

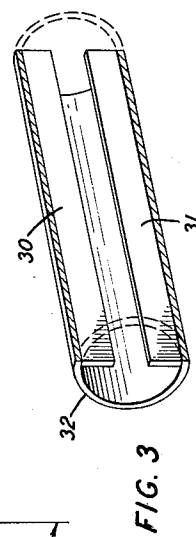
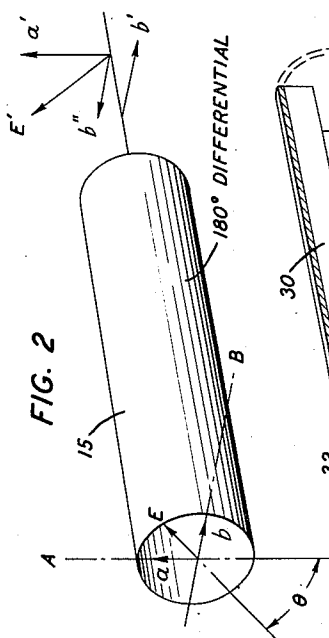
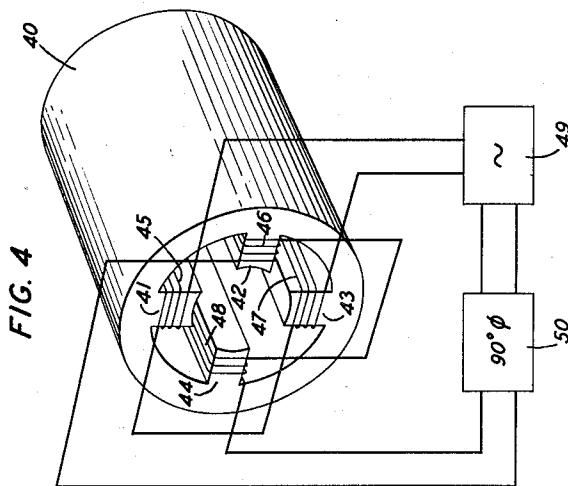
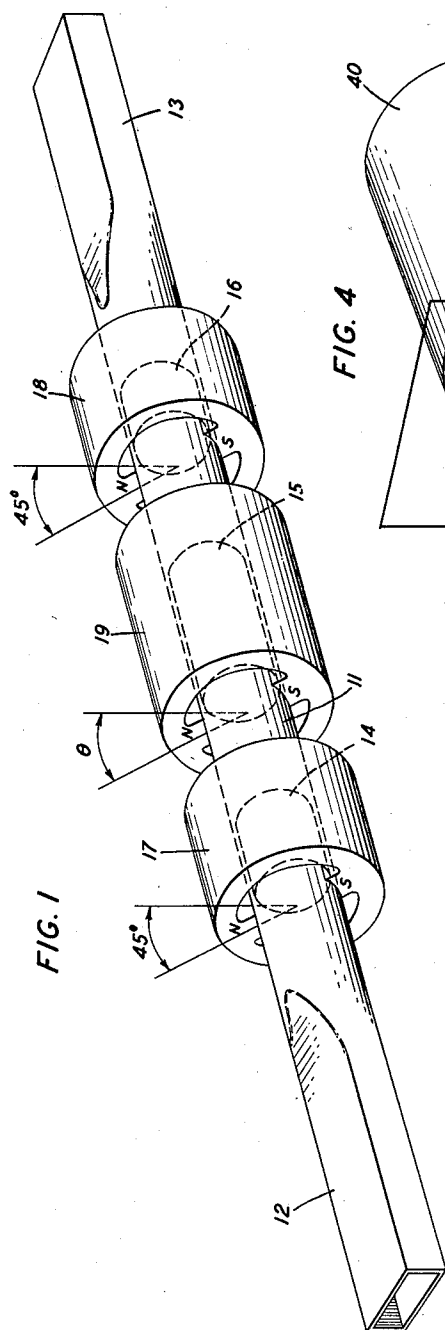
April 2, 1957

A. G. FOX
MAGNETICALLY CONTROLLED FERRITE PHASE SHIFTER
HAVING BIREFRINGENT PROPERTIES

2,787,765

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2 Sheets-Sheet 1



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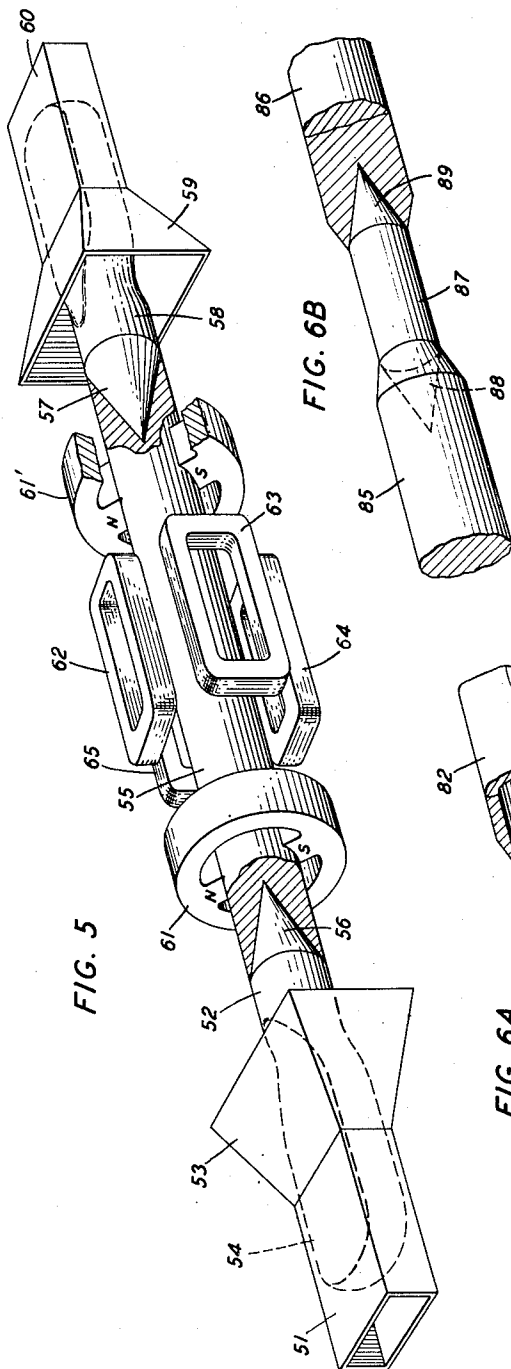


FIG. 5

FIG. 6B

FIG. 6A

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MAGNETICALLY CONTROLLED FERRITE PHASE SHIFTER HAVING BIREFRINGENT PROPERTIES

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Application August 15, 1952, Serial No. 304,609

11 Claims. (Cl. 533-21)

This invention relates to guided electromagnetic wave transmission systems and, more particularly, to phase changing or phase shifting devices for use in such systems.

It is an object of the invention to introduce an easily adjustable value of phase shift which may be either leading or lagging, fixed or continuously variable, to energy conveyed along said systems.

Continuously variable phase changers by means of which the phase of an output wave may be shifted with respect to the input wave are an essential component in the electromagnetic wave transmission art. Such phase changers heretofore have involved mechanically moving parts and were, therefore, inherently restricted to limited degrees of phase shift and to relatively low speeds of possible variation.

Another object of the invention is to shift the phase of an electromagnetic wave over a range which may exceed one cycle of phase shift by an entirely electrically controlled phase changer.

It is a further object of the invention to vary the value of phase shift introduced at an arbitrarily rapid rate.

In accordance with the invention, the unusual properties of ferromagnetic materials in the presence of exciting magnetic fields are utilized. In one embodiment, including the several variations thereof to be described in detail hereinafter, linearly polarized waves are converted to circularly polarized waves, applied to an element of ferromagnetic material which is excited by a transverse magnetic field, and then reconverted to linearly polarized waves. The instantaneous phase shift introduced by this combination depends upon the instantaneous angular relationship of the applied field to the polarization of the wave energy. Special features of the invention are found in the means for electrically, rapidly and continuously varying this angular relationship to correspondingly vary the introduced phase shift.

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

In the drawings:

Fig. 1 is a perspective view of a variable phase shifter, in accordance with the invention, for introducing a variable phase shift to electrical energy traversing there-through;

Fig. 2 is a schematic representation, given for the purpose of explanation, of a portion of the phase shifter of Fig. 1;

Fig. 3 represents an alternative variation of the phase shifter in Fig. 1, in accordance with the invention, by illustrating a structure which may be substituted for certain components of Fig. 1;

Fig. 4 illustrates suitable means for producing an electrically controlled rotating magnetic field, in accordance with the invention, which may be incorporated in the phase shifter of Fig. 1;

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Fig. 5 is a perspective view of a phase shifter, in accordance with the invention, for introducing a rapidly varying, electrically controlled phase shift to electromagnetic wave energy; and

Figs. 6A and 6B represent alternative modifications of Fig. 5, in accordance with the invention.

In more detail, Fig. 1 illustrates an embodiment of a variable phase shifter in accordance with the invention comprising a section of wave guide 11, which may be of circular cross-section, interposed between suitable transmission means for supporting linearly polarized electromagnetic waves and for applying these waves with a given polarization to guide 11. These transmission means are illustrated in the embodiment of Fig. 1 as sections of rectangular wave guides 12 and 13 which each taper smoothly and gradually into the circular cross-section of guide 11 to which they are integrally connected. Rectangular guides 12 and 13 will accept or support only linearly polarized waves in which the electric vector, which determines the plane of polarization of the wave, is parallel to the short side of the rectangular wave guide. The dimension of guide 11 is preferably chosen so that only the various polarizations of the dominant TE_{11} mode in circular guide can be propagated. By means of the smooth transition from rectangular guides 12 and 13 to circular guide 11, a TE_{10} mode, in either rectangular guide 12 or 13 may be coupled to and from the TE_{11} mode in circular guide 11 which has a similar or parallel polarization. It is obvious to one skilled in the art that any of a number of other well-known coupling means having polarization selective transmission characteristics may be employed in lieu of rectangular guides 12 and 13 to couple a linearly polarized wave to the proper polarization in circular guide 11.

Interposed in guide 11 between guides 12 and 13 in the order named are three elements of ferromagnetic material 14, 15, and 16 of the types and having the characteristics to be described. Surrounding guide 11 in the vicinity of elements 14 and 16 are suitable means for producing constant magnetic fields, transverse to the axis of guide 11 and passing through elements 14 and 16 in planes inclined at acute angles of 45 degrees to the plane of polarization of wave energy supported in rectangular guides 12 and 13. Surrounding guide 11 in the vicinity of element 15 is a means for producing a constant transverse magnetic field passing through element 15 in a plane inclined at a variable angle θ to the plane of polarization of wave energy supported in guides 12 and 13. As illustrated in Fig. 1, these fields may be supplied by permanent magnet structures having concentrated pole pieces N and S bearing against the outside wall of guide 11 along narrow, oppositely disposed areas. Thus, the magnetic fields for elements 14 and 16 are supplied by magnet structures 17 and 18, respectively, each having their pole pieces inclined at a fixed 45 degree angle. The field for element 15 is supplied by magnet 19 which is rotatably mounted on guide 11 to provide for the variable angle θ .

Elements 14, 15 and 16 may each be blocks of ferromagnetic material of the type exhibiting a Faraday-effect rotation when in the presence of a longitudinal magnetizing field. These materials comprise an iron oxide with a quantity of the oxide of nickel, magnesium, zinc, manganese, or other similar material in which the other oxides combine with the iron oxide in a spinel structure. This material is known as a ferromagnetic spinel or a ferrite. On the basis of their electrical properties, a particularly suitable designation of this class of materials is "gyromagnetic" to designate materials having electrons capable of being aligned by an external magnetic field and capable of exhibiting the precessional

motion of a gyroscopic pendulum. As a specific example, elements 14, 15 and 16 may each be cylindrical blocks of nickel-zinc ferrite prepared in the manner disclosed in the copending application of C. L. Hogan, Serial No. 252,432 filed October 22, 1951, which matured into United States Patent No. 2,748,353, May 29, 1956. It has been determined that when these materials are excited by a transverse magnetic field, they exhibit a permeability constant of one value to electromagnetic energy components polarized parallel to the exciting magnetic field and a different value to electromagnetic energy components polarized perpendicular to the field. This effect may theoretically be explained by the assumption that the ferromagnetic material contains unpaired electron spins which tend to line up with the applied magnetic field. An electromagnetic wave having its magnetic vector in the direction of the magnetic field (the electric vector perpendicular to the magnetic field) will be unable to reorient the electron spins to any appreciable extent and, hence, will see a permeability close to unity regardless of the strength of the magnetic field. A wave having its magnetic vector at right angles to the magnetic field will cause the electron spins to precess about the axis of the magnetic field in synchronism with the applied electromagnetic wave. Such a wave will see a permeability substantially different from unity because the precessing spins now yield a component of radio frequency flux density along the wave's magnetic vector. The amount of difference from unity will be determined by the strength of the magnetic field.

Since the phase velocity of a wave passing through a material depends upon the permeability of the material, a wave traversing the ferromagnetic material of element 12 with its electric vector polarized parallel to the magnetic field will exhibit a higher phase velocity than the wave polarized perpendicular to the magnetic field. An element having this property, namely, the ability to transmit two sets of waves polarized at right angles to one another with different speeds, will produce two different phase delays for the two polarizations and, accordingly, may be termed a "differential phase shift element." The value of this phase shift difference for a ferromagnetic element is approximately proportional to the thickness of the material traversed by the waves and to the intensity of the magnetization to which the material is subjected. It may be shown by mathematical analysis provided the frequency of the wave energy is substantially greater than the gyromagnetic resonance frequency of the ferromagnetic material, that this phase difference expressed in radians is substantially given by the expression

$$l\sqrt{\frac{\epsilon\mu}{2}\left[\frac{\gamma^2 M^2}{\omega} + \frac{\gamma^2 MH}{\omega}\right]}$$

in which l is the thickness of the material in meters, ϵ is the dielectric constant of the material, μ is its permeability without exciting magnetic field, M is the saturation magnetization of the material, H is the exciting magnetic field, ω represents the frequency of the wave energy and γ is the spectroscopic splitting factor of the material. In accordance with the invention, the differential phase shifts of elements 14 and 16 are made equal to 90 degrees and the differential phase shift of element 15 is made equal to 180 degrees, by properly choosing the thickness of the elements and the strength of the magnetic field applied to each, either by calculations in accordance with the above expression, or by adjustments on an empirical basis.

The apparatus thus far described serves to introduce a time phase shift to electromagnetic wave energy transmitted therethrough of two times the angle θ . If θ is continually varied by rotation of magnet 19 a continuous change in phase will be produced. This operation may most easily be analyzed by following the path of a linearly

polarized wave introduced by way of guide 12 and leaving the phase shifter by way of guide 13. The effect of 90 degree differential phase shift element 14 is to convert this linearly polarized wave into a clockwise rotating circularly polarized wave. A complete and detailed explanation of this effect is given in my copending application Serial No. 301,726, filed July 30, 1952. The clockwise rotating circularly polarized waves are then applied to the 180 degree differential phase shift element 15. In order to understand the effect of element 15 upon these waves, certain properties of a 180 degree differential phase shift section must be examined. This examination may most readily be made with reference to the schematic representation of Fig. 2 which shows the 180 degree differential phase shift element 15 separated from the other components of Fig. 1.

Referring therefore to Fig. 2, the axis A designates the plane of wave energy of greatest phase velocity, i. e., under the conditions described above, the electric polarization of wave energy parallel to the exciting magnetic field while the axis B designates the plane of wave energy of smaller phase velocity, i. e., the electric polarization of wave energy perpendicular to the exciting magnetic field.

Assume first that linearly polarized waves represented by vector E are being introduced from the left of the section, and these waves are polarized at an angle θ clockwise from axis A. Vector E may be resolved into components a and b along axes A and B, as shown on Fig. 2. Since the A-axis component travels at higher speed than the B-axis component, upon emerging from the other end of the section, b' lags behind a' by 180 degrees or one-half wavelength. Hence, at the position of a' the B-axis component will be pointing in the opposite direction from b' , as indicated by b'' . Now, when a' and b'' are added vectorially, the resultant will be a linearly polarized wave represented by E' polarized at an angle θ counterclockwise from the A axis. Thus, the effect of a 180 degree differential phase shift section upon linearly polarized waves is to cause a rotation of the angle of polarization in the direction of the A axis by 2θ , or twice the angle between the A axis and the input polarization. (The B axis could equally well have been chosen as the reference axis, and the same result would have been obtained.) If the input polarization remains fixed, rotation of the phase shift axes by angle θ will cause a rotation of the plane of the output polarization by twice θ .

Instead of a linearly polarized input, however, a clockwise-rotating circularly polarized wave is applied to element 15. This circularly polarized wave may be thought of as a linearly polarized vector which, however, is rotating in the clockwise direction. Since the angle between this input vector and axis A is constantly increasing in the clockwise direction, the analysis of the linearly polarized wave above shows that the angle of the output vector is constantly increasing in the counterclockwise direction. It is, therefore a property of the 180 degree differential phase element that it converts clockwise circularly polarized waves into counterclockwise circularly polarized waves. Furthermore, an examination of the field patterns existing at a particular instant in time will indicate that the instantaneous angle of the output vector of the circularly polarized wave will depend upon the instantaneous angle of the input vector with respect to the principal axes of the section. Therefore, by rotating the phase shift axis of the section by an angle θ the instantaneous output polarization will be rotated by an angle 2θ .

The circularly polarized waves emerging from element 15 are reconverted into linearly polarized waves by the 90 degree differential phase shift element 16. As disclosed in my abovementioned copending application, the emerging linear wave is polarized at an angle of 45 degrees to the planes of phase shift of element 16 and is, therefore, in the proper orientation for passage out guide

13. The instantaneous phase of this wave in guide 13 depends upon the time of transmission through element 16 and also upon the instantaneous phase of the wave at the input of element 16. But the instantaneous phase of the input circularly polarized wave depends upon, and is the same as, its instantaneous polarization or orientation at the input of element 16.

As pointed out above with particular reference to Fig. 2, this instantaneous orientation depends in turn upon the incidence angle of the wave at the input of element 15 with the principal planes of phase shift therein. Since the position of these planes are determined by the applied magnetic field, when the field is rotated through angle θ , a total angle displacement of 2θ will be introduced between the rotating electric vector found at the output of element 14 and the vector found at the input to element 16. Thus, a time phase of 2θ is introduced between the linearly polarized wave in guide 12 and the linearly polarized wave in guide 13. This time phase is in an advanced sense if the angle θ is in the direction of rotation of the circularly polarized wave leaving element 14 or is in retarded sense if θ is in the opposite direction. All that has been said holds for any state of polarization of the input of element 15 so it also holds at any instant if the planes of phase shift of element 15 are continuously rotated. There is then no limit to the range of phase control obtainable and continuous rotation of magnet 19 will cause continuous retardation or advancement of the phase. Also continuous rotation of magnet 19 at a constant speed will cause a fixed increase or decrease in the frequency of the transmitted wave. Furthermore, waves passing through the assembly of Fig. 1 will suffer the same phase shift regardless of the direction of transmission therethrough.

While the ferromagnetic means for converting between linearly polarized waves and circularly polarized waves of my above-mentioned copending application have been shown in Fig. 1 by way of illustration, it should be noted that other converters or transducers may be employed. For example, Fig. 3 shows a 90 degree differential phase shift section which may replace elements 14 or 16 and their associated magnetic fields. In Fig. 3 the phase shift section comprises two oppositely positioned metal fins 30 and 31, each extending perhaps one-fourth of the way across wave-guide section 32 which would replace a length of guide 11 of Fig. 1. Fins 30 and 31 produce a kind of capacitive loading and, accordingly, reduce the velocity of wave energy polarized parallel to the fins, the principal plane of phase shift of the section. The lengths of fins 30 and 31 are such that a 90 degree phase shift is introduced to this wave energy relative to the wave energy polarized perpendicular to the fins. Each of fins 30 and 31 may be tapered or introduced by a quarter wave transformer to prevent reflection loss at the edges thereof. When the plane of fins 30 and 31 is oriented at an angle of 45 degrees with respect to the linear polarization in guide 12, this wave energy is converted into circularly polarized waves.

In the embodiment of Fig. 1, the angle at which the transverse magnetic field is applied to element 15 is varied by physically rotating magnet 19 upon guide 11 by suitable mechanical means. A special feature of the invention resides in the combination by which the applied magnetic field is rotated electrically.

Referring to Fig. 4, an electromagnetic field source is shown which may replace magnet 19 of Fig. 1. As illustrated in Fig. 4, this source comprises a magnetic core structure 40 having, for example, four internally directed pole pieces 41, 42, 43 and 44, preferably equally displaced to bear upon the periphery of guide 11 along narrow oppositely disposed longitudinal lengths of the outside wall thereof when structure 40 is incorporated into Fig. 1 in place of magnet 19. Upon pole pieces 41, 42, 43 and 44 are placed turns of wire constituting solenoids 45, 46, 47 and 48, respectively. Opposite solenoids 45 and 47

are connected together to a source 49 of exciting alternating current. The remaining solenoids 46 and 48 are connected together to source 49 through phase shifter 50 introducing a 90 degree time phase to the currents supplied to solenoids 46 and 48 with respect to the current supplied to solenoids 45 and 47. Shifter 50 may be simply a circuit of passive reactance elements proportioned to produce the desired 90 degree lead or lag in current. The resultant magnetic field produced by the sum of the fields from 45 and 47, and 46 and 48, will rotate about the longitudinal axis of structure 40 at the frequency of source 49. Thus, a continuously variable phase shifter is provided which is entirely electrically controlled and which involves no moving parts. The phase change produced will be 4π radians per cycle of the frequency of source 49.

The rotating magnetic field produced by either permanent magnet 19 of Fig. 1 or the electromagnetic of Fig. 4 is suitable for exciting element 15 within guide 11 if the phase is to be changed slowly requiring a slow orientation of the magnetic field. However, if the phase is to be changed rapidly and continuously as might be required for continuous scanning in radar equipments, eddy currents set up in the conductive walls of guide 11 would tend to prevent the magnetic field from penetrating the ferromagnetic element therein. In the embodiment of the invention shown in Fig. 5 this difficulty is avoided.

Referring to Fig. 5 a phase changer is shown which is electrically identical so far as its principles of operation are concerned to the phase changer disclosed with reference to Fig. 1. In the embodiment of Fig. 5, however, the conductive shield is removed by employing the all-dielectric wave guide techniques as disclosed in my copending application Serial No. 274,313, filed March 1, 1952.

As there disclosed, electromagnetic wave energy, when properly launched upon a strip or rod of all-dielectric material, i. e., a rod without a conductive shield, will be guided by the rod with a portion of the energy conducted in a field surrounding the rod. It has been determined that the ferromagnetic materials herein considered may also serve as guiding structures. Because these materials have a much higher index of refraction than the more commonly employed dielectric materials, a sufficient amount of the wave energy will travel within the ferromagnetic material to be substantially affected by its permeability. Therefore, a differential phase shift will be introduced to the energy by the planes of different permeability.

In Fig. 5 dominant mode energy in rectangular metallic guide 51 is coupled to dielectric guide 52 of round cross-section by means of horn 53 comprising a flared out end of guide 51. Dielectric rod 52 is pushed through horn 53 to extend several wavelengths into guide 51. The match between guide 51 and guide 52 is improved by providing a taper 54, extending along several wavelengths of the portion of guide 52 within guide 51. Guide 52 may consist of any dielectric material having a dielectric constant substantially different from that of air, such as polyflex, polyethylene, to mention only two specific materials. Guide 52 is joined, as a continuation thereof, to rod 55 of ferromagnetic material having a round cross-sectional dimension similar to that of guide 52.

Since, as noted above, ferromagnetic guide 55 has a much higher index of refraction than the adjoining dielectric guide 52, a tapered joint 56 extending along several wavelengths is desirably employed at the point of junction of two materials to prevent excessive radiation losses. A similar taper 57 connects the other end of ferromagnetic rod 55 to dielectric guide 58 which is connected by horn 59 to rectangular metallic guide 60.

Permanent magnet structures 61 and 61', which may be identical to structures 17 and 18 of Fig. 1, are located at spaced points on rod 55 with their pole pieces inclined at 45 degrees to the polarization of wave energy in guides

51 and 60. Interposed between magnets 61 and 61' are four solenoids 62, 63, 64 and 65 which may be symmetrically arranged upon a suitable supporting structure about the center portion of rod 55. Opposite solenoids are connected together in pairs to sources of exciting current in the same manner as disclosed with reference to the structure in Fig. 4 to produce a rotating magnetic field transverse to the center portion of rod 55. When the strength of the magnetic field supplied by magnets 61 and 61' is adjusted to produce a 90 degree differential phase shift in the portion of rod 55 excited by these magnets, and when the field strength supplied by solenoids 62, 63, 64 and 65 is adjusted to produce a 180 degree differential phase shift in the center portion of rod 55, the single ferromagnetic element 55 serves the three functions of converting the linearly polarized wave into a circularly polarized wave, rotating the instantaneous polarity of the circularly polarized wave, and re-converting the rotated circularly polarized wave into a linearly polarized wave. Each of these functions is exactly similar to the corresponding function described above with reference to Fig. 1.

By way of illustrating the applications of the all-dielectric wave guide techniques to the present invention, each of the three functions described above were performed in a single ferromagnetic element. However, it should be noted that separate ferromagnetic elements may be used each separated from the other by a section of dielectric guide. On the other hand only the 180 degree differential section may comprise an unshielded ferromagnetic element while the 90 degree sections preceding and following it may be situated beyond dielectric guides 52 and 58 for example, within metallic guides 51 and 60 and may comprise therein phase shift means of the types illustrated in Fig. 1 or Fig. 3, for example. Horns 53 and 59 and tapers 54 would still be employed to launch the now circularly polarized waves upon the dielectric wave guides 52 and 58.

As noted above, tapered joints 56 and 57 are employed to prevent mismatches between the dielectric guides 52 and 58 and the ferromagnetic rod 55. As illustrated in Fig. 5 these tapers comprise conical points on the ends of guides 52 and 58 which fit into corresponding conical depressions in the ends of rod 55. Other methods of matching the materials may be employed. For example, the index of refraction of the dielectric material of guides 52 and 58 would be made the same as the index of refraction of the ferromagnetic material. This would tend to maintain the external field of the energy conveyed along the combination at a constant diameter. Alternatively, if the index of refraction of the magnetic material is higher than that of the dielectric material, the field of the energy may be maintained constant by providing the dielectric rod with a proportionately larger diameter than the diameter of the magnetic rod as shown in Figs. 6A and 6B. The transition between the two diameters may be made, for example as shown in Fig. 6A, by providing the dielectric rods 81 and 82 with conical points, such as 83, to fit within a corresponding impression in magnetic rod 84. The center core of rods 81 and 82 may then be drilled out or otherwise removed. In Fig. 6B the transition is made by providing conical points of equal taper upon the three rods 85, 86 and 87 and then providing corresponding conical impressions in dielectric rods 85 and 86 to receive the points 88 and 89, respectively, of magnetic rod 87.

The phase shifters of Figs. 1 and 5 are both reciprocal as has been noted, i. e., the same phase shift is introduced to wave energy transmitted in either direction there-through. Thus, if waves transmitted through the shifters a first time are reflected back by a mismatched termination, the reflected waves will have suffered twice the phase shift of a single traversal. Both phase shifts will be either in a lagging sense or both in a leading sense.

In Fig. 1 the ferromagnetic elements therein have been

illustrated by way of specific example, as cylindrical blocks of material substantially filling the interior space of the metallic shield wave guide. It should be noted, however, that the effect of the ferromagnetic material on electromagnetic waves continues if the material fills only a portion of this space. Furthermore, in order to prevent or cut down deflections from the faces of the elements, it may be found desirable to employ conical or otherwise tapered transition members, which members may be of dielectric material or of ferromagnetic material on one or both sides of the elements in accordance with usual practice.

In all cases, it is understood that the above-described arrangements are simply illustrative of a small number of many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with said principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. Variable phase shift apparatus for the transmission of electromagnetic wave energy comprising a pair of 90 degree differential phase shift sections, an element of gyromagnetic material interposed between said sections, electromagnetic solenoids disposed about said element to produce a magnetic field extending transversely through said element, the strength of said magnetic field and the thickness of said element being proportioned to produce a 180 degree differential delay between components of said wave energy polarized parallel to said field and components of said wave energy polarized perpendicular to said field.

2. Apparatus for the transmission of electromagnetic wave energy comprising in combination, means on the input side for converting said wave energy from linear to circular polarization, means on the output side for re-converting to linear polarization, an interposed element of gyromagnetic material in the path of said circularly polarized waves, and means for applying a magnetic field to said element in a direction transverse to the direction of propagation of said wave energy, the strength of said field falling outside the region of ferromagnetic resonance for said element at a frequency within the operating range.

3. Apparatus for the transmission of electromagnetic wave energy comprising in combination, a source of linearly polarized electromagnetic wave energy, an input means coupled to said source for converting said wave energy from linear to circular polarization, an output means for re-converting to linear polarization, an element of gyromagnetic material interposed between said input and output means in the path of said circularly polarized waves, and means for applying a magnetic field to said element in a direction transverse to the direction of propagation of said wave energy, the strength of said field falling outside the region of ferromagnetic resonance for said element at a frequency within the operating range.

4. Variable phase shift apparatus for the transmission of electromagnetic wave energy comprising in combination, means on the input side for converting said wave energy from linear to circular polarization, means on the output side for re-converting to linear polarization, an interposed element of gyromagnetic material in the path of said circularly polarized waves, and means for applying a magnetic field to said element in a direction transverse to the direction of propagation of said wave energy and for rotating said transverse field about the axis of the direction of propagation of said waves through said element.

5. Variable phase shift apparatus for the transmission of electromagnetic wave energy comprising in combination, a source of linearly polarized electromagnetic wave energy, an input means coupled to said source for converting said wave energy from linear to circular polarization

tion, an output means for reconverting to linear polarization, an element of gyromagnetic material interposed between said input and output means in the path of said circularly polarized waves, and means for applying a magnetic field to said element in a direction transverse to the direction of propagation of said wave energy and for rotating said transverse field about the axis of the direction of propagation of said wave energy through said element.

6. Variable phase shift apparatus for the transmission of electromagnetic wave energy comprising in combination, means on the input side for converting said wave energy from linear to circular polarization, means on the output side for reconverting to linear polarization, an interposed element of gyromagnetic material in the path of said circularly polarized waves, and means for applying a magnetic field to said element in a direction transverse to the direction of propagation of said wave energy and for rotating said transverse field about the axis of the direction of propagation of said waves through said element, the strength of said field falling outside the region of ferromagnetic resonance for said element at a frequency within the operating range.

7. Variable phase shift apparatus for the transmission of electromagnetic wave energy comprising in combination, a source of linearly polarized electromagnetic waves, an input means coupled to said source for converting said wave energy from linear to circular polarization, an output means for reconverting to linear polarization, an element of gyromagnetic material interposed between said input and output means in the path of said circularly polarized waves, and means for applying a magnetic field to said element in a direction transverse to the direction of propagation of said wave energy and for rotating said transverse field about the axis of the direction of propagation of said waves through said element, the strength of said field falling outside the region of ferromagnetic resonance for said element at a frequency within the operating range.

8. Variable phase shift apparatus for the transmission of linearly polarized electromagnetic wave energy comprising in combination, means on the input side for converting said wave energy from linear to circular polarization, means on the output side for reconverting to linear polarization, an interposed element of gyromagnetic material in the path of said circularly polarized waves, and a plurality of separately excited solenoids disposed about said element to produce a resultant magnetic field passing through said element in a direction transverse to the direction of propagation of said wave energy and at a variable angle dependent upon the relative excitation of said solenoids.

9. Variable phase shift apparatus for the transmission of linearly polarized electromagnetic wave energy comprising in combination, means on the input side for converting said wave energy from linear to circular polarization, means on the output side for reconverting to linear polarization, an interposed element of gyromagnetic material in the path of said circularly polarized waves, and a plurality of separately excited solenoids disposed about said element to produce a resultant magnetic field passing through said element in a direction transverse to the direction of propagation of said wave energy and at a

variable angle dependent upon the relative excitation of said solenoids, the strength of said field falling outside the region of ferromagnetic resonance for said element at a frequency within the operating range.

10. Variable phase shift apparatus for the transmission of linearly polarized electromagnetic wave energy comprising in combination, a source of linearly polarized electromagnetic wave energy, input means coupled to said source for converting said wave energy from linear to circular polarization, output means for reconverting to linear polarization, an element of gyromagnetic material interposed between said input and output means in the path of said circularly polarized waves, and a plurality of separately excited solenoids disposed about said element to produce a resultant magnetic field passing through said element in a direction transverse to the direction of propagation of said wave energy and at a variable angle dependent upon the resultant excitation of said solenoids.

11. Variable phase shift apparatus for the transmission of linearly polarized electromagnetic wave energy comprising in combination, a source of linearly polarized electromagnetic wave energy, input means coupled to said source for converting said wave energy from linear to circular polarization, output means for reconverting to linear polarization, an element of gyromagnetic material interposed between said input and output means in the path of said circularly polarized waves, and a plurality of separately excited solenoids disposed about said element to produce a resultant magnetic field passing through said element in a direction transverse to the direction of propagation of said wave energy and at a variable angle dependent upon the resultant excitation of said solenoids, the strength of said field falling outside the region of ferromagnetic resonance for said element at a frequency within the operating range.

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