

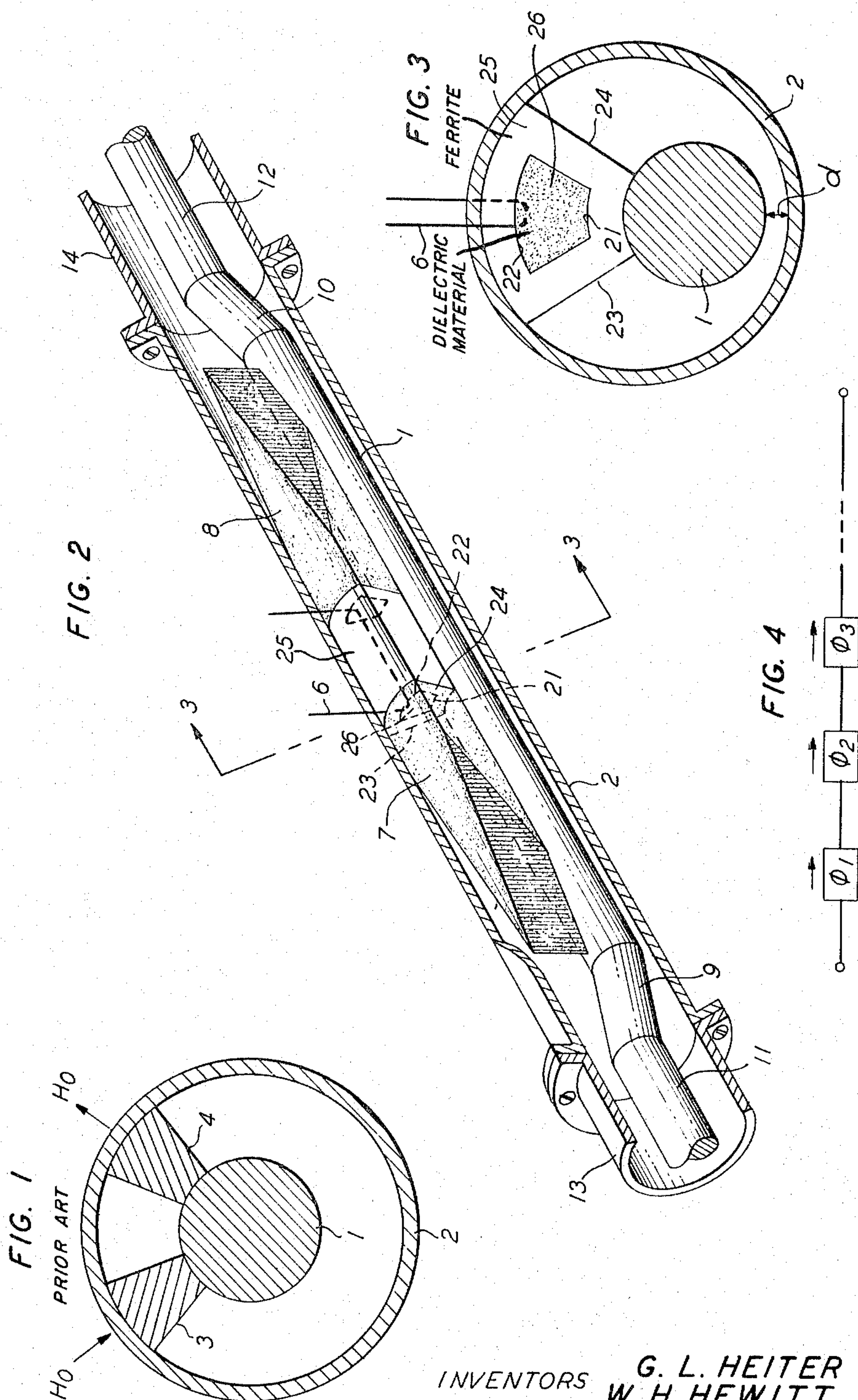
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LATCHING TYPE NONRECIPROCAL COAXIAL PHASE SHIFTER HAVING
ECCENTRICALLY POSITIONED CENTER CONDUCTOR
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LATCHING TYPE NONRECIPROCAL COAXIAL PHASE SHIFTER HAVING ECCENTRICALLY POSITIONED CENTER CONDUCTOR

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This invention relates to electromagnetic transmission systems and more particularly to structures having non-reciprocal properties for use in such systems.

Nonreciprocity in transmission systems has been achieved in prior art structures such as phase shifters and isolators by the use of gyromagnetic material such as ferrite. The nonreciprocity is attained by arranging the ferrite members for interaction with electromagnetic waves being propagated through the transmission system. When a ferrite member biased by means of an externally applied magnetic field is placed in the path of a transmitted wave having a circularly polarized magnetic field, the transmission properties of the structure will depend upon the sense of rotation of the circularly polarized component of the propagated magnetic field relative to the direction of rotation of the precessing electron spin established within the ferrite. For example, with a magnetic biasing field of fixed direction and circularly polarized energy having one direction of rotation, the transmitted wave will experience one phase shift in its transmission, while circularly polarized wave energy having a second direction of rotation will experience a second and different phase shift.

Various arrangements exist in the prior art for constructing nonreciprocal phase shifters. However, when it is desired to obtain such phase shifters for operation at lower frequencies, hollow conductively bounded, rectangular and circular wave guide structures are found to be inadequate due to the large dimensions required by the low frequency cutoff dimension limitations. As a consequence of these limitations, resort has been made to coaxial transmission line structures with zero or D.C. theoretical lower cutoff frequency. However, in using coaxial structures having the capacity to support transmission of lower frequency wave energy, a problem arises when nonreciprocal transmission is desired, since the dominant mode capable of being propagated therein is a TEM or transverse electromagnetic wave having no component of the magnetic field vector in the direction of transmission and consequently having no circularly polarized magnetic field component.

Prior art devices have obtained a circularly polarized component of magnetic field in such coaxial structures with the dominant mode comprising a transverse magnetic wave by the insertion of dielectric material of relatively high permittivity in a portion of the space between the conductors. The theoretical considerations involved in explaining how the insertion of a sufficient bulk of ferrite dielectric material having a relatively high permittivity in comparison to the surrounding dielectric material in order to achieve this nonreciprocity, may be found in volume 28, No. 2, February 1957, Journal of Applied Physics, page 218. Another explanation for the conversion of electric energy in a transverse magnetic mode to a circularly polarized component of wave energy for interaction with the gyromagnetic ferrite material is found in Patent No. 3,078,425 of February 1963 to B. J. Duncan wherein it is conceived that, because of the different velocities of the electric wave energy in dielectric materials having different permittivities, bending of the magnetic field lines results to produce circularly polarized wave energy.

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While the prior art structures obtain nonreciprocity in the manner described, a problem exists therein with respect to the external biasing magnetic field required. Since this field must be transverse to the direction of propagation within the coaxial structure and therefore transverse to the conductors themselves, large permanent or electric horseshoe magnets are needed to supply the required magnetic field. Moreover, if a variable phase shift is desired, permanent magnets cannot be used and resort must be had to electromagnets requiring large and continuous source of power to produce the magnetic field required. In addition, it is desirable to obtain in these coaxial structures a larger figure of merit, defined as phase shift per unit longitudinal length per decibel loss, without a corresponding change of dimensions which would produce an undesirable change in characteristic impedance of the line.

Accordingly, it is an object of this invention to non-reciprocally transmit relatively low frequency electromagnetic wave energy propagating in the transverse electromagnetic transmission mode.

It is another object of this invention to provide an improved nonreciprocal phase shifting device for use in coaxial transmission systems.

It is still another object of this invention to provide a latching type differential phase shifter for use in a coaxial transmission line in order to eliminate the need for power consuming, bulky, external sources of magnetic biasing fields.

In accordance with the objects of this invention, it has been found that an improved nonreciprocal differential phase shifting device is attained if a section of coaxial line is modified by offsetting the center conductor for eccentric positioning therewithin. This modification produces a marked increase in the figure of merit in addition to a region of larger spacing between conductors permitting the insertion of a larger bulk of material in the form of a closed circuit magnetic structure of ferrite material to produce latching type operation. The advantages flowing from the use of this closed circuit of magnetic material are considerable, since by means of a coil wound about the magnetic circuit, a current pulse of short duration is capable of saturating the ferrite material to produce the external biasing magnetic field heretofore provided by an external horseshoe magnet. Not only is the resulting field transversely polarized in a simple manner but also the power required to produce this field need not be supplied continuously.

Accordingly, a principal feature of this invention is the provision of an offset eccentric center conductor in a coaxial transmission line.

Another feature of this invention is the provision of a closed loop magnetic circuit for both latching type operation and for providing gyromagnetic nonreciprocity.

These and other objects and features of this invention will be better understood upon a consideration of the following detailed description of the invention as presented hereinbelow in connection with the accompanying drawings in which:

FIG. 1 shows in cross section the structure of a typical coaxial nonreciprocal device found in the prior art;

FIG. 2 shows in perspective an embodiment of the invention in its basic form and the manner in which it is coupled to a conventional coaxial line;

FIG. 3 shows a cross sectional view of FIG. 2 taken along line 3-3; and

FIG. 4 shows in schematic form another embodiment of the invention.

Referring more particularly to FIG. 1 wherein a cross sectional view of a nonreciprocal coaxial transmission line such as that found in the above-referred-to article in vol-

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ume 28 of the February 1957 Journal of Applied Physics is shown, it may be seen that the coaxial conductors 1 and 2 are concentric and that the structure is loaded with longitudinally placed ferrite members 3 and 4 disposed radially between the conductors. Elements 3 and 4 are composed of ferrite material which may be, for example, a combination of iron oxide and a small amount of one or more materials such as nickel, magnesium, zinc, manganese or aluminum. These materials are characterized by the fact that they exhibit gyromagnetic properties at the microwave frequencies of interest and can therefore be spoken of as gyromagnetic materials. As a specific example, elements 3 and 4 may be made of magnesium-manganese-aluminum ferrite prepared in the manner described by C. L. Hogan in his Patent 2,748,353, issued May 29, 1956. Because of the different dielectric constants of the ferrite and the surrounding dielectric, non-reciprocity is attained in accordance with the theoretical considerations found in the above-referred-to article.

A qualitative summary of the nonreciprocal operation of the device as described in the references mentioned above is had by considering the fact that the velocity of propagation of an electric wave in a medium is inversely proportional to the square root of the product of the permeability μ and the permittivity ϵ of the medium. Therefore, due to an abrupt discontinuity in the value of ϵ found at the boundaries of the dielectrics as an arcuate path is traversed, the transverse magnetic field energy being transmitted is disturbed sufficiently to provide a circularly polarized component. When this circularly polarized component interacts with the gyromagnetic material biased by the externally applied magnetic field H_0 , directed as shown in members 3 and 4, gyromagnetic interaction takes place and nonreciprocal transmission results.

FIG. 2 shows in perspective an embodiment of the invention in its simplest form and the manner in which it is coupled by means of flanges into a conventional concentric coaxial line as represented by conductors 11 and 13 on one side and conductors 12 and 14 on the other side. The phase shifter comprises an outer cylindrical conductor 2 with an eccentrically positioned cylindrical conductor 1. A closed magnetic circuit of ferrite material 25 is longitudinally placed in the larger gap between conductors 1 and 2 in a manner such that two legs 23 and 24 of the circuit are radially oriented to be in a transverse plane with respect to conductors 1 and 2 and the remaining two legs 21 and 22 of the circuit are peripherally placed between the radial members so that member 21 is contiguous to conductor 1 while member 22 is contiguous to conductor 2. As will be described below, the radial members 23 and 24 support a biasing magnetic field for gyromagnetic interaction with a circularly polarized transmitted wave and the arcuate members 21 and 22 serve to provide not only a portion of the bulk of dielectric required between the conductors for conversion of electromagnetic energy in the TEM mode to circularly polarized electromagnetic energy, but also as a means for providing a low reluctance path between radial members 23 and 24. A coil 6 is threaded through the aperture of the closed magnetic circuit 25 to provide the magnetizing currents required. Latching occurs in response to a current pulse which produces the remanent flux in core 25 in accordance with the well-known right-hand rule because of the retentivity of the ferrite material. Therefore, a current pulse in coil 6 having a first direction causes the ferrite material to saturate in one of its two stable magnetic states with flux containing to flow about the circuit path after the disappearance of the pulse source. A current pulse in a second direction through coil 6 reverses the direction of the flux flow in the legs of core 25 in a similar manner.

The center of core 25 is filled with a dielectric material 26 the function of which will be described below. Elements 7 and 8 are composed of dielectric material having cross sectional dimensions at their respective junc-

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tions with the core 25 which are identical therewith and are provided with wedge-like tapers to minimize reflections of wave energy and thus to provide smooth electrical coupling between the ferrite filled and the air filled sections. The permittivity of elements 7 and 8 is chosen so as to obtain optimum matching in accordance with theoretical considerations familiar to those versed in the art. The phase shifter can be coupled to the conventional concentric coaxial line by bolted flanges as shown. Coupling is also facilitated by providing the phase shifter with an outer conductor 2 of the same diameter as conductors 13 and 14 of the concentric line and by providing conductors 9 and 10 as transition connections between conductors 11 and 12 of the concentric line and conductor 1 of the eccentric coaxial line of the phase shifter.

A section 3—3 taken through the embodiment of FIG. 2 is shown in FIG. 3 to facilitate the explanation of the operation of the invention and to clearly display the distinguishing features of the invention which produce the improvement over the prior art structures. FIG. 3 shows in cross section the eccentric conductors 1 and 2, ferrite core 25 consisting of radial legs 23 and 24 and arcuate legs 22 and 21 joined in the closed magnetic circuit and the coil 6 threaded through the center of the core as shown. The center of the core shown dotted contains dielectric material 26. Since it is desirable to increase the radial dimension of members 23 and 24 for reasons to be explained below, and since the characteristic impedance of the line is a function of the ratio of the diameters of conductors 1 and 2, by offsetting conductor 1 as shown, the radial dimension of members 23 and 24 is increased as desired while maintaining the diameters and consequently the ratio of the diameters of conductors 1 and 2 constant. Moreover, as compared with the arrangement shown in FIG. 1 the eccentricity produces a region of greater spacing, or gap, between conductors 1 and 2 in which a larger volume of dielectric material can be inserted to more efficiently circularly polarize a portion of the transverse magnetic wave energy, in addition to providing sufficient space for the closed magnetic circuit presented by core 25. As a result of the arrangement shown, a differential latching type phase shifter having a relatively high figure of merit is produced without the requirement of bulky external horseshoe magnets or electromagnets requiring the continuous supply of large currents and without introducing a mismatch of impedance.

The figure of merit as previously defined is the ratio of phase shift per unit length of ferrite material to the insertion loss measured in decibels. The marked increase in this figure of merit is a result of both an increase the phase shift increases as a result of the present structural arrangement since the radial dimension of the core members 23 and 24 has been increased above that found in prior art structures of similar dimensions and characteristic impedance. As a consequence of this increased radial dimension, there is available a greater quantity of ferrite material with electron spins that can be properly oriented for gyromagnetic interaction with a circularly polarized wave in a plane perpendicular to the electron spin precession as explained in the references cited above.

The other contribution to the increase in figure of merit of the invention is due to a decrease in the insertion loss. Since the strength of the circularly polarized component (and consequently the magnitude of phase shift per unit length of ferrite) is proportional to both the arcuate length of dielectric and the permittivity of this dielectric filling the cavity between conductors 1 and 2, and since ferrite dielectric is inherently more lossy than nonferrite high permittivity dielectric, the walls of core 25 are reduced in thickness and nonferrite permittivity dielectric 26 is inserted in the aperture of core 25 to provide the required bulk in the arcuate direction. The insertion loss is thereby reduced without an impairment of the latching or

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gyromagnetic functions served by the ferrite core and without materially affecting the conversion of the TEM wave energy to circularly polarized wave energy, or indeed, without materially affecting the phase shift introduced.

As noted above the problem of supplying a biasing field to produce gyromagnetic interaction with the circularly polarized magnetic energy for nonreciprocal transmission is obviated by using the closed magnetic circuit of core 25 since the required magnetic field is obtained within the core by means of a relatively short duration current pulse applied to winding 6. As described above, the direction of current flow in winding 6 determines the orientation of the magnetic flux within the magnetic circuit. Therefore, a current pulse of a first polarity produces a first orientation of flux flow which in turn produces a first value of phase shift while a pulse of current in a reverse direction reverses the flux flow and consequently causes, in accordance with gyromagnetic principles, a second value of phase shift. If desired, in order to minimize any interaction occurring between the electromagnetic field within the coaxial structure and the portion of coil 6 threaded through the aperture of core 25, one quarter wavelength shorting stubs can be used at appropriate points as conduits for the coil conductors in a manner familiar to those versed in the art.

Therefore, the use of the closed magnetic circuit of core 25 obviates the need for bulky or power consuming external horseshoe magnets while at the same time provides structure for realizing a differential phase shift. By providing arcuate members 21 and 22 which serve to complete and close a low reluctance magnetic path, the phase shift can be made bivalued by the simple expediency of the reversal of polarity of a current pulse applied to winding 6. Moreover, it is the specific arrangement of members 23 and 24 as shown that provides the transverse biasing field—transverse to conductors 1 and 2 and consequently to the direction of propagation and plane of circular polarization of the propagating wave—required for gyromagnetic interaction.

FIG. 4 shows in schematic form an arrangement of the invention as a digital phase shifter of arbitrarily small incremental phase shift. The figure represents the device shown in FIG. 2 modified by including, in addition to core 25, an arbitrary number of cores along the length of the phase shifter between tapered members 7 and 8. Each core has its own winding (similar to coil 6), is of selected length and is separated from the adjacent cores by dielectric spacers. By pulsing the coils of selected cores the phase shift can be varied from 0 to 360 degrees in arbitrarily small increments of arbitrary size. If, for example, there are n cores the lengths of which are constructed to be in ratio of 2^n then the increments of phase shift will be in multiples of $360/2^n$. Thus, if three cores are used and the first is constructed to be of unit length corresponding to a 45-degree phase shift capability, and the second and third cores are made to be two and three times as long respectively as the unit length, then the phase shift can be varied between 0 and 360 degrees in 45-degree increments. In terms of FIG. 4, Φ_1 is 45 degrees, Φ_2 is 90 degrees and Φ_3 is 180 degrees.

It is understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. A nonreciprocal transmission path comprising a coaxial cable having a first conductor and an eccentrically positioned second conductor, an element of gyromagnetic material extending longitudinally between said first and second conductors substantially filling the larger cross sectional area between said eccentrically positioned conductors, and means for magnetizing said element with a

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field polarized mutually transverse to each of said conductors.

2. In a transmission system for propagating wave energy of solely transverse magnetic field distribution, a pair of eccentric conductors longitudinally disposed one within the other, means for obtaining nonreciprocal wave transmission including a closed loop of gyromagnetic material longitudinally positioned in the region of largest distance between said pair of conductors for interacting with said transverse magnetic field to produce wave energy having circular polarization and means responsive to current pulse excitation for producing within said loop remanent magnetization transversely oriented with respect to each of said conductors for interaction with said circularly polarized wave energy.

3. A nonreciprocal phase shifting device for electromagnetic wave energy in a transverse magnetic mode comprising a first hollow cylindrical conductor having a longitudinally extending axis, a second cylindrical conductor disposed parallel to and within said first conductor and having its axis offset so that a maximum and a minimum gap exists between said conductors, a closed magnetic circuit of gyromagnetic material having a pair of stable remanent magnetic states longitudinally placed between said conductors in the region of said maximum gap, said magnetic circuit having a cross section comprising a pair of radially positioned elements interconnected by elements positioned respectively on the periphery of each of said conductors and means for selectively exciting either of said stable magnetic states in response to a current pulse for discretely varying the phase shift introduced.

4. In a coaxial transmission line having a pair of concentric conductors, a nonreciprocal differential phase shifter comprising a first hollow cylindrical conductor having a longitudinally extending axis, a second cylindrical conductor eccentrically disposed parallel to said first conductor so that a maximum and a minimum gap exists between said conductors, a plurality of cores of gyromagnetic material exhibiting a pair of stable remanent magnetic states longitudinally placed between said conductors in the region of said maximum gap and separated by dielectric spacers, each of said cores being of selected length and having a cross section comprising a dielectric center about which is placed a pair of arcuate members interconnecting a pair of elements radially placed between said first and second conductors, individual winding means coupled to each of said cores for selectively exciting either of said stable magnetic states in one or a group of said cores to incrementally vary the phase shift introduced, and transition means for coupling said phase shifter to said line including a first electrical connection coupling said first conductor to one of said pair of concentric conductors of said line, a second electrical connection coupling said second conductor to a second of said pair of concentric line conductors and a tapered dielectric member positioned at each end of the longitudinal alignment of said plurality of cores for reducing reflective distortions within said phase shifter.

5. A nonreciprocal phase shifting device comprising a first and a second section of coaxial transmission line having respectively a pair of concentric conductors for supporting the propagation of electromagnetic wave energy in a transverse magnetic mode, a first means for converting a portion of said transverse magnetic wave energy into circularly polarized wave energy and for providing a magnetic biasing field transversely polarized with respect to said circularly polarized wave energy for gyromagnetic interaction therewith including a first hollow cylindrical conductor having a longitudinally extending axis, a second cylindrical conductor eccentrically disposed parallel to said first conductor so that a maximum and a minimum gap exists between said conductors, a closed magnetic circuit of ferrite material having a pair of stable remanent magnetic states longitudinally placed between said conductors in the region of said maximum

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gap, said magnetic circuit having a cross section comprising a first pair of elements positioned transversely to said first and second conductors and a second pair of elements interconnecting said first pair and positioned respectively on the periphery of each of said conductors, dielectric material filling said magnetic circuit cross section, winding means imbedded in said dielectric and coupled to said magnetic circuit for selectively exciting either of said stable magnetic states in response to a current pulse for discretely varying the phase shift introduced, and transition means interconnecting said first means with said first and second sections of coaxial transmission line including a first and a second pair of conductors interconnecting said first and second cylindrical conductors in said first means to each of said pair of concentric conductors respectively and a pair of tapered dielectric members extending from either side of said magnetic circuit toward each of said sections of coaxial transmission line for reducing reflective distortions within said phase shifting device.

6. A nonreciprocal latching type phase shifting structure comprising a first cylindrical conductor, a second cylindrical conductor disposed parallel to and within said first conductor for supporting the propagation of electromagnetic wave energy in a transverse mode, a closed magnetic circuit of gyromagnetic material having a pair of stable remanent magnetic states disposed between said conductors for converting a portion of said transverse magnetic wave energy to circularly polarized wave energy, and means responsive to a current impulse excitation for selectively exciting either of said stable magnetic states to produce a polarized field within said magnetic circuit for nonreciprocal interaction with said circularly polarized wave energy.

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7. A nonreciprocal latching type phase shifting structure comprising a first hollow cylindrical conductor having a longitudinally extending axis, a second cylindrical conductor disposed within said first conductor for supporting the propagation of solely transverse magnetic wave energy, a closed magnetic circuit of gyromagnetic material having a pair of stable remanent magnetic states and longitudinally placed between said conductors, said magnetic circuit having a cross section comprising a pair of elements positioned to support a magnetization mutually transverse to said first and second conductors, said gyromagnetic material further positioned to convert a portion of said transverse magnetic wave energy to circularly polarized wave energy, and means responsive to a current pulse excitation for selectively exciting either of said stable magnetic states within said pair of elements for interaction with said circularly polarized wave energy.

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