Jan. 1, 1963 SHINICHIRO YOSHIDA 3,071,740

NON-RECIPROCAL TEM DEVICE

Filed March 21, 1960 3 Sheets-Sheet 1

FIG. 1a

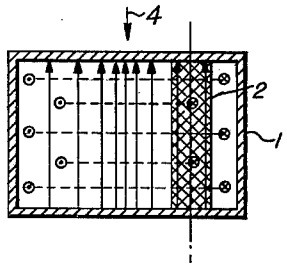


FIG. 1c

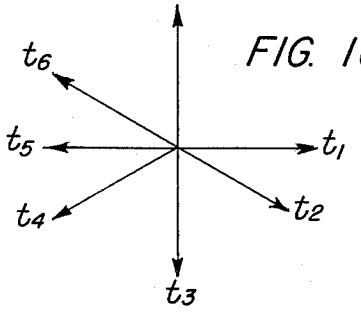


FIG. 1b

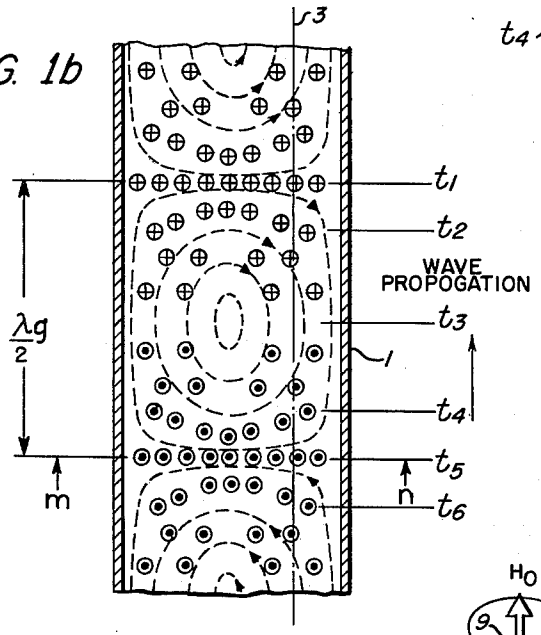
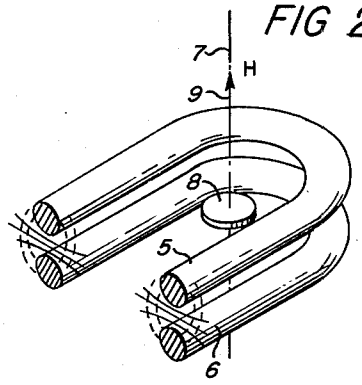


FIG 2



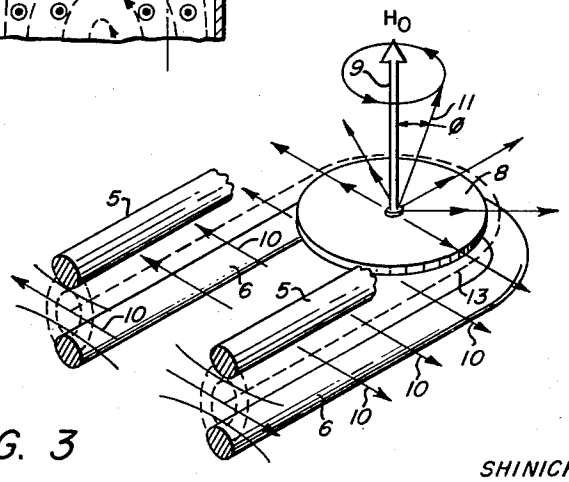


FIG. 3

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NON-RECIPROCAL TEM DEVICE

Filed March 21, 1960 3 Sheets-Sheet 2

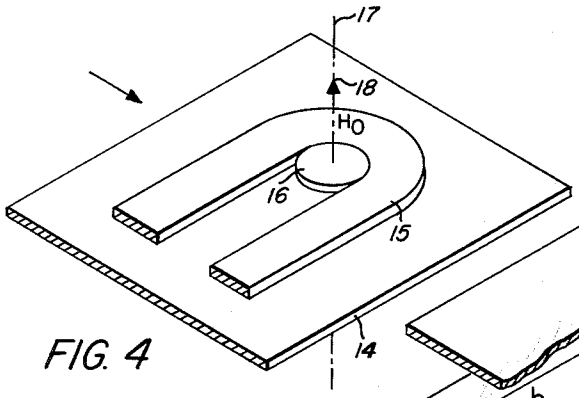


FIG. 4

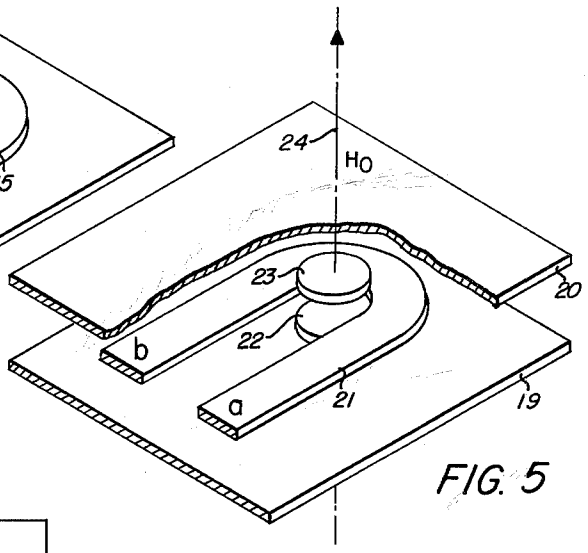


FIG. 5

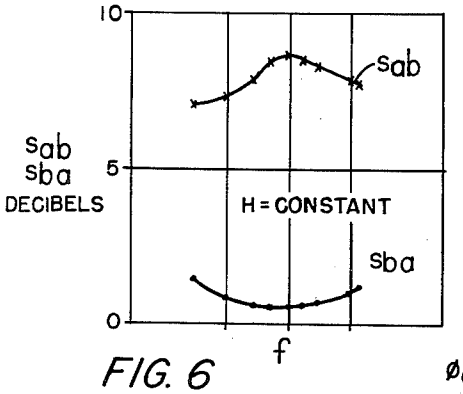


FIG. 6

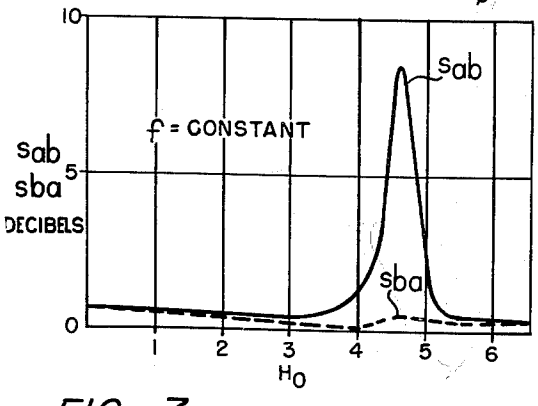


FIG. 7

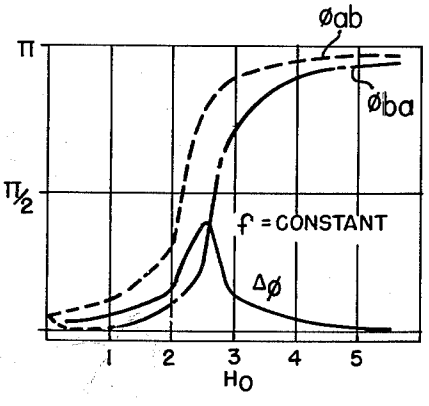


FIG. 8

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Jan. 1, 1963 SHINICHIRO YOSHIDA 3,071,740

NON-RECIPROCAL TEM DEVICE

Filed March 21, 1960 3 Sheets-Sheet 3

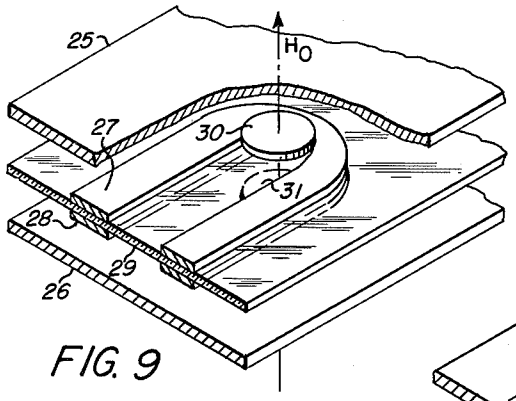


FIG. 9

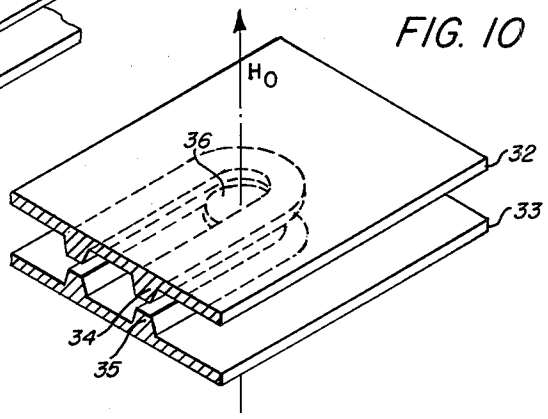


FIG. 10

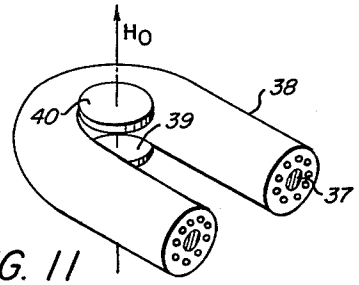


FIG. 11

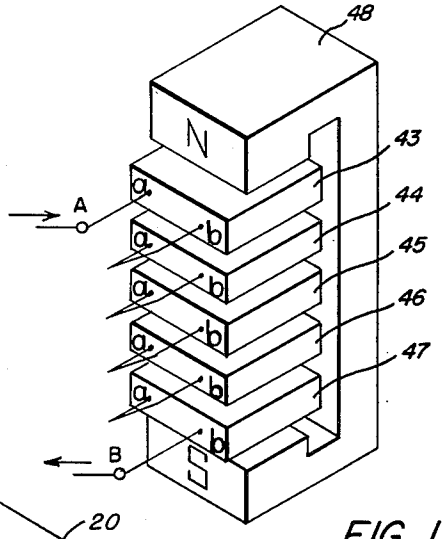


FIG. 13

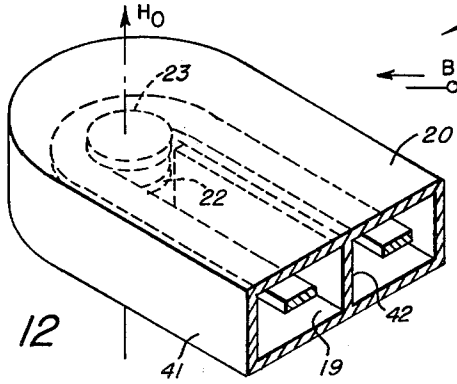


FIG. 12

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NON-RECIPROCAL TEM DEVICE

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7 Claims. (Cl. 333—24.2)

This invention relates to non-reciprocal transmission devices, and more particularly, to methods and means of construction of a transmission line whereby amplitude and phase changes of signals propagated therein depend upon the direction of propagation.

Heretofore, ferrite materials have been employed in waveguides to produce non-reciprocal qualities of transmission in the waveguides. These ferrite materials exhibit ferromagnetic resonance whereby the material absorbs microwave or RF energy at certain resonant frequencies. The apparent permeability of the ferrite material at the resonant frequencies is effected when the material is in the presence of a steady magnetic field transverse to the propagation of RF energy. According to one theory, microscopic magnetic moments produced by electrons in orbit about atoms in the material precess about the direction of a steady magnetic field applied thereto. This precession is sometimes called "Larmor precession." When the microwave frequency transmitted in a waveguide in a given direction equals this precession frequency, resonance occurs, the apparent magnetic permeability of the material reaches a sharp maximum and microwave energy is absorbed by the material. The resonant frequency depends upon the strength of the transverse magnetic field since the Larmor precession rate is proportional to the strength of the transverse magnetic field.

One common example of a ferrite non-reciprocal device is the ferrite isolator in its numerous forms. In all forms of such an isolator the above-mentioned phenomena pertaining to magnetic moment precession rate and ferromagnetic resonance is relied upon. Furthermore, the microwave or RF energy is usually transmitted or propagated in a waveguide because the mode of propagation must induce circularly or elliptically polarized fields in some aspect in order to effect a resonant interaction of the propagated RF wave with the above-mentioned magnetic moment precession. The ferrite is located within the waveguide so that the external magnetic field applied to the ferrite causes the above-mentioned Larmor precession for interaction with the circularly or elliptically polarized fields induced in the waveguide by the propagating wave. Ordinarily, the strength of the magnetic field is adjusted to achieve the desired precession rate and resonant frequency of the ferrite. Some examples of the use of ferrites to achieve isolation in a waveguide are mentioned below.

The Faraday rotation isolator employs a ferrite material in a circular waveguide positioned so as to intercept the circularly or elliptically polarized fields induced by a resonant RF wave propagated therein. A steady magnetic field is applied axially to the waveguide through the ferrite, thus magnetizing the ferrite substantially in the direction of propagation of the wave. The plane of polarization of the propagated wave is rotated upon passing through the ferrite material and this rotated wave is separated at a waveguide port suitably rotated.

Another type of isolator is the field displacement isolator in which a ferrite is fixed in a waveguide and a magnetic field is applied through the ferrite transversely to the waveguide, preferably in an area of the guide where the transmitted wave induces strong circularly or elliptically polarized fields. As a result, it has been found that the maximum electrical field within the guide will be displayed differently for wave propagation in one direction then for wave propagation in the opposite direction. Consequently, a resistive wave or card may be inserted in the guide, preferably next to the ferrite, for absorbing energy propagating in one direction but not in the other.

Another type isolator is commonly called the electrical or magnetic plane resonance isolator depending on the location of the ferrite pieces. In the electric plane resonance isolator, the ferrite piece is usually located transversely to the widest dimension of the waveguide where the mode of the transmitted wave produces the required circularly or elliptically polarized fields. In the magnetic plane resonance isolator, pieces of ferrite are usually located against the widest walls of the waveguide, again at a location where the propagated wave induces circularly or elliptically polarized RF fields and a steady external magnetic field is applied thereto perpendicular to the widest wall of the waveguide. In these isolators, non-reciprocal transmission qualities are gained only when the frequency of the transmitted wave is at or near the resonant frequency of the of the ferrite established by the material itself and magnitude of the steady external magnetic field.

In all of the above-mentioned isolators employing ferrite materials in a waveguide, the phenomena of ferromagnetic resonance is employed in one way or another to achieve the desired results, and this phenomena results from the interaction of a circularly or elliptically polarized RF field, inherent to propagation within the waveguide, with the microscopic precessing magnetic moments within the ferrite material responding to a steady external magnetic field applied thereto. When the rate of precession becomes equal to the frequency of the transmitted RF wave, resonance occurs and the ferrite will absorb energy from the transmitted wave. Heretofore ferrite materials in such non-reciprocal devices have been used in conjunction with a waveguide since circularly or elliptically polarized RF fields required for resonant interaction are inherent to propagation in a waveguide. Consequently, ferrites have not been employed for producing non-reciprocal effects in other types of transmission means such as the two conductor transmission line in which no circularly or elliptically polarized fields are induced. Therefore, it is the principal object of the present invention to provide means for imposing non-reciprocal qualities to transmission devices in which there are inherently no induced elliptical or circularly polarized fields resulting from RF wave propagation.

It is another object to provide means for imparting non-reciprocal qualities to a two or more element transmission line.

It is another object to provide means for imparting non-reciprocal qualities to a microstrip or strip line type transmission line.

It is another object to provide means for imparting non-reciprocal qualities to a coaxial transmission line.

It is another object to provide means for imparting non-reciprocal qualities to a surface wave transmission line.

It is another object to provide means for imparting non-reciprocal qualities to a gap type transmission line.

It is another object to provide a non-reciprocal two element transmission line whereby RF energy conducted in one direction is attenuated considerably more than RF energy conducted in the opposite direction, depending on the magnitude of a controlled externally applied magnetic field; and in which phase shift of RF signals conducted in said one direction differs considerably from phase shift of RF signals conducted in said opposite direction, also depending on the magnitude of said externally applied magnetic field.

It is another object to provide a simple method for employing a ferrite material in conjunction with a two element transmission line whereby attenuation of signals

conducted in one direction through said transmission line is considerably greater than attenuation of signals conducted in the opposite direction through said transmission line and in which phase shift of signals transmitted in said one direction may be varied with respect to the phase shift of signals transmitted in said opposite direction by at least $\pi/2$ radians, depending on the magnitude of an externally applied magnetic field.

It is another object that the difference between phase shift in said one direction and phase shift in said opposite direction be a maximum when the magnitude of the externally applied field is substantially different than required for maximum attenuation of signals propagated in said one direction.

The above-mentioned objects and others are achieved in the present invention by providing a non-reciprocal transmission device including conductive means for propagating electromagnetic RF energy around a bend and a ferrite body disposed at said bend to intercept the magnetic field of said propagated energy and to magnetize the ferrite body.

It is another feature of the present invention to dispose a body of ferromagnetic material within the bend of a transmission line whereby the magnetic field produced by RF waves propagated in said line is intercepted by the body of ferromagnetic material where the RF field is substantially circularly or elliptically polarized and to apply a steady magnetic field to the body of ferromagnetic material substantially perpendicular to the plane of said polarization so that a part of the energy of the RF waves will be absorbed by the material when the waves are propagated in one direction but not when waves are propagated in the opposite direction.

It is another feature of the present invention to produce a circularly polarized magnetic field from a single or multiple conductor transmission line by turning the transmission line on an axis and to impart non-reciprocal qualities to said transmission line by inserting a ferromagnetic or ferrimagnetic material on said axis between conductors and to magnetize the ferromagnetic material substantially in the direction of the axis.

It is another feature of the present invention that the radius of the above-mentioned bend be substantially equal to one half wavelength of the desired resonant frequency of the inserted ferromagnetic material.

It is a feature of some embodiments of the present invention employing a transmission line comprising more than two conductors for conducting RF waves around a bend, to dispose a plurality of ferrite bodies on the axis of the bend interlaced between the conductors and to apply a magnetic field parallel to the axis through said ferrite bodies.

Other features and objects of the present invention will be more apparent from the following specific description of prior methods for achieving non-reciprocal qualities in a waveguide employing ferrite materials and from diagrams explaining the theory of the present invention and from numerous embodiments of the present invention represented by structures and a representation of an advantageous use of the present invention, all taken in conjunction with specific descriptions included herein. The figures include the following:

FIGS. 1*a*, 1*b* and 1*c* are figures pertaining to the disposition of electric and magnetic fields induced in a typical waveguide forming, for example, the TE_{01} propagation mode from which to gain an understanding of the non-reciprocal effects achieved in the past by inserting a ferromagnetic material within said waveguide;

FIG. 2 depicts a simple embodiment of the present invention employing a two conductor transmission line, a body of ferromagnetic material and an external magnetic field all disposed with respect to each other to effect non-reciprocal transmission qualities in said line;

FIG. 3 is a diagram from which to gain an understanding of the principles of operation of the present invention;

FIG. 4 depicts an embodiment of the present invention employing a two conductor strip line;

FIG. 5 depicts an embodiment employing a three conductor strip line;

FIGS. 6, 7 and 8 are curves showing the non-reciprocal insertion loss and phase shift qualities of a typical embodiment of the present invention, such as shown in FIG. 5;

FIG. 9 shows an embodiment employing a four conductor strip line;

FIG. 10 shows an embodiment employing a gap transmission line;

FIG. 11 shows an embodiment employing a surface wave transmission line;

FIG. 12 depicts an embodiment employing a shielded conductor transmission line; and

FIG. 13 shows a convenient method of cascading any of the numerous embodiments of the present invention to increase the degree of non-reciprocal attenuation or phase shift.

Turning first to FIGS. 1*a* and 1*b*, there are shown views of a typical waveguide **1** propagating a frequency f of wavelength λ. FIG. 1*b* shows a view through the broad face of the waveguide, the broken lines depicting an RF magnetic field induced within the waveguide by an RF electrical field such as represented by the solid lines in FIG. 1*a*. The small circles with an X at the center in FIG. 1*b* represent the RF electric field lines directed into the page and the small circles with a dot in the center represent RF electric field lines directed out of the page. Consequently, the view of such electrical field lines depicted in FIG. 1*a* is a sectional *mn* taken through FIG. 1*b* where electrical field lines directed out of the page are most concentrated. It is convenient to imagine all of the RF magnetic and electric field lines shown in FIG. 1*b* as moving in the direction of the arrow denoted "wave propagation." The velocity of this movement is usually termed phase velocity and is greater than the velocity of light since the phase velocity wavelength λ_g is greater than λ. Consider a position within the waveguide where a ferrite **2** might be located and then imagine the electric and magnetic RF field structure shown in FIG. 1*b* as traveling through the ferrite and note the direction of the RF magnetic field as the wave travels through. It is apparent that the RF magnetic field vector propagating through the ferrite is rotating in a clockwise manner as viewed in FIG. 1*b*. Therefore, let the position of the ferrite **2** shown in FIG. 1*a* be represented by the centerline **3** in FIG. 1*b* and note the direction of the magnetic field represented by the broken lines at various instants of time along centerline **3**. Referring to FIG. 1*c*, at time t_1 the RF magnetic field is directed as shown by vector t_1, at time t_2 by vector t_2, at time t_3 by vector t_3, etc. Obviously, the RF magnetic field at the ferrite **2** rotates in a clockwise manner and it appears this rotation is elliptical in the example shown. However, it might well be circular depending on the location of the position and the mode of transmission of the RF wave propagated in the waveguide. If a steady external magnetic field is applied to the waveguide in the direction of arrow **4** causing Larmor precession of microscopic magnetic moments within the ferrite, such precession will also be clockwise as viewed from above, just as the rotation of the magnetic vector of the RF wave passing through the ferrite. Hence, it is seen from the above description that such prior application and use of a ferrite in a waveguide to impair non-reciprocal properties to RF wave propagated therein relies upon the circularly or elliptically polarized RF magnetic fields characteristic of the mode of propagation in the waveguide.

Turning next to FIG. 2 there is shown an embodiment of the present invention whereby non-reciprocal attenuation and phase qualities are obtained in a simple two conductor transmission line. As shown in FIG. 2, the two elements, **5** and **6**, of the transmission line are bent

around an axis 7 and a ferrite body 8 which may be, for example, disc-shaped is inserted on said axis so that the plane of the disc lies substantially between the two conductors 5 and 6. An external steady magnetic field H_0, substantially parallel to axis 7, is applied to the ferrite disc. This magnetic field is represented by vector 9. The RF magnetic field between the conductors 5 and 6, produced by an RF wave propagated therein, is represented by the solid lines and the RF electric field is represented by broken lines.

In FIG. 3 there is shown a diagram of the same two conductor transmission line, somewhat exaggerated, from which to understand how non-reciprocal qualities occur. Consider an RF magnetic field vector 10 which might be, for example, at the front of a wave propagated through the conductors 5 and 6. At successive equal intervals of time, vector 10 will move to positions equally displaced as shown in FIG. 3. If the displacements of vector 10 shown in the figure are $\lambda/8$ apart, then the wave represented by this vector will travel around the loop in one-half a wave-length and the field represented by this RF magnetic field vector will pass substantially through the center of the ferrite disc 8 and will rotate π radians as the wave propagates around the loop. Meanwhile, a steady external magnetic field H_0 is applied in the direction of arrow 9 through the ferrite disc 8 causing microscopic magnetic moments 11 within the ferrite to precess at a rate ω around the direction of H_0. If ω is equal in magnitude and direction to the rotation rate of the RF magnetic field vector 10 propagating around the loop, then there will be resonant interaction and the ferrite will absorb energy from the RF wave propagated in conductors 5 and 6. It is apparent that the rotation rate of vector 10 about the center of the ferrite disc 8 will be equal to $2\pi f$ radians/sec., where f is the frequency of the RF wave, provided the radius of the bend from the center of the ferrite to the center of the conductors, (represented by broken line 12), is substantially equal to $\lambda/2\pi$; where λ is the electrical wavelength of the RF signal propagated in conductors 5 and 6. As already mentioned, the permeability of a ferrite material is changed when a magnetic field is applied thereto. Furthermore, this change depends upon the frequency and direction of propagation of a circularly or ellipticaly polarized RF magnetic field propagating through the ferrite. Such a change in permeability will alter the inductive impedance to the RF signal in a non-reciprocal manner and, consequently, a phase shift of such an RF signal propagating in one direction will be different from the phase shift if propagated in the opposite direction.

Turning next to FIG. 4 there is shown another embodiment of the present invention comprising a conductive plate 14 and strip line 15 which may be separated from each other by a suitable dielectric material. A single ferrite disc 16 is preferably located between plate 14 and strip line 15 at or substantially near the axis 17 about which the strip line 15 is bent. A magnetic field H_0 parallel to axis 17 and represented by arrow 18 is applied to the ferrite disc 16.

In FIG. 5 there is shown a three conductor strip type transmission line including conductive plates 19 and 20 with a U-shaped strip line 21 disposed therebetween and forming terminals a and b as shown. The strip line 21 may be separated from plates 19 and 20 by a suitable dielectric material. In this embodiment it is preferable that two ferrite discs such as 22 and 23 be disposed as shown on the axis of the bend, disc 22 preferably lying between strip line 21 and plate 19, and disc 23 preferably lying between strip line 21 and plate 20. A magnetic field is applied substantially in the direction of arrow 24 and passing through both of the discs 22 and 23.

In FIGS. 6, 7 and 8 there are shown curves depicting the performance of such a three conductor strip line. For example, FIG. 6 depicts insertion loss from terminal a to b, denoted S_{ab}, through the strip line as a function of RF frequency propagated therein and insertion loss from b to a, denoted S_{ba}, through the strip line as a function of RF frequency when the magnetic field applied to the ferrite discs is constant. In FIG. 7 there are shown curves of S_{ab} and S_{ba} vs. applied magnetic field strength for a given RF frequency propagated therein. In FIG. 8 there are shown curves of RF phase shift between terminals a and b, denoted ϕ_{ab} and ϕ_{ba}, vs. the magnitude of the applied magnetic field. There is shown in FIG. 8 a plot of differential phase shift $\Delta\phi$ (where $\Delta\phi=\phi_{ab}-\phi_{ba}$) vs. the magnitude of the applied magnetic field. As can be seen from FIGS. 7 and 8, maximum phase differential $\Delta\phi$ and maximum attenuation (S_{ab}) do not occur at the same magnitude of H_0.

FIGS. 9 to 12 depict other embodiments of the present invention employing different types of multiple conductor transmission lines; for example, FIG. 9 depicts a four conductor strip line including two conductive plates 25 and 26 with two U-shaped strip lines 27 and 28 disposed therebetween and separated by a suitable insulator 29. The strips 27 and 28 and plates 25 and 26 are separated by suitable dielectric material. In such an embodiment, it is preferable that at least two ferrite discs 30 and 31 be inserted in the dielectric material on the axis of the bends, one to lie between strip line 27 and plate 25 and the other between strip line 28 and plate 26 as shown.

FIG. 10 depicts a gap transmission line embodying principles of the present invention and including two conductive plates 32 and 33 having protuberances 34 and 35 therefrom to create a narrow gap around a bend. In this embodiment it is preferable that the ferrite disc 36 be located at the axis of the bend and substantially in the same plane as the gap.

FIG. 11 shows a surface wave transmission line including a center conductor 37 concentric with a cylinder of suitable dielectric material 38. The conductor is bent around an axis on which is disposed two ferrite discs 39 and 40. Disc 40 is preferably located in a plane above the plane of conductor 37 and disc 33 in a plane below the plane of conductor 37 so that both intercept the RF magnetic field propagating around the bend. Here again, a steady magnetic field H_0 is applied substantially parallel to the axis of the bend and through the ferrite discs 39 and 40 as shown.

FIG. 12 shows another embodiment very similar to the three conductor strip line shown in FIG. 5 but including in addition a conductive shield 41 forming an enclosure with plates 19 and 20 enclosing strip line 21 and ferrite pieces 22 and 23, and a partition shield 42 running between the two arms a and b of the strip line. The two ferrite discs are located substantially as already described with reference to FIG. 5.

In FIG. 13 there is shown a method of cascading any of the non-reciprocal devices represented by the various embodiments of this invention already described. As shown in FIG. 14 each of the cascaded non-reciprocal loops includes two terminals denoted a and b. Any number of loops may be cascaded such as 43, 44, 45, 46 and 47 and they may be identical to each other or they may be different and each may be designed for ferromagnetic resonance at a different frequency. As shown in FIG. 13, terminal b of loop 43 is coupled to terminal a of loop 44, terminal b of loop 44 is coupled to terminal a of loop 45, etc. If the insertion loss from a to b in each loop is the same and represented by S_{ab}, then the insertion loss from the input terminal A to the output terminal B of the system, denoted S_{AB}, for a cascade of 5 such units as shown in FIG. 13 is equal to $(S_{ab})^5$. On the other hand, if each of the loops 43 to 47 is resonant at different selected frequencies, it is possible to achieve wide band non-reciprocal qualities with regard to signals at A and B. In both instances, it is convenient to employ a single steady magnetic field

such as produced by a magnet 48 which may be a permanent or an electrical magnet. Obviously, if magnet 48 is an electrical magnet the external magnetic field applied to the ferrites may be controlled to alter the ferromagnetic resonance frequencies of each of the loops 43 and 47 and thereby achieve a variety of desired results.

The specific descriptions of embodiments of the present invention, included herein, taken in conjunction with the figures include, briefly, the following: a transmission line for conducting RF waves around a bend, a body of ferrite material located at the bend and means for magnetizing said material transversely to the plane of the bend so that transmission of RF energy is non-reciprocal when the frequency of the RF wave propagated in the line is substantially equal to the ferromagnetic resonant frequency of the ferrite, as established by the ferrite material itself and the magnitude of an externally applied magnetic field, provided the radius of the bend is substantially equal to the wavelength of said RF wave as propagated therein. While there is described herein numerous simple embodiments of the present invention and one means for cascading such embodiments to produce certain desired effects, for example, wide band characteristics, it is to be clearly understood that these descriptions are made only by way of examples and do not limit the spirit and scope of the present invention as set forth in the following claims.

What is claimed is:

1. A non-reciprocal device comprising means for conducting an electromagnetic wave of electrical length λ in a TEM mode over an arcuate path of radius substantially equal to $\lambda/2\pi$, bodies composed of a ferromagnetic material disposed substantially near the origin of said radius to intercept the magnetic field of said propagated wave, and means magnetizing said body substantially perpendicular to the plane of said radius..

2. A nonreciprocal device as in claim 1 and in which said means for conducting an electromagnetic wave comprises a two-element transmission line defining said arcuate path, the portion of each of said elements adjacent said arcuate path lying in separate planes on opposite sides of said arcuate path.

3. A device as in claim 1 and in which said means for conducting an electromagnetic wave comprises a strip transmission line including an arc-shaped center conductors defining said arcuate path disposed between two outer conductors and in which said bodies of ferromagnetic material include at least one such body disposed substantially near said origin between said center conductor and one of said outer conductors and at least one other of said bodies disposed substantially near said origin between said center conductor and the other of said outer conductors.

4. A nonreciprocal device as in claim 1 and in which the ends of said center conductor are shielded from each other by a conductive body disposed between said ends and between said outer conductors and in which the outer peripheries of said outer conductors are connected by conductive material to thereby attenuate radiation from said means for conducting electromagnetic waves.

5. A nonreciprocal device as in claim 1 and in which said means for conducting an electromagnetic wave comprises a gap transmission line including two plates disposed parallel to each other with ridges on each plate defining said arcuate path therebetween and in which said bodies of ferromagnetic material include at least one body substantially near the origin of said radius disposed between said ridges.

6. A nonreciprocal device as in claim 1 and in which said means for conducting an electromagnetic wave comprises a surface wave transmission line including a center conductor defining said arcuate path in a given plane, and dielectric material having a generally cylindrical shape concentric with said center conductor and in which said bodies of ferromagnetic material incluude at least one such body substantially near the origin of said radius and disposed on one side of said given plane and another such body substantially near the origin of said radius disposed on the other side of said given plane.

7. A nonresciprocal circuit comprising a plurality of nonreciprocal devices as in claim 1 and in which said plurality of devices are disposed one above another so that said origins of radius are in line and including transmission lines coupling said devices together, and in which said magnetizing means includes opposite magnetic poles disposed on said line at opposite ends of said circuit whereby the nonreciprocal effects of each of said devices are combined in said circuit.

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