is delivered to the load resistor **11**.

However, for energy transmitted in the reverse direction, the sense of rotation of the resultant magnetic field is also reversed. This may be shown by considering the effect upon the circuit when the output mesh is energized by a voltage E_2 (not shown) in series with load resistor **11**. E_2 is merely representative of a disturbance in the circuit of an undesirable nature. The resulting current **28** caused to flow by E_2 is in time phase with E_2 and is so represented in the time vector diagram in FIG. 5. The component of current **22** flowing through inductor **13** is also in time phase with E_2, whereas the component of current **23** in inductor **15** is in time quadrature with E_2. The spatial orientation of the magnetic fields produced by these currents is shown in FIG. 6. As in the case of transmission in the forward direction, the field components f_{22} and f_{23} are at right angles to each other. However, for the reverse transmission case, the direction of the current flow **22** in coil **13** is reverse with respect to current **20** and hence the field f_{22} is 180° out of phase with field f_{20}. As a consequence, the resultant field producted by fields f_{22} and f_{23} appears to rotate in a positive or clockwise sense as viewed along the direction of the biasing fields H_{dc}. This sense of rotation is the same as the preferred sense for precession of the magnetic moments in the core material and hence energy is absorbed from the circuit and dissipated in the core material.

In a second embodiment of the invention shown in FIG. 7, the reciprocal and the nonreciprocal coupling between the input and output meshes have been separately provided for. The reciprocal coupling, which establishes the necessary time phase relationship between the energizing currents, is provided by a transformer comprising coils **70** and **71**. The nonreciprocal coupling, in turn, is provided by coils **72** and **73** and gyromagnetic material **81**.

The input mesh is energized by means of generator **74** which has an output impedance **75**. Variable capacitor **76** is adjusted to tune the input mesh. The output mesh provides power to the output load **77**, and is likewise tuned to resonance by means of the variable capacitor **78**.

As a result of the excitation provided by generator **74**, a current **79** flows through coil **70** and coil **72**. With the output mesh tuned to resonance, the induced current **80** lags the primary current **79** by ninety degrees. The relationship between the currents is shown in the time vector diagram of FIG. 8. As in the embodiment shown in FIG. 1, coils **72** and **73** are wound on a common core **81** of gyromagnetic material so that their magnetic fields intersect at right angles to each other. The resulting magnetic flux produced by the coils **72** and **73** under the influence of currents **79** and **80** is circularly polarized and appears to rotate in a counterclockwise sense as viewed in the direction of the biasing field H_{dc}.

In the reverse direction, a current **82** induced by some source of excitation (not shown) in the output mesh, induces a current **83** that lags current **82** by ninety degrees. Thus, as can be seen in FIG. 8, for the reverse direction of transmission through the network, the current in coil **72** is reversed. This has the effect of reversing the sense of rotation of the resulting field vector so as to produce a resulting magnetic flux that is circularly polarized and rotating in a clockwise sense as viewed in the direction of the biasing field H_{dc}. As has been indicated previously, clockwise rotation of the magnetic field vector causes coupling to the magnetic precession of the gyromagnetic material and power dissipation.

It had been mentioned previously that the loops **13** and **15** of FIG. 1 and loops **72** and **73** of FIG. 7 are loosely coupled to the gyromagnetic material. The significance of this statement may best be understood by referring to FIG. 9 which is essentially FIG. 7 redrawn, with the nonreciprocal coupling network of loops **72**, **73** and core **81** replaced by its equivalent circuit **91**.

It may be shown that coils **72** and **73**, and element **81** may be represented by the equivalent network **91** which includes the nonreciprocal phase shifter **92** and inductors L_1, L_2, L_3, capacitor C and resistor $\omega L_3 Q$. L_1 and L_2 are primarily the self-inductance of loops **72** and **73** with a small addition due to the coupling by the gyromagnetic material. These quantities are relatively small and for the purpose of the following discussion may be neglected. The quantity L_3 is an equivalent inductance proportional to both the loop coupling to the gyromagnetic material and the actual magnetization value of the material. C is the equivalent tuning capacitor which tunes the network to gyromagnetic resonance, and the shunt resistor $\omega L_3 Q$ is defined by the material Q and the coupling L_3.

If the coupling between the loops and the gyromagnetic material is large, L_3 and consequently the shunt resistor $\omega L_3 Q$ are extremely large and the resistive interaction between the shunt resistor and the rest of the network is small. If, on the other hand, the coupling is small, there is essentially a short circuit across the network at resonance and again there is little interaction between the network and any dissipative component. However, for the range of coupling about critical coupling, the value of the shunt resistance is such as to introduce a substantial dissipative element in the circuit. It remains to be shown, however, that the lossy element $\omega L_3 Q$ is not involved in transmission in the forward direction, but is for transmission in the reverse direction.

In considering FIGS. 7 and 8, it was shown that when the input mesh was excited by generator **74**, the current **80** in coil **73** lagged the current **79** in coil **72** by ninety degrees. These currents are shown in FIG. 9 as current $I_p\underline{|0^\circ}$ entering network **91** at terminal **1** and apparently leaving by terminal **1'** and as current $I_s\underline{|-90^\circ}$ entering network **91** at terminal **2'** and apparently leaving by terminal **2**.

Referring current **80** to the input side of the nonreciprocal phase shifter **92**, the current undergoes a ninety degree phase advance and as a consequence is now in time phase with current **79**. It is as if current entering at terminal **1** leaves at terminal **2**, and current entering at terminal **2'** leaves at terminal **1'**. In this situation, continuity throughout the circuit is maintained without the necessity of any current flowing through the lossy element $\omega L_3 Q$.

For transmission in the reverse direction, however, the current **83** in the input mesh lags the current **82** in the output mesh by ninety degrees. To be consistent with the vector diagram of FIG. 8, current **82** is designated as $I_{s'}\underline{|-90^\circ}$ and current **83** is designated as $I_{p'}\underline{|-180^\circ}$. Both are shown as dotted lines. Again referring $I_{s'}$ to the input side of the nonreciprocal phase shifter **92**, the current undergoes a 90° phase advance and now has a zero phase angle associated with it. As a consequence of this phase advance, current **82** is 180° out of time phase with current **83**. This implies that the direction of flow of current $I_{p'}$ was incorrectly assumed and that in fact $I_{p'}$ actually flows in the reverse direction. If the sense of direction of $I_{p'}$ is reversed as shown in FIG. 9, then the currents $I_{s'}$ and $I_{p'}$ are in phase. It is therefore as if the currents $I_{p'}$ and $I_{s'}$ enter the nonreciprocal coupler at terminals **1'** and **2'** respectively, flow towards each other and up through the resistive element $\omega L_3 Q$, then separate and flow out through terminals **1** and **2** respectively. Thus, in the reverse direction, the lossy element in the equivalent circuit **91** is involved in the transmission path and is a measure of the attenuation experienced by signals propagating in the reverse direction.

In all preceding discussions, the rotating magnetic field induced in the gyromagnetic material was referred to as being circularly polarized. This assumes that the two orthogonally directed magnetic field components making up the equivalent rotating field are of equal amplitude. In a well-designed isolator, this will be so since any inequality in these two fields gives rise to an equivalent elliptically polarized field. Since an elliptically polarized field may be resolved into oppositely rotating circularly polarized field components, the effect is to induce losses in the system for transmission in the forward direction and to reduce the attenuation experienced in the reverse direction.

The system therefore is designed to match the load impedance to the generator source by means of the reciprocal coupler and to equalize the field components produced by the resulting energizing currents by adjusting the turns ratio of the coils associated with the nonreciprocal coupler.

It is a feature of the invention that changes in the load impedance which would normally react upon the source and in some instances adversely affect the operation of the source, instead tend to unequalize the relative amplitudes or modify the quadrature phase relationship of the orthogonal field components. This, in turn, tends to induce elliptical polarization in the gyromagnetic material. As a result of these changes in the system, the unbalance in the network does not tend to react upon the source but rather produces an unbalance in the exciting fields which results in that por-

tion of the energy that would normally be reflected being absorbed in the gyromagnetic material. This loss mechanism produces an inherent stability in the system which tends to isolate the source from any changes in the load as well as from spurious signals originating elsewhere in the system.

In the particular embodiments of the invention shown in FIGS. 1 and 7, circular polarization was induced in the gyromagnetic material by making both the time phase and the space phase of the exciting field components ninety degrees. It should be noted, however, that there are other combinations of time and space phasings which also produce a circularly polarized resultant field. It can be shown that, in general, for any arbitrary space orientation, α, of the two field components (where α is assumed to be positive) there is a time phase β that produces circular polarization, where $\beta=(2n+1)\pi-\alpha$, n being any whole number. Thus, in other circuit arrangements and for other applications which more readily lend themselves or which require time phase differences other than 90 degrees, circular polarization may nevertheless be induced by arranging the field components at an angle in accordance with the above equation.

In all cases it is understood that the above-described arrangements are illustrative of a small number of the many possible 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 passive four-terminal network comprising a pair of inductive coils having substantially mutually perpendicular axes intersecting at a point, first means for exciting said coils substantially ninety degrees out of time phase with respect to each other, second means for exciting said coils to a substantially smaller degree than said first means comprising a magnetically polarizable element exhibiting gyromagnetic effects over the operating frequency of said network located in a region including said point, and means for magnetically biasing said element in a direction normal to the plane of said intersecting axes.

2. In an electromagnetic transmission system means for producing nonreciprocal attenuation comprising a pair of conductive coils, first means for exciting said coils β degrees out of time phase with respect to each other, said coils when excited being supportive of magnetic fields having components intersecting in a region at an angle α where β equals $(2n+1)\pi-\alpha$, n being an integer, second means for exciting said coils to a substantially smaller degree than said first means comprising a magnetically polarizable element exhibiting gyromagnetic effects over the operating frequency of said system located in said region, and means for magnetically polarizing said element in a direction normal to said intersecting components.

3. In an electrical transmission system means for producing isolator effects comprising first and second serially connected inductive coils, a first condenser connected in series with said first coil to form a first resonant circuit tuned to a frequency f_1, a second condenser connected in shunt with said second coil to form a second resonant circuit tuned to said frequency f_1, the axes of said first coil being substantially perpendicular to the axes of said second coil to substantially preclude coupling therebetween, input means connected across both serially connected coils and said first condenser, output means connected across said second coil and said second condenser, nonreciprocal coupling means for loosely coupling said coils comprising a magnetically polarizable element exhibiting gyromagnetic effects over a range of frequencies including said frequency f_1 and means for magnetically

biasing said material to gyromagnetic resonance at said frequency f_1 in a direction normal to both of said axes.

References Cited in the file of this patent

UNITED STATES PATENTS

2,647,239	Tellegen	July 28, 1953
2,697,759	Tellegen et al.	Dec. 21, 1954
2,764,676	Bradley	Sept. 25, 1956
2,944,229	De Vries	July 5, 1960

FOREIGN PATENTS

716,257	Great Britain	Sept. 29, 1954
1,041,549	Germany	Oct. 23, 1958

OTHER REFERENCES

Tellegen: "Philips Research Reports," vol. 3, April 1948, pages 81–101.

Gianola et al.: "Journal of Applied Physics," vol. 27, No. 5, June 1956, pages 608–609.