Aug. 27, 1963 H. SEIDEL 3,102,244

NONRECIPROCAL WAVE TRANSMISSION COMPONENTS

Filed Jan. 11, 1961 2 Sheets-Sheet 1

FIG. 1

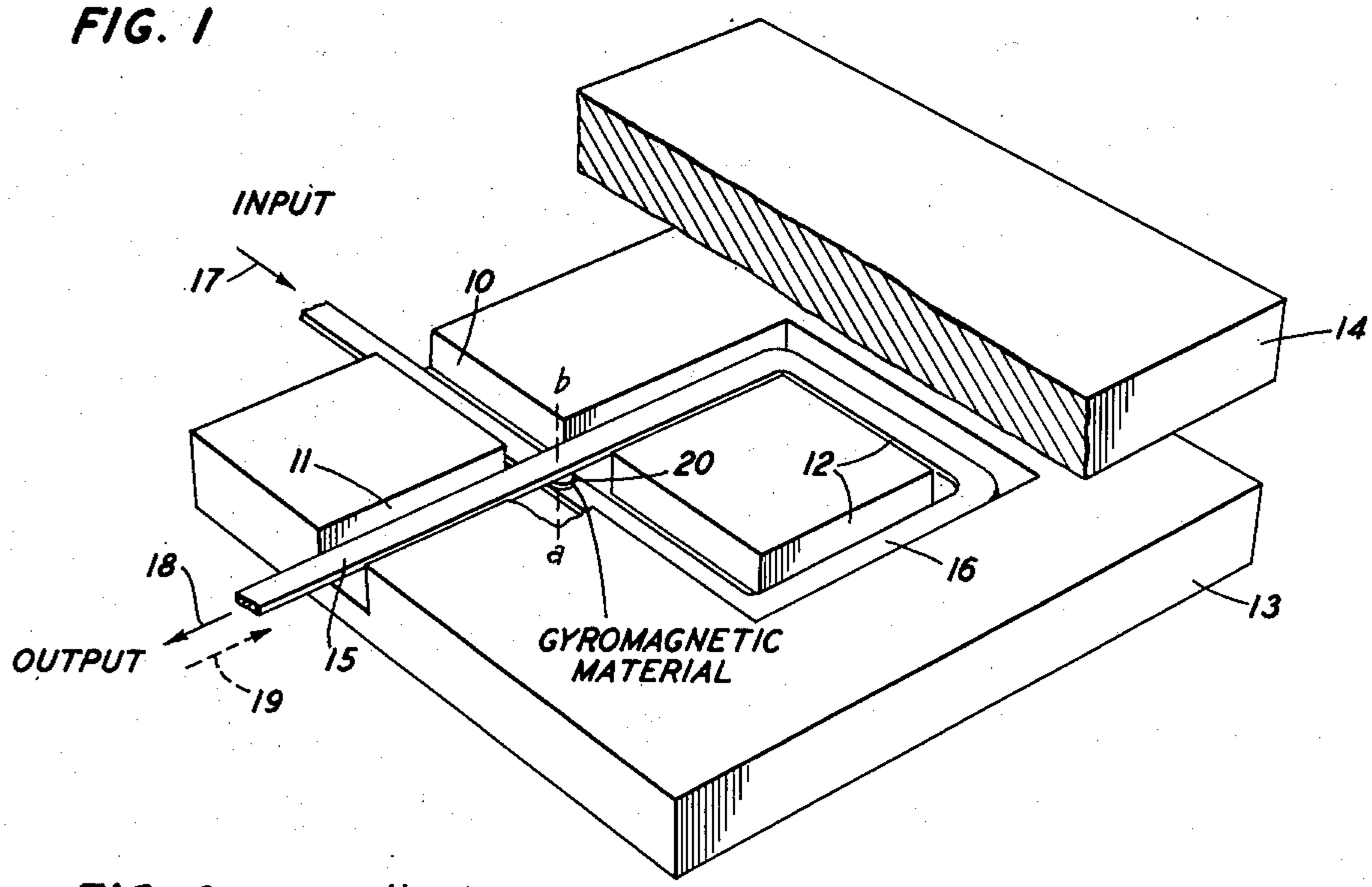

FIG. 2

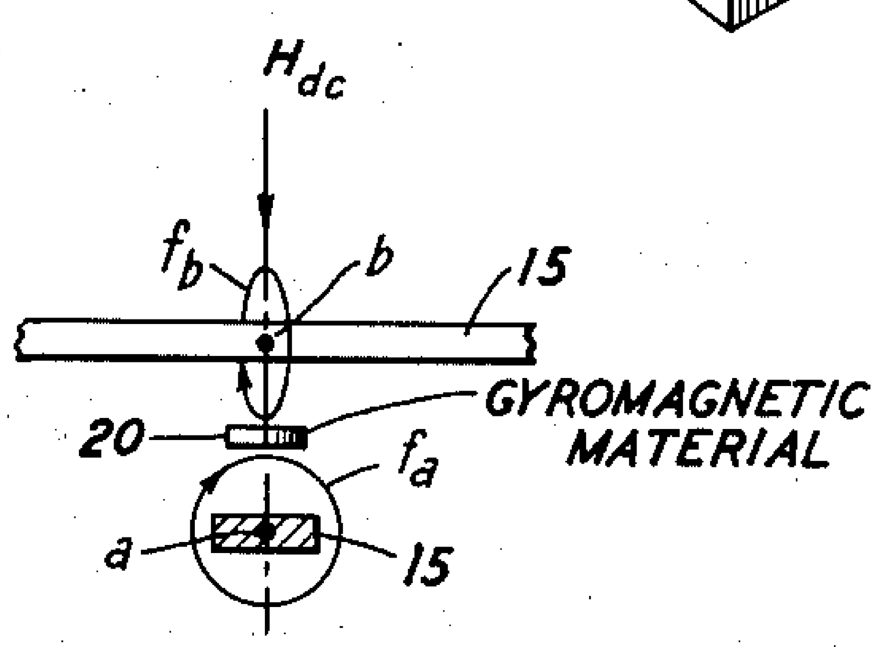

FIG. 3

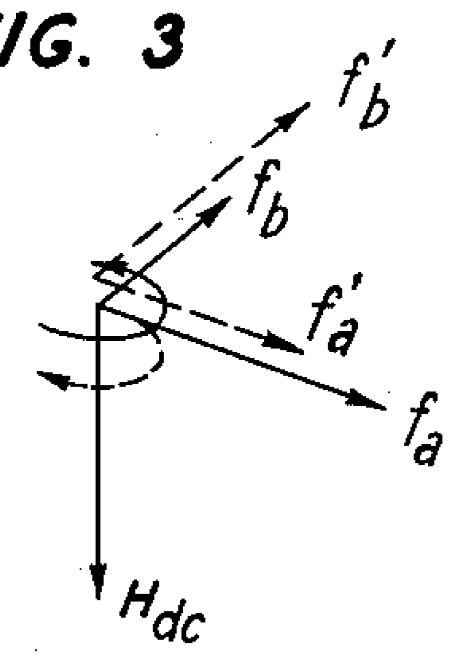

FIG. 4

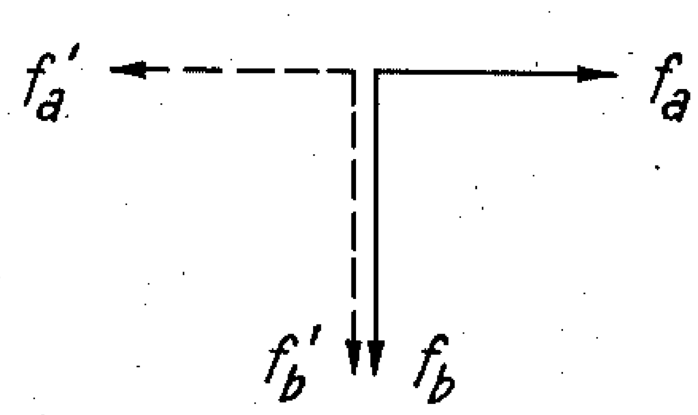

FIG. 5

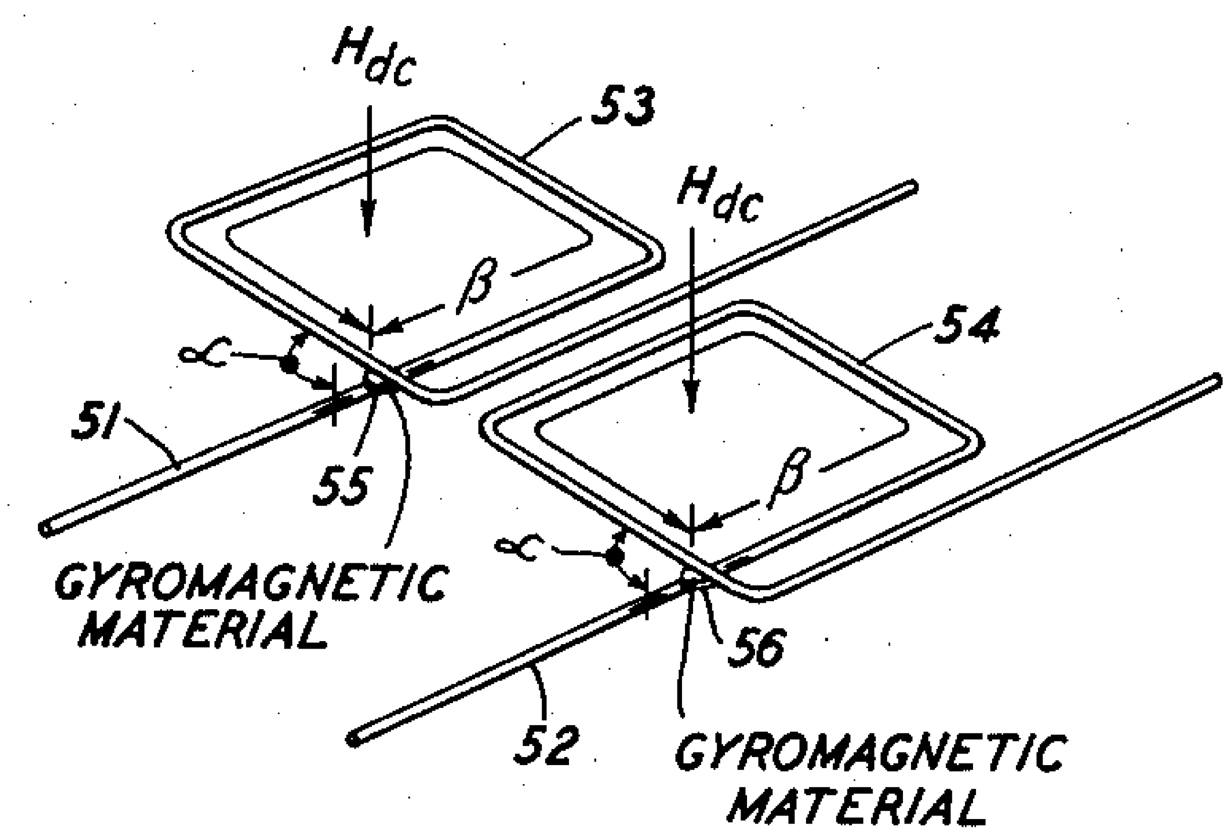

FIG. 7

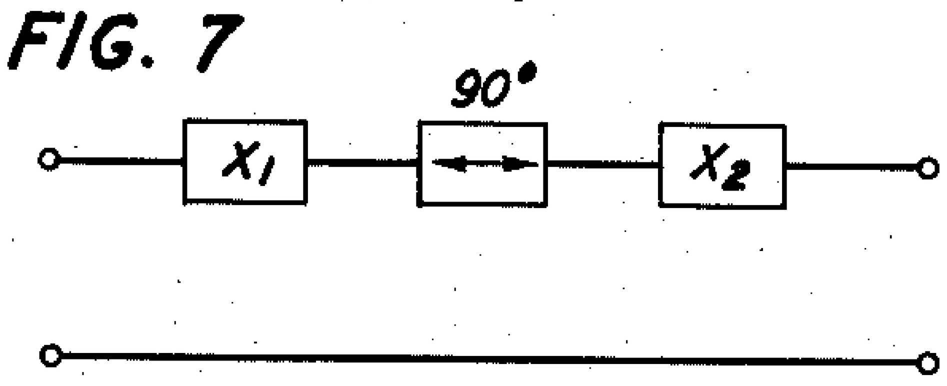

FIG. 8

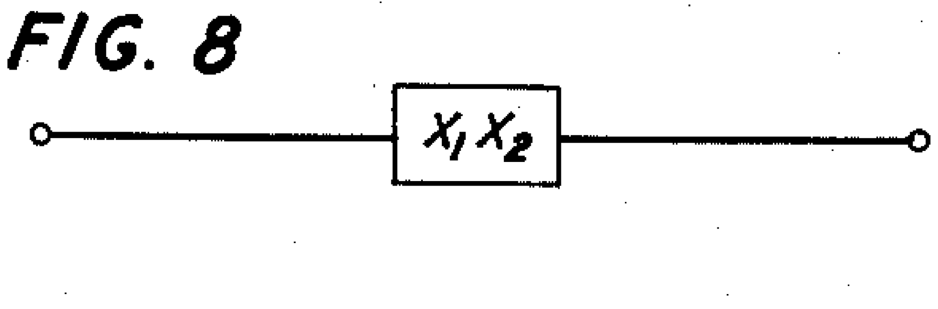

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FIG. 6

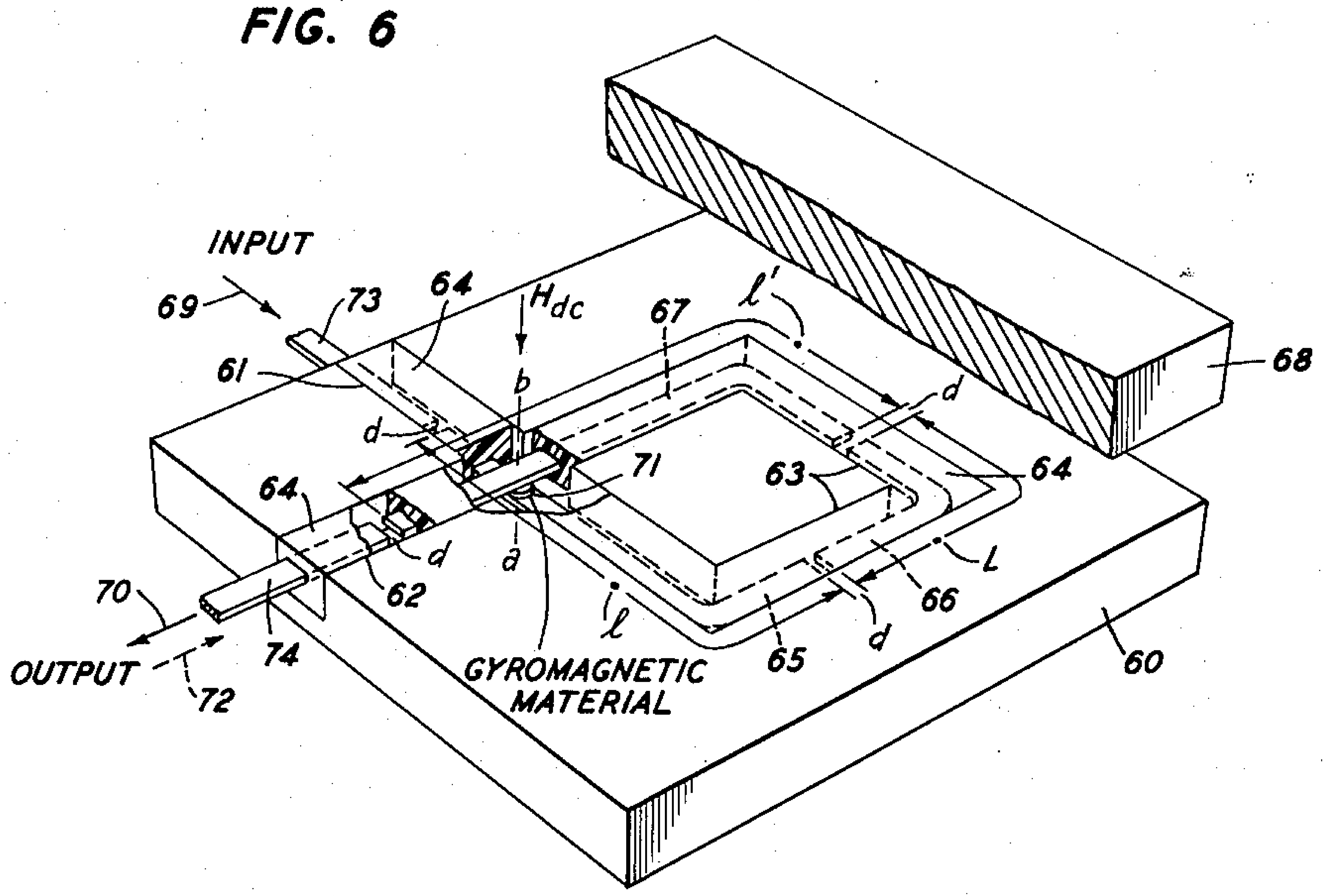


FIG. 9

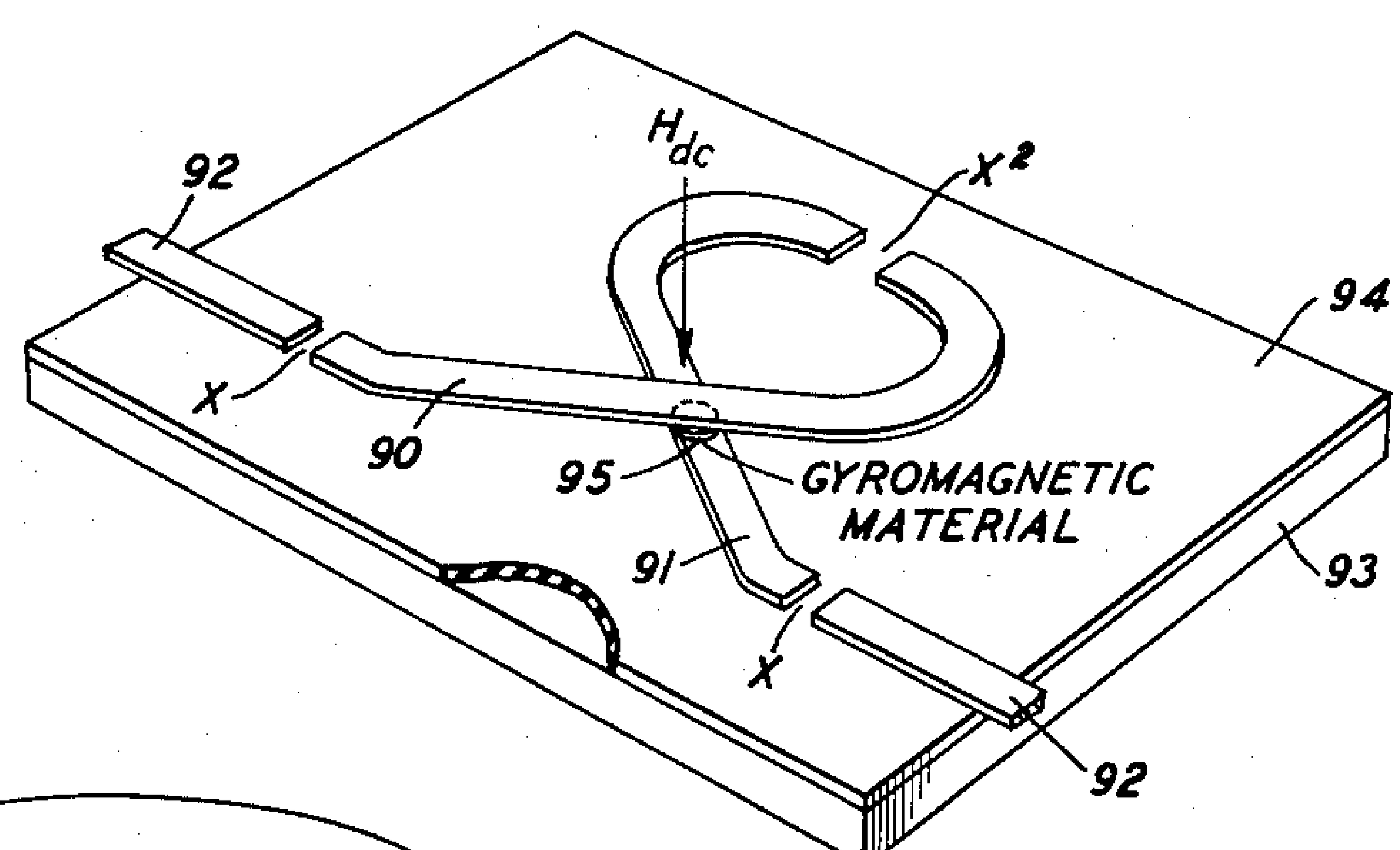
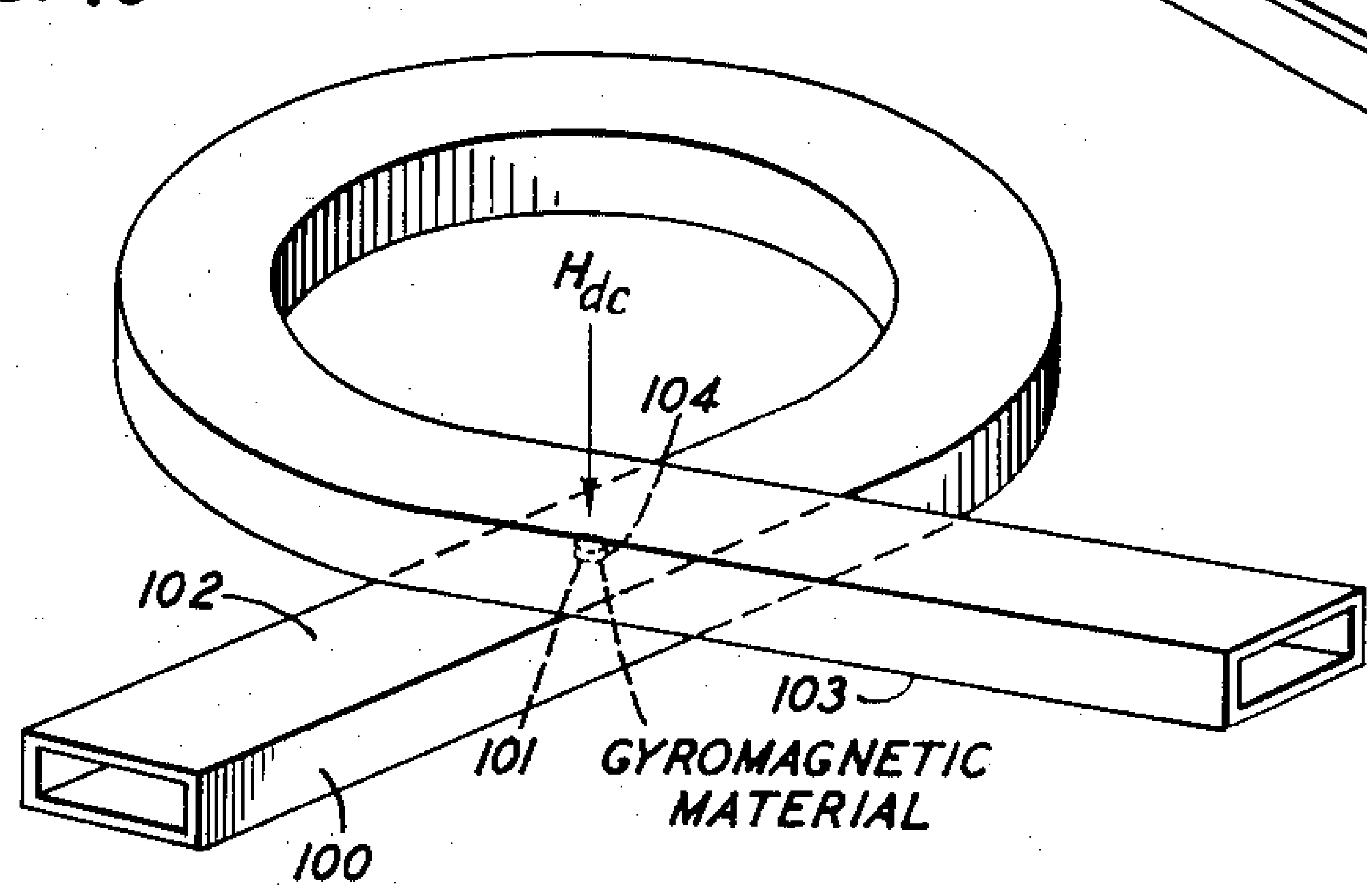


FIG. 10



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NONRECIPROCAL WAVE TRANSMISSION COMPONENTS

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20 Claims. (Cl. 333—24.2)

This invention relates to electromagnetic wave transmission systems and more particularly to directional or nonreciprocal attenuators and phase shifters for use in such systems. Whereas special emphasis is devoted to two-element transmission systems operating in the TEM mode, the invention can readily be practiced using hollow, conductively bounded waveguides or other types of transmission media.

This application is a continuation-in-part of my copending applications Serial No. 777,924, filed December 3, 1958, now abandoned, and Serial No. 858,244, filed December 8, 1959, now abandoned.

The use of materials having gyromagnetic properties to obtain both reciprocal and nonreciprocal effects in microwave transmission circuits is widely known in the art. These materials have found numerous and varied applications in propagation structures employing waveguide components, and are therefore limited in their operation to the microwave frequency range and above. A résumé of the early work done using waveguide elements is contained in technical papers too numerous to mention. The need for nonreciprocal circuit elements, however, is at least as great in the lower frequency ranges in which two-line transmission components operating in the TEM mode are used. These lower frequency ranges include the ranges designated as very high frequency and ultra high frequency.

It is, therefore, the broad object of this invention to produce nonreciprocal transmission effects in in transmission systems operating in the TEM mode.

In United States Patents 2,895,114 and 2,892,160, issued to J. H. Rowen on July 14, 1959 and June 23, 1959, respectively, and in United States Patent 2,892,161, issued to J. M. Clogston on June 23, 1959, there are disclosed structures and techniques for utilizing one or more of the several nonreciprocal effects produced by polarized elements of gyromagnetic material at frequencies of wave energy below a few thousand megacycles. These structures comprise two branch coaxial or balanced transmission line networks capable of introducing a nonreciprocal attenuation or nonreciprocal phase shift to wave energy in the frequency range in which coaxial and balanced transmission lines are used.

Like their microwave counterparts, the lower frequency isolaters and nonreciprocal phase shifters described in the above-mentioned patents operate by exciting in an element of polarized gyromagnetic material a circularly polarized component of radio frequency magnetic field that rotates in one sense relative to the steady polarizing field when the radio frequency wave is propagating in one direction, but in the opposite sense when the wave is propagating in the opposite direction. When the polarizing field is adjusted to the strength necessary to produce gyromagnetic resonance in the gyromagnetic material, a substantial part of the energy is absorbed for one direction of rotation and direction of propagation, but it is substantially unaffected for the other direction of rotation and direction of propagation. When the polarized field is adjusted to a strength substantially below that necessary to produce gyromagnetic resonance, a nonreciprocal phase shift is produced. The prior art devices, however, tend to be large and relatively complicated in their structure, and

require a fairly large piece of gyromagnetic material. Furthermore, they are, in general, nontunable.

It is therefore a more specific object of this invention to simplify the means for generating circularly polarized radio frequency magnetic fields whose sense of rotation is a function of the direction of the wave propagation.

In accordance with the invention, an element of gyromagnetic material is simultaneously coupled to two electrically spaced regions of a transmission system. The delayed portion of the propagating signal is fed back, and coupled to, a small element of gyromagnetic material so as to induce a magnetic field component at an angle to that induced by the other coupled region. By properly relating the electrical delay and the spatial phase angle of the intersecting fields a circularly polarized resultant radio frequency magnetic field is produced in the gyromagnetic material whose sense of rotation is opposite directions of propagation of the wave energy. Depending upon the degree of coupling to the gyromagnetic material, low-loss nonreciprocal phase shift or nonreciprocal attenuation effects are obtained. A steady biasing field is directed normal to the two radio frequency magnetic vectors and is adjusted to produce gyromagnetic resonance in the material.

It is a feature of the invention that the nonreciprocal device so produced is readily tunable with frequency merely by changing the spatial phase angle at which the radio frequency magnetic fields intersect in the gyromagnetic material, and by adjusting the magnetic biasing field intensity. These adjustments may be gauged and made simultaneously as the frequency is varied.

It is a further feature of the invention that the element of gyromagnetic material used is extremely small, as is the entire structure.

In a first principal embodiment of the invention, nonreciprocal effects are obtained in a two-wire transmission system by bending at least one of the wires back upon itself to form a loop. The electrical length of the loop and the spatial angle at which the wire crosses itself are adjusted to produce a circularly polarized magnetic field at the crossover point. A magnetically polarized element of gyromagnetic material is located in the region of the circularly polarized high frequency magnetic field to produce nonreciprocal transmission effects.

In the above-described illustrative embodiment the magnetic fields that build up within the loop structure are essentially only those of a unidirectional traveling wave. As a consequence, a relatively small magnetic field density is developed resulting in a correspondingly small interaction between the gyromagnetic material and the electromagnetic wave energy associated with the propagating wave. One way of increasing the energy interaction between the traveling wave and the gyromagnetic material is to increase the size of the material, thereby extending the region over which the wave and material can interact. This technique has been used before with the obvious disadvantages that large pieces of material are needed and the dielectric losses are substantially increased. On the other hand, the same effect can be produced by causing the wave to traverse a small gyromagnetic element many times. This latter result can be readily produced by coupling the small element of gyromagnetic material to a resonant section of transmission line wherein successive reflections from the line ends produced the effect of multiple passes.

Waveguide cavities which operate between electric walls are well documented and understood. It is equally feasible, however, to form a cavity by housing a length of transmission line between two magnetic walls (that is, open ends). In the case of an electric wall cavity, coupling is accomplished by opening up small holes in the short circuit wall. Similarly, in the open circuit cavity, coupling of the input and output transmission lines to the cavity structure is accomplished by placing said lines in close proximity to the cavity ends. A typical form of coaxial line cavity then, is one in which a nominally half-wave center conductor is coupled by fringing fields to gap-spaced transmission lines at either end. For all practical purposes, if the gaps are relatively small they may be represented as small series capacitors over the frequency band of operation.

Applying the technique of multiple reflections, improved nonreciprocal two-element transmission components are produced, in accordance with the invention, by coupling an element of gyromagnetic material to two series-connected sections of transmission line, such as a pair of coaxial cavities, crossed in the region of their current maximum points.

In a second principal illustrative embodiment of the invention, the coaxial cavities are crossed at right angles and the output of the first cavity is delayed a quarter-wave before being coupled to the input of the second cavity. The entire structure is observed to take on the form of a loop in which the time and spatial phase angles of the intersecting magnetic field components are such as to produce a circularly polarized resultant radio frequency magnetic field in the gyromagnetic material whose sense of rotation is opposite for opposite directions of propagation of the wave energy. If the coupling between the gyromagnetic material and the resonant cavities is in the region of critical coupling or below, nonreciprocal attenuation effects are produced. At couplings greater than critical coupling, the lossy effect is diminished and the primary effect is that of nonreciprocal phase shift.

The use of resonantly tuned cavities greatly enhances the interaction between the gyromagnetic material and the propagating electromagnetic wave energy by producing, in effect, a substantially greater magnetic field intensity in the region of the gyromagnetic material. As a result, the attenuation or phase shift produced is much greater for a given volume of gyromagnetic material.

In one configuration of the second principal embodiment of the invention, the ninety degree phase delay is obtained by inserting an appropriate length of transmission line between the output of the first cavity and the input of the second cavity. However, as is known in the filter art, two large series reactances separated by a quarter wavelength can be recomposed into a single larger reactance substantially equal to the product of the two reactances divorced of any spacing whatsoever.

Accordingly, in an alternative configuration of the invention, the required time delay is produced by adjusting the amplitude of the coupling between the output of the first cavity and the input of the second cavity. This results in a nonreciprocal coaxial component of greater simplicity and compactness of design.

While, as indicated above, special emphasis has been placed upon coaxial, or two-wire, transmission systems, this in no way was intended to restrict the application of the principles of the invention to such systems. To the contrary, the principles of the invention can be readily practiced using hollow, conductively bounded waveguides or other transmission media.

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 perspective view of the first principal embodiment of the invention showing a coaxial nonreciprocal device;

FIG. 2 is a close-up view of the crossover region showing the magnetic fields in the region of the gyromagnetic material;

FIG. 3 shows, by way of illustration, the space orientation of the magnetic field vectors in the region of the gyromagnetic material;

FIG. 4 is a time vector diagram of the radio frequency magnetic fields in the region of the gyromagnetic material;

FIG. 5 shows an alternative arrangement of the first principal embodiment of the invention using parallel wire transmission lines;

FIG. 6 is a perspecitve view of the second principal embodiment of the invention employing resonant sections of coaxial line;

FIG. 7 is a block diagram equivalent of the delay network;

FIG. 8 is an alternative block diagram representation of the delay network;

FIG. 9 shows an alternative arrangement of the second principal embodiment of the invention; and

FIG. 10 illustrates the application of the principles of the invention to other transmission media.

Referring more particularly to FIG. 1, a perspective view of the first principal illustrative embodiment of the present invention is shown connected and utilized to produce nonreciprocal transmission effects. Such a device comprises the two intersecting channels **10** and **11** which, for convenience, may be integrally constructed by milling or casting them in a block **13** having a suitable cover plate **14**. Channels **10** and **11** are connected to each other within block **13** by means of an additional channel **12** and thus form a continuous channel from the input of channel **10** to the output of channel **11**.

Suitably supported within channels **10**, **11** and **12** and extending longitudinally therein in a plane parallel to the walls of said channels is the conductive member **15**. Together, member **15** and the walls of the several channels, serving as the conductive ground plane therefor, form a strip-line or coaxial wave supporting structure. It will be noted that in conforming to the channel boundaries, conductor **15** bends back upon itself in a plane essentially parallel to the ground planes to form a loop **16** which extends from a point *a* on conductor **15** to a point *b* on conductor **15**. From the crossover point defined by the axis *ab* normal to the plane of loop **16**, the transmission line continues in both directions away from loop **16** and connects to the rest of the transmission system. As shown, the input signal is supplied from a source to member **15** in channel **10**, whereas the output connects to that portion of member **15** in channel **11**.

Located between the two adjacent ends of loop **16** along the axis *ab* is an element of gyromagnetic material **20**. 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 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, a gyroscopic moment 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, aluminum-substituted yttrium iron oxide is used.

The element of gyromagnetic material **20**, in the illustrative embodiment of FIG. 1, is in the shape of a disk, disposed with its faces normal to axis *ab*. Element **20**, however, may assume any other convenient shape since the particular shape is not essential to the operation of the invention. A static magnetic field H_{dc} is applied parallel to axis *ab* (normal to the faces of the disk) and is adjusted as will be explained in greater detail hereinafter.

The biasing field H_{dc} may be supplied by any suitable means (not shown) such as an electric solenoid, a permanent magnetic structure or in some instances the disk **20** itself 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. As 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 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 of 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 field 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 patricular 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 system.

FIG. 2, given for the purposes of explanation, shows diagrammatically the component magnetic field patterns in the region of the crossover point. In particular, the magnetic fields in the vicinity of conductor **15** are illustrated by the closed loops f_a and f_b representing magnetic field components having substantially equal amplitudes encircling conductor **15** at points *a* and *b*, respectively. The planes of the respective loops are normal to the longitudinal axis of conductor **15**. Since the two ends of loop **16** formed by conductor **15** are normal to each other, the magnetic field components f_a and f_b are likewise normal to each other in the region of disk **20**. The magnetizing field H_{dc}, also shown, is directed substantially normal to the plane of loop **16**, and consequently normal to both field components f_a and f_b. The spatial orientation of the various magnetic fields in the region of the gyromagnetic material is shown in the space vector diagram of FIG. 3.

Because of the time delay experienced by the wave energy in traveling from point *a* to point *b* along conductor **15**, there is a corresponding time delay associated with the fields f_a and f_b. In particular, if at a particular operating frequency the loop **16** is made to be a quarter of a wavelength in length between points *a* and *b*, field f_b lags field f_a by ninety degrees, as shown in the time vector diagram of FIG. 4. Because of this ninety degree time difference, as field f_a passes through its maximum amplitude and starts to decrease towards zero, field f_b is passing through zero and is starting to increase towards its maximum value. The effect of having the field components f_a and f_b varying in this manner, is to produce the equivalent of a single resultant field vector which appears to rotate in space in the region of the gyromagnetic material **20**. With the polarizing field H_{dc} directed normal to the plane of field components f_a and f_b, as shown in FIG. 3, a negative or counterclockwise rotation is produced when viewed along the direction of the biasing field. This sense of circularly polarizing 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 gyromagnetic material and substantially all the wave energy introduced into the system in the forward direction, as indicated by arrow **17**, continues to propagate substantially unattenuated along conductor **15** past loop **16**.

However, for energy propagating in the reverse direction, as indicated by the dotted arrow **19**, there is a change in the sense of rotation of the resultant magnetic field vector. For transmission in the reverse direction, the resulting magnetic field loops f'_a and f'_b are, as before, ninety degrees out of space phase and are so shown as dotted vectors in FIG. 3. There is, however, a change in the relative time phase relationship between the magnetic field vectors such that the phase of f'_a lags f'_b by ninety degrees, as shown in FIG. 4. As a consequence, the resultant field produced by f'_a and f'_b appears to rotate in a positive or clockwise sense as viewed along the direction of the biasing field H_{dc}. This sense of rotation is the same as the preferred sense of precession of the magnetic moments in the gyromagnetic material and hence energy is absorbed from the circuit and dissipated in the gyromagnetic material.

In an alternative embodiment of the invention, a pair of loops are inserted in the two elements of a parallel wire transmission line. Referring more particularly to FIG. 5, an illustrative embodiment of a parallel line type nonreciprocal device constructed in accordance with the principles of the invention is shown, comprising a pair of parallel elongated conductive elements **51** and **52**. Each of the elements **51** and **52** have at least one loop **53** and **54**, respectively, included along their lengths. At the respective crossover points there are located disks of gyromagnetic material **55** and **56**. Each disk is magnetically biased by an external biasing field H_{dc} applied in a direction normal to the plane of loops **53** and **54**.

In the particular embodiment of the invention shown in FIG. 1, 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 equal field components (where α is assumed to be positive angle) there is a relative time phase, β, that produces circular polarization where

$$\alpha=(2n+1)\pi-\beta \quad (1)$$

where n is a whole number. Thus, if in the embodiment of FIG. 5 loops **53** and **54** have an electrical length other than a quarter wavelength, the angle α at the crossover points may be adjusted to an appropriate angle in accordance with the above-mentioned relationship. Furthermore, if the angle α is made adjustable, the device may be tuned as a function of frequency. Thus, for example, as the frequency is changed and the electrical lengths of the loops **53** and **54** correspondingly change, circular polarization may nevertheless be induced in the gyromagnetic material by appropriately varying the crossover angle α.

In the description relating to the embodiment of FIG. 1, the device was referred to as an isolator. In my copending application Serial No. 774,389, filed November 17, 1958, now Patent No. 3,010,085, an equivalent network for the gyromagnetic material was given, and it was shown that whether or not energy is absorbed in the gyromagnetic material depended upon the degree of coupling between the system and the gyromagnetic material. In particular, it was there shown that optimum isolator action is obtained for the range of coupling about critical coupling. It can similarly be shown that for tight coupling a low-loss nonreciprocal phase shifter is essentially obtained rather than a nonreciprocal attenuator. Thus, depending upon the degree of coupling, it is possible to obtain either nonreciprocal attenuation or nonreciprocal phase shift.

In the first principal embodiment of the invention described above, the high-frequency magnetic fields in the crossover region are those associated with a unidirectional traveling wave. As was also indicated above, the resulting interaction between the gyromagnetic material and the propagating wave energy is relatively small. In the second principal embodiment of the invention to be described hereinafter, this interaction is substantially increased by resonating the transmission line in the crossover region. Such an arrangement is illustrated in FIG. 6.

The device of FIG. 6 comprises a conductive block **60** into which there is milled the two intersecting channels **61** and **62**. Channels **61** and **62** are connected to each other within block **60** by means of an additional channel **63**, thus forming a continuous pathway from the input to channel **61**, to the output of channel **62**.

Suitably supported within channels **61**, **62** and **63** by the low-loss dielectric material **64**, and extending longitudinally therein parallel to the several walls of said channels, are the conductive members **65**, **66** and **67**. Each member is physically separated from each adjacent member by a given distance d so as to form a conductive gap therebetween. Together members **65**, **66** and **67**, in conjunction with the walls of the several channels (including cover plate **68**) which serve as the conductive ground plane therefor, form a stripline or coaxial wave supporting structure. Electromagnetic wave energy is coupled into and out of the structure by means of members **73** and **74**, which are similarly separated from the ends of members **65** and **67**, respectively.

It will be noted that in conforming to the channel boundaries, the center conductor of the transmission line comprising members **65**, **66** and **67** bends back upon itself in a plane essentially parallel to the ground planes to form a loop which extends from a point a on conductor **65** to a point b on conductor **67** and includes member **66** therebetween. From the crossover point defined by the axis ab normal to the plane of the loop, the transmission line continues in both directions away from the loop and connects to the rest of the transmission system. As shown in FIG. 6, the input signal, indicated by the arrow **69**, is supplied from a source to member **65** in channel **61**, while the output, indicated by the arrow **70**, is coupled to member **67** in channel **62**. The element of gyromagnetic material **71**, in the illustrative embodiment of FIG. 6, is in the shape of a disk, disposed with its faces normal to axis ab. Element **71**, however, may assume any other convenient shape since the particular shape is not essential to the operation of the invention. A static magnetic field H_{dc} is applied parallel to axis ab (normal to the faces of the disk) and is adjusted as was expalined in connection with FIG 1.

The biasing field H_{dc} may be supplied by any suitable means (not shown) such as an electric solenoid, a permanent magnetic structure, or in some instances the disk **71** itself may be permanently magnetized. Thus, in its basic aspects, the structure of FIG. 6 is similar to that of FIG. 1.

In the preceding description of the operation of the nonreciprocal attenuator of FIG. 1, it was explained how the radio frequency magnetic field interacts with the gyromagnetic material and how, under certain conditions, energy is transferred from the signal to the gyromagnetic element and dissipated therein. Let us now consider the amount of energy thus dissipated. It can be shown that the energy absorbed in the gyromagnetic element is a function of the susceptance of the gyromagnetic material, μ'', and the intensity of the high-frequency magnetic field H_{rf}. Specifically the absorbed power P_{ab} is proportional to the product of μ'' and the square of the field strength,

$$P_{ab}=a\mu''H_{rf}^2 \qquad (2)$$

where a is a constant.

It is apparent from this relationship that by increasing the value of H_{rf}, the attenuation of the isolator in the reverse, or lossy direction can be substantially increased.

In accordance with the invention, the radio frequency magnetic field components in the region of the gyromagnetic element **71** are maximized by resonating the conductive members **65** and **67** and crossing them in the region of their current maxima. Accordingly, the length l of conductor **65** and the length l' of conductor **67** are adjusted to be approximately an integral number of half wavelengths at the frequency to be attenuated. As is well known, the current distribution along an open-ended resonant cavity is essentially sinusoidal, being a minimum at the ends, and a maximum at odd multiples of a quarter wavelength from the ends. Accordingly, for maximum interaction conductive members **65** and **67** are made to cross each other at points along their lengths that are odd multiples of a quarter wavelength from their respective ends, thus maximizing the radio frequency magnetic field to which the gyromagnetic material is subjected.

For the case where both l and l' are approximately equal to half a wavelength, conductive members **65** and **67** are crossed at their midpoints. This particular location is not to be regarded as a limitation, however. Thus, where less than maximum interaction is preferred in some specific application, the crossover region (and the location of the gyromagnetic material) may be shifted to some other point along the resonant sections of line. Obviously, a large range of interactions may be realized by varying the position of the crossover region.

In the description of the embodiment of FIG. 6 the cavity lengths l and l' were characterized as approximately equal to half a wavelength, or whole multiples thereof. However, a modification of the cavity length over its nominal half wavelength value must be made to take into account the series reactance introduced by the coupling gaps adjacent to each end of the resonant line. The correction to the length for each gap is given by the formula

$$\gamma=\frac{1}{2}\arctan\frac{2}{X}$$

where γ is in electrical degrees and X is the gap reactance. Applying the correction twice to take into account both gaps, the electrical length θ of the coaxial cavity is given by

$$\theta=n\pi+\frac{1}{2}\left[\arctan\frac{2}{X_1}+\arctan\frac{2}{X_2}\right] \qquad (3)$$

where n is an integer, and X_1 and X_2 are the series reactances introduced by the conductive gaps between the cavity and its adjacent members. In the embodiment of FIG. 6, where the gap lengths, d, are equal

$$\theta = n\pi + \arctan \frac{2}{X} \quad (4)$$

The bandwidth of each strip cavity is related to its loaded Q, which is given by

$$Q = \frac{\pi}{2} X^2 \quad (5)$$

The overall Q of the two cavities is that of a quarter wave coupled resonant pair and is given as

$$Q = \frac{\pi}{2\sqrt{2}} X^2 \quad (6)$$

The electrical length φ of the quarter wave delay network (member **66**) is given by

$$\varphi = (2m+1)\frac{\pi}{2} + \frac{1}{2}\left[\arctan \frac{2}{X_1} + \arctan \frac{2}{X_2}\right] \quad (7)$$

where m is an integer.

If X_1 and X_2 are equal,

$$\varphi = (2m+1)\frac{\pi}{2} + \arctan \frac{2}{X} \quad (8)$$

In the embodiment of the invention shown in FIG. 6 and herein described, the cavities have been oriented so that the magnetic field components intersect at right angles, and the time delay was adjusted to be ninety degrees. However, as was pointed out above, circular polarization of the radio frequency magnetic field may be obtained by causing the magnetic field components to intersect at some angle α other than ninety degrees, provided the time phase delay, β, is adjusted such that

$$\alpha = (2n+1)\pi - \beta \quad (9)$$

where n is an integer.

There is, therefore, freedom in choosing the crossover angle provided the delay section is correspondingly modified to satisfy the condition set forth in Equation 9. It turns out, however, that for the special case where α and β are both equal to ninety degrees, the maximally flat bandpass characteristic is obtained. A nonreciprocal device so constructed is then not limited by the loaded Q of either resonator, but rather by the line width of the gyromagnetic material alone.

Some simplification of the embodiment of FIG. 6 can be obtained by modifying the network used to obtain the ninety degree phase delay between the signal field components f_a and f_b. In FIG. 7 there is shown the equivalent circuit of the delay network which comprises conductive member **66** and its two adjacent gaps. The network comprises the two series reactances X_1 and X_2 produced by the gaps between member **66** and the adjacent members **65** and **67**, and the ninety degree reciprocal phase shift produced by member **66**.

It is known in the filter art that two large series reactances separated by a quarter wavelength can be recomposed into a single large reactance substantially equal to the product of the two reactances divorced of any spacing whatsoever. The alternate filter structure, shown in FIG. 8, is usually described as a direct couple filter as opposed to the quarter wave filter of FIG. 7.

Applying this technique to the isolator of FIG. 6 results in an alternate embodiment of the invention, shown in FIG. 9, having greater simplicity and compactness of design. The isolator of FIG. 9 comprises the two crossed resonantly tuned sections **90** and **91** inserted in one branch **92** of the two-element transmission paths comprising conductors **92** and **93**. Conductor **93** is conductively insulated from the tuned sections **90** and **91** and conductor **92** by a sheet of low-loss dielectric material **94** inserted therebetween.

The spacing between the tuned segments **90** and **91** and conductor **92** produces a series reactance X between each of the resonant sections and the transmission line. Accordingly, the spacing between section **90** and section **91** is adjusted to produce a series reactance substantially equal to X^2. So adjusted, the circuit of FIG. 9 has exactly the same electrical properties as the circuit of FIG. 6, and may be utilized in precisely the same manner. Thus, a resonantly biased element of gyromagnetic material **95** placed between the cavities in the crossover region will produce nonreciprocal transmission effects in the manner explained hereinbefore.

So far we have only considered two-wire or coaxial line transmission systems. However, as was previously indicated, the techniques described above may be readily applied to other transmission media. One simple illustration of this application is given in FIG. 10 where a hollow, conductively bounded rectangular waveguide **100** is caused to bend back upon itself to form the familiar loop structure. An aperture **101** extending through the contiguous wide walls **102** and **103** in the crossover region will expose magnetic field components having particular spatial and time phase differences. By adjusting these phase differences in accordance with Equation 9, a region of circular polarization may be established. Nonreciprocal effects can then be obtained by inserting a suitably magnetized element of gyromagnetic material **104** through aperture **101**. The operation of the structure of FIG. 10 is, in all respects, substantially as described above.

In all cases it is understood that the above-described arrangements are illustrative of but a small number of the many possible specific embodiments which can represent applications of the principles of the invention. For example, whereas the embodiment of FIG. 9 is shown comprising a section of unbalanced strip-line, the invention can be practiced in principle using balanced strip-line, coaxial cable or two-wire transmission line. Similarly the waveguide in FIG. 10 may be resonated in the crossover region. Thus, 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 wave transmission component comprising a two-conductor transmission line, at least one of said conductors forming a loop of electrical length β, said one conductor crossing itself at an angle α, such that $\alpha = (2n+1)\pi - \beta$, n being an integer, an element of magnetically polarizable material exhibiting gyromagnetic effects over the operating frequency range of said component located between opposite ends of said loop at said crossover point, and means for biasing said element in a direction substantially normal to the plane of said loop.

2. The combination according to claim 1 wherein the electrical length of said loop is a quarter wavelength of a frequency within said operating range and said opposite ends of said loop formed by said one conductor cross each other at an angle of ninety degrees.

3. The combination according to claim 1 wherein one of said conductors surrounds the other of said conductors.

4. In an electromagnetic wave transmission system supportive of a range of operating frequencies, means for selectively attenuating a band of frequencies within said range comprising a pair of parallel elongated conductive members, means for energizing said members, said members when energized having a field pattern including loops of magnetic field, at least one of said members being bent back and crossing over itself at an angle α to form a loop of electrical length β at a frequency within said band such that α and β satisfy the relationship $\alpha = (2n+1)\pi - \beta$, wherein n is an integer, an element of magnetically polarizable material capable of exhibiting gyromagnetic effects over said range of operating

frequencies located at the crossover point, means for magnetically polarizing said element, means for varying said band of frequencies and means for varying the crossover angle α as said electrical loop length β varies to maintain said relationship between α and β.

5. A nonreciprocal electromagnetic wave device supportive of wave energy in the TEM transmission mode comprising a section of two-conductor transmission line having an input end and an output end, means for applying wave energy at a given frequency to the input end of said line, said wave energy propagating from said input end toward said output end past first and second successive portions of said line having a time phase difference β therebetween, an element of material capable of exhibiting gyromagnetic effects at said given frequency located in a region proximate to said line, means coupling wave energy exclusively between said two distinct portions of said line and said element, said coupling means being supportive of magnetic field components with the wave energy at the first of said portions inducing first magnetic field components in said region predominantly of a single polarization and with the wave energy at the second of said portions producing second magnetic field components in said region also predominantly of a single polarization, said first and said second components intersecting in said region at an angle α where $\alpha=(2n+1)\pi-\beta$, n being an integer, to produce circular polarization in said element, and means for magnetically polarizing said element in a direction perpendicular to said intersecting components.

6. The combination according to claim 5 wherein said portions are a quarter wavelength apart at said given frequency and wherein said first and said second field components intersect at right angles.

7. The combination according to claim 5 wherein said gyromagnetic material is biased to gyromagnetic resonance.

8. The combination according to claim 5 wherein the coupling between said portions and said element is in the region of critical coupling to produce nonreciprocal attenuation.

9. The combination according to claim 5 wherein the coupling between said element and said portions is greater than critical coupling to produce low-loss nonreciprocal phase shift effects.

10. In an electromagnetic wave system supportive of wave energy in the TEM mode at a given frequency, an isolator comprising first and second series connected sections of two-conductor transmission line each tuned to resonance at said given frequency and spatially oriented to cross each other at right angles in a region along each of said sections wherein the current is a maximum, an element of gyromagnetic material disposed in said region, means for magnetically biasing said material to gyromagnetic resonance at said frequency, an input circuit coupled to one end of said first section, means for producing a ninety degree phase delay in said wave energy coupled between the other end of said first section and one end of said second section, and an output circuit coupled to the other end of said second section.

11. A nonreciprocal wave transmission device supportive of wave energy in the TEM mode at a given frequency comprising a section of transmission line having first and second conductively insulated metallic members each tuned to resonance at said given frequency and spatially oriented to cross each other at a point along their respective lengths at which the current in each is a maximum, an element of gyromagnetic material disposed between said members at said crossover point, means for magnetically biasing said material to gyromagnetic resonance at said given frequency, means for coupling an input circuit to one end of said first member defining a first reactive impedance, means for coupling the other end of said first member to one end of said second member delayed in time, and means coupled to the other end of said second member to an output circuit defining a second reactive impedance.

12. The combination according to claim 11 wherein said means for coupling the other end of said first member to said one end of said second member comprises a third conductively insulated metallic member disposed between and electromagnetically coupled to said first and said second members.

13. The combination according to claim 12 wherein said electromagnetic coupling between said third and said first members defines a third reactive impedance, and wherein said electromagnetic coupling between said third and said second member defines a fourth reactive impedance.

14. The combination according to claim 13 wherein said third member has an electrical length α equal to

$$(2m+1)\frac{\pi}{2}+\frac{1}{2}\left[\arctan\frac{2}{X_3}+\arctan\frac{2}{X_4}\right]$$

wherein m is an integer and X_3 and X_4 are said third and fourth reactive impedances, respectively.

15. The combination according to claim 13 wherein said first member has an electrical length θ_1 equal to

$$n\pi+\frac{1}{2}\left[\arctan\frac{2}{X_1}+\arctan\frac{2}{X_3}\right]$$

wherein n is an integer and X_1 and X_3 are said first and said third reactive impedances, respectively.

16. The combination according to claim 13 wherein said second member has an electrical length θ_2 equal to

$$n\pi+\frac{1}{2}\left[\arctan\frac{2}{X_2}+\arctan\frac{2}{X_4}\right]$$

wherein n is an integer and X_2 and X_4 are said second and said fourth reactive impedances, respectively.

17. A nonreciprocal wave transmission component comprising a pair of serially connected resonant sections supportive of electromagnetic wave energy at a given frequency, said energy as supported in each of said sections having a standing wave magnetic field pattern, said sections oriented with components of the magnetic field pattern of the first of said sections intersecting at right angles components of the magnetic field pattern of the second of said sections, a magnetically polarized element of gyromagnetic material disposed in the region of said intersecting magnetic field components, means for coupling electromagnetic wave energy into said first section defining a first reactive impedance X_1, means for coupling said wave energy out of said first section into said second section ninety degrees delayed in time defining a second reactive impedance X_2, and means for coupling said wave energy out of said second section defining a third reactive impedance X_3, wherein $X_2=X_1X_3$.

18. In an electromagnetic wave system, means for producing nonreciprocal wave transmission comprising a two-element transmission line, means for supporting said elements in fixed spaced relationship with respect to each other comprising a low-loss dielectric material disposed therebetween, at least one of said elements comprising a plurality of conductively insulated sections extending in longitudinal succession with adjacent ends of said sections spaced apart to form gaps in the conductive continuity of said one element, the first of said sections and the last of said sections crossing each other at a given angle at a point substantially midway along their respective lengths, an element of gyromagnetic material located between said sections at their point of crossing, and means for magnetically biasing said element.

19. A nonreciprocal electromagnetic wave device comprising a section of transmission line having an input end and an output end, means for applying wave energy at a given frequency to the input end of said line, said wave energy propagating from said input end toward said output

end past first and second successive portions of said line having a time phase difference β therebetween, an element of material capable of exhibiting gyromagnetic effects at said given frequency located in a region proximate to said line, means for coupling wave energy exclusively between said two distinct portions of said line and said element said coupling means being supportive of magnetic field components with the wave energy at the first of said portions inducing first magnetic field components in said region predominantly of a single polarization and with the wave energy at the second of said portions inducing second magnetic field components in said region also predominantly of a single polarization, said first and said second components intersecting in said region at an angle α where $\alpha=(2n+1)\pi-\beta$, n being an integer, to produce circular polarization in said element, and means for magnetically polarizing said element in a direction perpendicular to said intersecting components.

20. A nonreciprocal wave transmission component comprising a section of hollow, conductively bounded waveguide forming a loop having an electrical length β between respective ends, said section crossing over itself at an angle α where $\alpha=(2n+1)\pi-\beta$, n being an integer, an element of magnetically polarizable material exhibiting gyromagnetic effects over the operating frequency range of said component located between said ends of said loop at said crossover region and extending into said guide at both of said ends through apertures in the wall of said guide, and means for biasing said element in a direction substantially normal to the plane of said loop.

No references cited.