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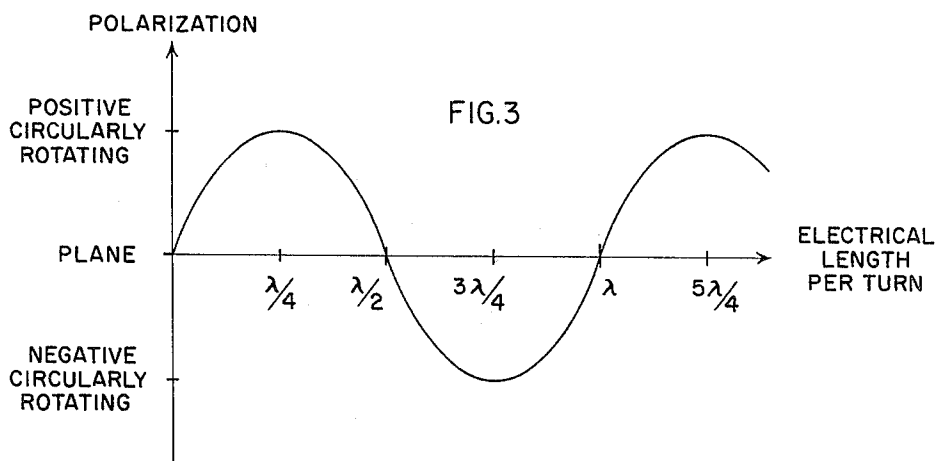
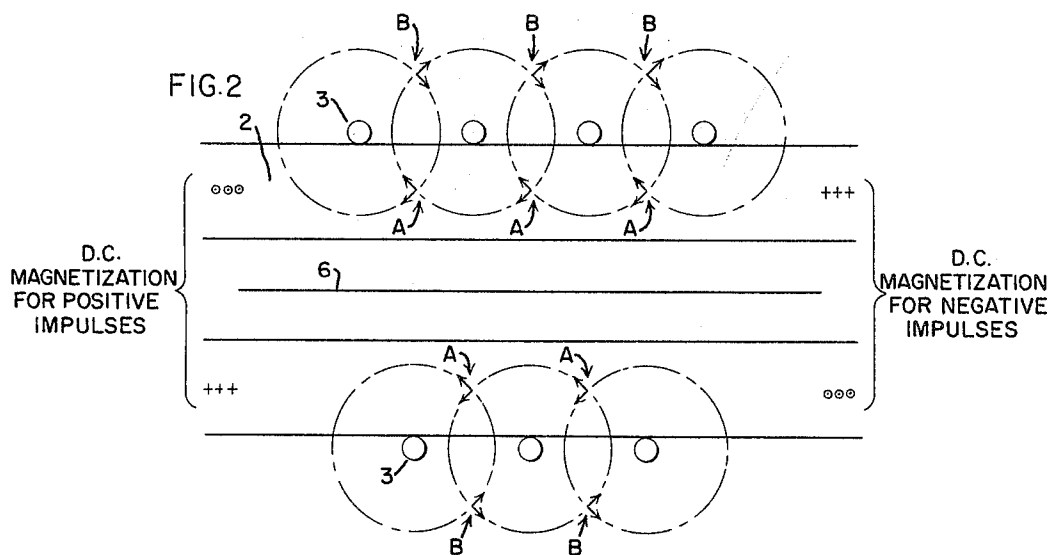
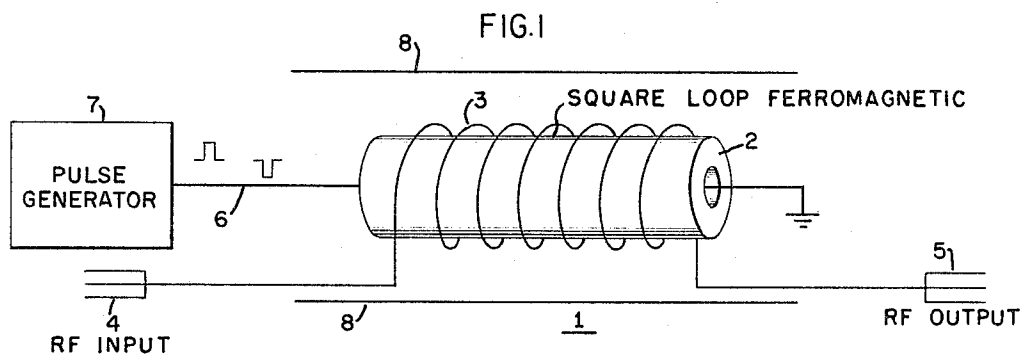
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3,290,622

MICROWAVE FERROMAGNETIC PHASE SHIFTER HAVING
CONTROLLABLE D.C. MAGNETIZATION

Filed Nov. 27, 1963

2 Sheets-Sheet 1



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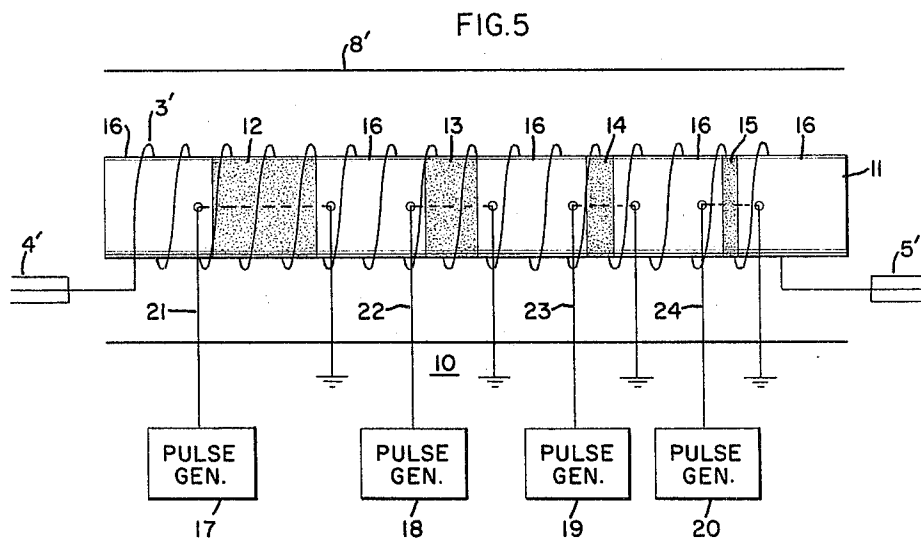
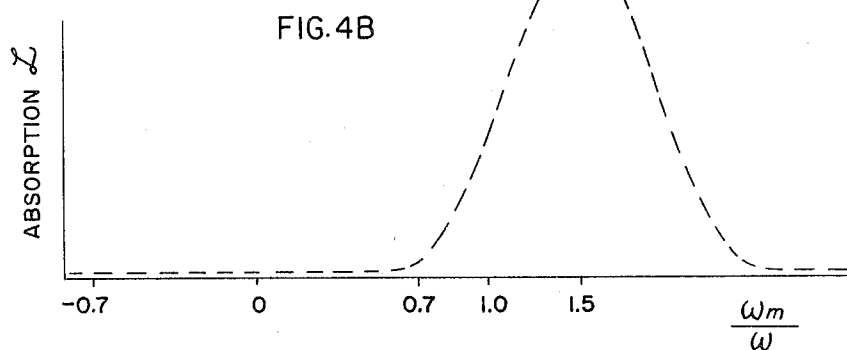
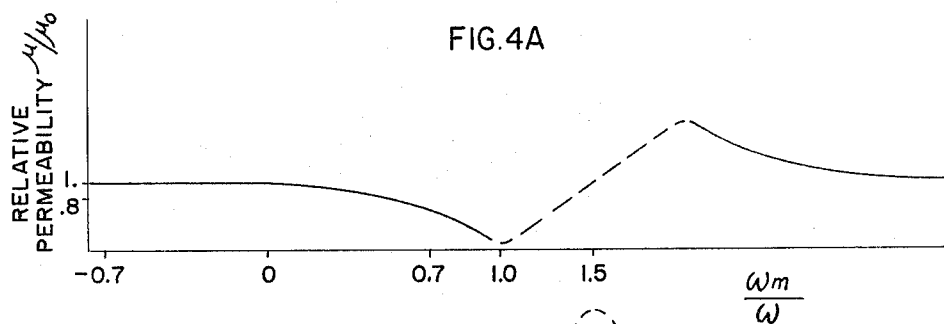
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2 Sheets-Sheet 2



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MICROWAVE FERROMAGNETIC PHASE SHIFTER HAVING CONTROLLABLE D.C. MAGNETIZATION

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Filed Nov. 27, 1963, Ser. No. 326,582
13 Claims. (Cl. 333-24.1)

The present invention relates to radio frequency ferromagnetic phase shifter devices. More particularly the invention relates to novel and improved ferromagnetic phase shifters for operation in a frequency range above 100 megacycles and offering the most significant advantage when operated from L-Band (one to two kilomegacycles) through C-Band (four to eight kilomegacycles).

As an aid in understanding the principles of operation and theory of the devices to which the invention relates, it is desirable to refer to the classical concept of electron spins in a ferromagnetic body. Accordingly, in the classical electron spin concept the electrons of the ferromagnetic body are each said to be in a state of constant spin with respect to their respective axes. Each spinning electron behaves like a tiny magnet having a magnetic dipole moment oriented along the axis of spin. When considering an unmagnetized body, bundles of aligned electron spin axes, grouped within the various domains of the body, assume random directions so that the magnetization or net dipole moment of the body is zero. Under the application of a D.C. magnetic field the domains are swept out and all spin axes tend to align in the direction of the D.C. field providing a net dipole moment that is a function of the D.C. magnetizing field and the configuration and material characteristics of the ferromagnetic body. With an additional variable (or RF) magnetic field applied in a direction orthogonal to the D.C. field, the electron spin axes are caused to precess about their bias positions. Precession occurs but in a single direction for a given D.C. magnetic field orientation. The natural frequency of precession, or ferromagnetic resonant frequency, is a function of the magnitude of the applied D.C. field. Thus, $\omega_r = \gamma H_r$, where ω_r is the resonant frequency, γ is the gyromagnetic ratio and H_r is the resonant D.C. magnetic field. Further, the amplitude of the precessional swing, for a given D.C. magnetic field, is a function of the operating frequency and the configuration and magnitude of the RF orthogonal magnetic field.

The interaction between the RF orthogonal magnetic field and the precessing electron spins or magnetization of the ferromagnetic body determines the RF permeability of the ferromagnetic body. Further, it is known that a circularly rotating RF magnetic field rotating in the single direction in which precession can occur reacts with the magnetization, to produce a first value of RF permeability that has been designated as μ_+ . A circularly rotating RF magnetic field rotating in the opposite direction reacts to a significantly lesser degree with the magnetization, to produce a second value of RF permeability designated as μ_- . A more complete discussion of this phenomenon is presented in an article entitled "The Elements of Nonreciprocal Microwave Devices" by C. Lester Hogan, appearing in the Proceedings of the IRE, October 1956.

The above and related principles find application in various microwave ferromagnetic devices of the prior art.

Directing attention to microwave ferromagnetic phase shifters, various types of these devices are known to exist. One of the earlier forms was described in an article entitled "A New Technique in Ferrite Phase Shifters for Beam Scanning of Microwave Antennas" by F. Reggia and E. G. Spencer, appearing in the Proceedings of the

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IRE, November 1957. The described device employs a ferrite slab inserted longitudinally in a waveguide. A solenoid wound about the outside walls of the guide applies a longitudinal D.C. magnetic field through the ferrite and thereby controls the phase shift of the microwave energy propagated through the waveguide. Although this device presents advantages over the then existing art in size and power requirements for providing large phase shifts per unit length by electrical means, with respect to present day demands, and particularly for phased array radar antennas requiring a great many such devices, the device is often unsatisfactory. Relative to modern requirements, it is found to be of appreciable size and weight, requires considerable switching and bias power and is relatively slow in its operation. Thus far, the ferromagnetic phase shifter devices that have been proposed in an effort to improve these characteristics have met with but limited success. The instant invention presents a significant step forward to this end.

It is accordingly a principal object of the present invention to provide a ferromagnetic phase shifter that is small, light weight and of low switching power requirements.

A further object of the invention is to provide a ferromagnetic phase shifter which is capable of extremely rapid control.

A further object of the invention is to provide a ferromagnetic phase shifter having a memory characteristic.

Another object of the invention is to provide a ferromagnetic phase shifter having the characteristics above noted which is capable of furnishing a wide range of digital phase shifts.

These and other objects of the invention are accomplished in a ferromagnetic phase shifter device which in one basic embodiment includes a RF energy propagating helix wound along a cylinder of ferromagnetic material having a remanent circumferential D.C. magnetization therein oriented in one of two opposing directions. The relationship of the diameter and pitch of the helix to the wavelength of the RF energy provides in response to said energy a rotating RF magnetic field. The rotating magnetic field is disposed in orthogonal spatial relationship with the D.C. magnetization, and extends longitudinally within said cylinder. A D.C. control winding is coupled through the cylinder, said winding being selectively energized so as to switch the direction of the remanent D.C. magnetization. With the polarity of the D.C. magnetization oriented in one direction a considerable interaction occurs between the RF magnetic field and the magnetization, producing a first RF permeability and corresponding first phase delay of the propagating energy. With the polarity oriented in the opposite direction a minimum interaction occurs between the RF magnetic field and the magnetization, producing a second RF permeability and corresponding second phase delay of said propagating energy appreciably different than said first phase delay.

In accordance with a further embodiment of the invention, a range of digital phase shifts is provided by employing a plurality of variable length, coaxially arranged cylindrical segments of ferromagnetic material. Each cylindrical segment has a remanent circumferential D.C. magnetization therein oriented in one of two opposing directions. A RF energy propagating helix is wound along said segments to provide a rotating RF magnetic field within each of the segments, corresponding to the previously described embodiment. A separate D.C. control winding is coupled through each segment and selectively energized to individually switch the remanent D.C. magnetizations, thereby applying to the RF energy a total phase delay that is the sum of the individual delays of the various segments.

While the specification concludes with claims particularly pointing out and distinctly claiming the invention, it is believed that the invention will be better understood from the following description taken in connection with the accompanying drawings in which:

FIGURE 1 is a schematic diagram of a ferromagnetic phase shifter device in accordance with a basic embodiment of the invention;

FIGURE 2 is a cross sectional view of a few turns of the helix of FIGURE 1 showing the RF magnetic field distribution around said helix;

FIGURE 3 is a plot of the polarization of resultant RF magnetic field components within the ferromagnetic cylinder of FIGURE 1 as a function of helix electrical length per turn;

FIGURE 4A is a graph of the RF permeability of the ferromagnetic cylinder of FIGURE 1 plotted as a function of the normalized operating frequency;

FIGURE 4B is a graph showing the absorption loss of the ferromagnetic cylinder plotted as a function of the normalized operating frequency; and

FIGURE 5 is a schematic diagram of a multiple digit ferromagnetic phase shifter device in accordance with the invention.

Referring now to FIGURE 1 there is illustrated a ferromagnetic digital phase shifter device 1 operating typically in the microwave region in which microwave energy propagating through the device is selectively provided with one of two discrete phase delays. The device 1 includes a ferromagnetic cylinder 2 having wound thereabout a helical conductor 3 to which is electrically coupled the microwave energy. Thus, microwave energy is introduced to the helix 3 from a source, not shown, by an input coaxial connector 4 and retrieved by an output coaxial connector 5. As will be seen, the microwave energy generates a circularly rotating RF magnetic field within the cylinder 2. A D.C. magnetizing current conductor 6, shown as a single turn but which may also be a few turns, is passed longitudinally through the bore of the cylinder 2. In response to a current impulse of positive or negative polarity applied from a suitable pulse generating source 7, conductor 6 initially induces a remanent circumferential D.C. magnetization within the cylinder in one of two opposing directions and thereafter provides a circumferential magnetic field which controls the orientation of said remanent D.C. magnetization. Application of said positive or negative impulse acts to selectively change the electrical wavelength of the device 1, thereby selectively introducing one of two discrete phase delays to the propagating microwave energy.

In accordance with the above description, the ferromagnetic material of the cylinder 2 should exhibit some degree of remanent magnetization. It may be appreciated that for a remanent operation the bias power for maintaining a given D.C. magnetization state is zero and the switching power requirements are low. Materials exhibiting a square loop hysteresis characteristic with high remanent properties, which introduce the greatest phase shift, are preferred. It is also desirable that the material have low dielectric and magnetic losses. Further, it should exhibit a saturation magnetization $4\pi M_s$ which in terms of frequency is offset from the operating frequency so that operation is in a region of relatively low loss. Normally the operating frequency ω is selected so that $\gamma 4\pi M_s < \omega$, where γ is the gyromagnetic ratio of the ferromagnetic material. Typical commercial materials that have been employed in operating embodiments of the invention are ferrite and garnet type compositions such as a garnet commercially identified as MCL 300, manufactured by Microwave Chemicals Laboratory, New York, N.Y. and a ferrite identified as 42L, manufactured by General Electric Company.

An outer sheath conductor 8, typically constructed of brass, surrounds the helically wound ferrite cylinder 2. In addition to its shielding function, the sheath 8 serves

to modify and optimize the magnetic field distribution of the microwave energy, thereby increasing the bandwidth of the device. It also provides the phase shifter device 1 with properties of a sheath helix transmission line.

In response to electrical energization of the helical conductor 3, there is provided a rotating microwave magnetic field in the vicinity of the helix and, in particular, within a region extending longitudinally through the wall of the cylinder 2. The rotating magnetic field results from the phase relationship of the microwave energy in adjacent windings of the helix, as will be further considered, and is therefore a function of the electrical length per turn of said windings. For a given frequency of the microwave energy, the electrical length per turn is determined primarily by the helix diameter and pitch, the dielectric constant of the ferromagnetic material and the outer sheath diameter. In general, for circularly rotating magnetic field components of the microwave field to exist these various parameters are selected so as to provide an electrical length per turn of $(2n-1)\lambda/4$, where n may be an integer and λ is the wavelength of the propagating microwave energy in free space.

The magnetic field configuration associated with the helix 3 is schematically illustrated in FIG. 2 which shows in a cross sectional view a plurality of adjacent turns wound about a portion of the ferromagnetic cylinder 2. It may be seen that in the regions denoted as A and B, A being within and B outside the cylinder wall, there are magnetic field components associated with the current in adjacent turns that are intersecting and orthogonally related in space. The orthogonal spatial relationship in combination with a phase difference of the energy in adjacent turns corresponding to an electrical length per turn of $(2n-1)\lambda/4$ produces resultant circularly rotating magnetic field components in the regions A and B which components are in planes perpendicular to the direction of the D.C. magnetization. It may be appreciated that in regions surrounding A and B where the magnetic field components of adjacent turns intersect in an oblique manner, there are resultant elliptically rotating magnetic field components, the ellipticity of said components being of varying degrees. For the device under immediate discussion only the regions within the cylinder wall are of significance since obviously only in these regions do reactions between the RF rotating magnetic field components and the magnetization occur, which reactions are employed to provide a differential phase shift of the propagating energy, as will be explained more fully.

Although a circular rotation of the resultant magnetic field components in the regions A provide optimum performance for the phase shifter devices of the present invention, elliptical rotations in these regions as dictated by electrical lengths per turn of other than $(2n-1)\lambda/4$, are also feasible. Elliptical rotations occur when operating over a band of frequencies when only the center frequency satisfies the above constraint. In FIGURE 3 is illustrated a plot of the polarization of the resultant RF magnetic field components in the regions A as a function of the helix electrical length per turn. It is seen that positive circularly rotating field components occur at $\lambda/4$, $5\lambda/4$, etc.; negative circularly rotating field components occur at $3\lambda/4$, $7\lambda/4$, etc.; and linear, non-rotating field components occur at $\lambda/2$, λ , etc. Intermediate the discrete values indicated, varying degrees of elliptical rotation occur in accordance with the sinusoidal nature of the illustrated function. The bandwidth selected for operation may be appreciated to be primarily a function of the degree of ellipticity that can be tolerated within given performance requirements.

In one specific operating embodiment designed for operation at S-Band (two to four kilomegacycles) an electrical length per turn of $3\lambda/4$ at the center frequency was found to be optimum. In this design the ferromagnetic cylinder 2 can be readily fabricated to have relatively small cross sectional and longitudinal dimensions, while

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providing a relatively large phase shift per unit length. It may be noted that employing a shorter electrical length per turn, e.g., $\lambda/4$, is less desirable for operating frequencies at S-Band and higher because it is difficult to construct devices having suitably small cylinder samples and still maintain the D.C. magnetizing current conductor outside of the RF magnetic field. Setting n in the above expression for electrical length per turn to a value larger than 2, is also less desirable because the sample size then need be increased to an extent greater than necessary. The fractional operating bandwidth is decreased as well. In addition, as n is increased, higher order, fast wave, coaxial modes can be generated between the helix and the sheath. This degrades the operation of the device by altering the magnetic field configuration and shortening the interaction length. With the above considerations in mind, the electrical length per turn should be selected in accordance with good design requirements for whatever operating frequencies are desired.

In describing the operation of the phase shifter device of FIGURE 1, reference will be made to FIGURES 4A and 4B. In FIGURE 4A relative RF permeability μ/μ_0 is plotted against saturation magnetization normalized to the operating frequency, ω_m/ω , where ω_m is the saturation magnetization expressed in terms of frequency, which varies with different sample materials. In FIGURE 4B is plotted the sample absorption loss L as a function of ω_m/ω . Thus, for a single sample of fixed ω_m , the indicated variations in μ/μ_0 and L are as a function of operating frequency. Alternatively, if the frequency is fixed, the variations in μ/μ_0 and L are as a function of different sample saturation magnetizations. Positive values of ω_m/ω indicate positive D.C. magnetizations of the sample. For these values relatively appreciable interaction occurs between the RF magnetic field and the sample magnetization, producing a permeability designated as $\mu+$, the magnitude of which varies a function of ω_m/ω . Negative values of ω_m/ω indicate negative D.C. magnetizations of the sample. For these values a minimum of interaction between the RF magnetic field and the sample magnetization occurs, producing a permeability designated as $\mu-$, the magnitude of which is essentially constant.

When considering a sample of given magnetization characteristics and a given operating frequency, it may be seen that in the operation of the phase shifter device there result two discrete operating values of ω_m/ω of the same magnitude, one positive and the other negative. Preferably these operating values are at points where the absorption losses are low and the differential between $\mu+$ and $\mu-$ is substantial.

Accordingly, with a D.C. impulse of positive polarity applied to the D.C. magnetizing current conductor 6 by pulse generator 7, e.g., providing a positive ω_m/ω of ± 0.7 , a remanent circumferential D.C. magnetization in the positive direction is produced in the cylinder 2. The circumferential magnetization is oriented so as to appear in FIGURE 2 out of the plane of the paper in the upper half of the cylinder and into the plane of the paper in the lower half. The spatial relationship between the D.C. magnetization when in this direction and the rotating RF magnetic field is such as to cause interaction between the RF field and the magnetization resulting in a value of μ/μ_0 of about 0.8 for the curve shown in FIGURE 4A.

Upon pulsing the D.C. magnetizing current conductor 6 with a negative impulse from pulse generator 7, now providing a negative ω_m/ω of -0.7 , the remanent circumferential D.C. magnetization in the cylinder is switched in a direction opposite to that previously considered, as indicated in FIGURE 2. In this direction a minimum interaction occurs between the magnetization and the rotating RF magnetic field so that μ/μ_0 is rapidly switched to a value of about 1.0. Switching normally occurs within one microsecond.

The phase delay of propagating microwave energy in

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the helical conductor 3 is as given by the relationship $\phi = \beta l$, where ϕ is the phase delay, β is the phase constant and l is the length of the helix conductor. Further $\beta = \omega \sqrt{\mu_{\text{eff}} \epsilon_{\text{eff}}}$ where μ_{eff} is the effective permeability and ϵ_{eff} the effective dielectric constant of the combined media surrounding the helix. Since μ_{eff} includes the permeability of the ferromagnetic material its value changes as switching occurs between $\mu+$ and $\mu-$, producing the requisite phase shift.

Although the graphs of FIGURES 4A and 4B are plotted with respect to saturation rather than remanent magnetization, for greater standardization, operation is modified at remanence only to the extent that the permeability differential between $\mu+$ and $\mu-$ is somewhat less in accordance with the difference in magnitude between the saturation and remanent magnetizations.

In one specific operating embodiment of the phase shifter device of FIGURE 1 the following parameters were employed. These values are given for purposes of illustration and are not to be construed as limiting.

Cylinder dimensions	-----	Length 1.0 inches, outside diameter 0.5 inch. inside diameter 0.25 inch.
Helix	-----	Copper wire .030 inch diameter 10 turns per inch.
Switching current	-----	5 ampere pulses providing a pulsed magnetic field of 2-3 oersteds.
Center operating frequency	-----	3.3 kilomegacycles.
Phase shift	-----	360 degrees.
Insertion loss	-----	1 db.

The switching frequency may be as desired up to two to three megacycles.

Although a specific embodiment of the invention has been principally described where operation is well below ferromagnetic resonance (ferromagnetic resonance being where the absorption loss peaks, which in FIGURE 4B is at ω_m/ω equal to about 1.5) it may be appreciated that the device may also be operated above resonance. For this operation it is required that a ferromagnetic material be employed having loss characteristics that are low in the region above resonance where operation is selected. In addition, it should be possible to operate very near ferromagnetic resonance provided that a ferromagnetic material is employed having a sufficiently narrow line width resonance. It may be appreciated that with operation near resonance the greatest differential phase shift may be obtained since the permeability drops off sharply in this region, as illustrated in FIGURE 4A.

A further modification of the device illustrated in FIGURE 1 may be made within the basic concepts disclosed, which modification consists essentially of winding a helical conductor within a ferromagnetic cylinder. For this embodiment it is necessary to provide relatively large diameter helixes and therefore large diameter ferromagnetic samples to avoid placement of the D.C. magnetizing current conductor within the magnetic field provided by the microwave energy.

In FIGURE 5 there is illustrated a microwave ferromagnetic digital phase shifter device 10 in which propagating microwave energy is selectively provided with one of a multiplicity of discrete phase delays. In the device 10 the ferromagnetic cylinder 2 of FIGURE 1 is replaced by a cylinder 11 which is composed of a plurality of cylindrical segments of ferromagnetic material, typically four segments shown as 12, 13, 14 and 15, separated by abutting segments of dielectric material 16 for providing magnetic isolation between the ferromagnetic segments. The ferromagnetic cylindrical segments 12 through 15 are of varying lengths so as to provide varying phase delays as a function of length. A D.C. magnetizing current conductor and pulse generating source are provided for each ferromagnetic segment. Accordingly, pulse gen-

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erators 17, 18 19 and 20 are coupled by conductors 21, 22, 23 and 24, respectively, to segments 12, 13, 14 and 15, respectively. The conductors 21 through 24 are wound through the bore of their associated cylindrical segment for applying in a selective manner positive or negative current pulses to said segments for switching the remanent circumferential D.C. magnetization therein. As in FIGURE 1, a helical conductor 3' is wound about the cylinder 11, being coupled at either end to coaxial connectors 4' and 5', and an outer sheath 8' encloses the helical conductor 3'.

The operation of the device of FIGURE 5 is comparable to that described with respect to FIGURE 1 except that a greater range and variation in phase shift of the propagating microwave energy may be accomplished. For example, in one specific operating embodiment of the device shown in FIGURE 4, the segment 12 was of a length L appropriate for providing a differential phase shift of 180°. The segment 13 had a length of L/2 for providing a differential phase shift of 90°; the segment 14 had a length of L/4 for providing a differential phase shift of 45°; and the segment 15 had a length of L/8 for providing a differential phase shift of 22½°. Thus, it may be seen that there are obtained discrete differential phase shifts ranging from 22½° through 360°, with increments of 22½°, by selectively pulsing the segments 12 through 15.

It may be recognized that the number and arrangement of the cylindrical segments employed may be modified in accordance with the principles above disclosed and various combinations of phase delays may be provided other than those provided by the device illustrated in FIGURE 5. Further, it is noted that in addition to the tandem configuration of FIGURE 5, a plurality of ferromagnetic cylindrical segments may be mounted in a parallel relationship around a common axis with a single helical conductor common to all cylinders wound about the exposed outer surfaces of said cylinders. As in FIGURE 5, a separate D.C. magnetizing current conductor is provided for each cylinder. The advantages of a parallel arrangement are reduced longitudinal dimensions and greater ease in winding the D.C. magnetizing current conductors.

For purposes of clear and complete disclosure the invention has been described with respect to particular exemplary embodiments. It is recognized, however, that numerous modifications may be made by those skilled in the art to the specific devices disclosed which do not exceed the basic teachings set forth herein. For example, although a cylindrical configuration for the ferromagnetic sample appears most desirable, other shapes, such as, e.g., octagonal or rectangular may be employed. Further, it should be recognized that an analog operation can also be employed with the disclosed devices wherein the D.C. magnetic field is continuously and variably applied rather than momentarily pulsed. Although requiring appreciably more power, analog operation may provide added flexibility. It is intended that the appended claims include all such modifications falling within the true spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. A ferromagnetic device for applying a controllable phase shift to RF energy propagating through said device comprising:

- (a) a ferromagnetic element having a central bore,
- (b) means, including a D.C. magnetizing current conductor wound through said bore, for selectively applying within said element a D.C. magnetization oriented in one of two opposing directions,
- (c) a conductor having coupled thereto said RF energy, said conductor being wound along said element so as to produce in response to said RF energy a rotating RF magnetic field within said element disposed in orthogonal spatial relationship with said mag-

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netization, said RF energy being of sufficiently high frequency capable of supporting interaction between said RF magnetic field and precessing electron spins of said ferromagnetic element, whereby an applied D.C. magnetization in one direction provides an appreciable interaction and thereby a first phase delay of the propagating RF energy and an applied D.C. magnetization in a second direction provides essentially no interaction and thereby a second phase delay of said propagating RF energy.

2. A ferromagnetic device as in claim 1 wherein an outer conductive sheath encloses said ferromagnetic element and wound conductor for modifying the RF magnetic field configuration.

3. A ferromagnetic device for applying a controllable digital phase shift to RF energy propagating through said device comprising:

- (a) a ferromagnetic cylinder exhibiting remanent circumferential D.C. magnetization,
- (b) means for selectively switching the direction of said remanent circumferential D.C. magnetization in one of two opposing directions, and
- (c) a helical conductor having coupled thereto said RF energy, said conductor being wound about the outside of said cylinder so as to produce in response to said RF energy a rotating RF magnetic field within said cylinder disposed in orthogonal spatial relationship with said D.C. magnetization, said RF energy being of sufficiently high frequency capable of supporting interaction between said RF magnetic field and precessing electron spins of said ferromagnetic element, whereby switching said D.C. magnetization in one direction provides an appreciable interaction and thereby a first phase delay of the propagating RF energy and switching said D.C. magnetization in a second direction provides essentially no interaction and thereby a second phase delay of said propagating RF energy.

4. A ferromagnetic device as in claim 3 wherein said means for selectively switching said remanent circumferential D.C. magnetization includes a D.C. magnetizing current conductor wound through the bore of the cylinder having a source of current pulses of positive and negative polarity coupled thereto.

5. A ferromagnetic device as in claim 4 wherein an outer conductive sheath encloses the helically wound ferromagnetic cylinder for modifying the RF magnetic field configuration.

6. A ferromagnetic device for applying a controllable multidigital phase shift to RF energy propagating through said device comprising:

- (a) a plurality of commonly mounted cylindrical ferromagnetic elements, each element exhibiting remanent circumferential D.C. magnetization,
- (b) means for selectively and independently switching the direction of the remanent circumferential D.C. magnetization within each element in one of two opposing directions, and
- (c) a helical conductor having coupled thereto said RF energy, said conductor being wound about the outside of said ferromagnetic elements so as to produce in response to said RF energy a rotating RF magnetic field within each element disposed in orthogonal spatial relationship with said D.C. magnetization, said RF energy being of sufficiently high frequency capable of supporting within each element interaction between said RF magnetic field and precessing electron spins of said each element, each element providing one of two different phase delays to the RF energy associated therewith in accordance with the degree of interaction provided as governed by the direction in which its D.C. magnetization is oriented, whereby the total phase delay of said RF energy is controlled by selectively switching the D.C. magnetization within each ferromagnetic element.

7. A ferromagnetic device as in claim 6 wherein said

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plurality of cylindrical ferromagnetic elements are co-axially arranged in a tandem configuration.

8. A ferromagnetic device as in claim 7 wherein each cylindrical element has wound thereabout a different number of turns of said helical conductor so that the individual phase delay of said total phase delay contributed by each of said elements is different.

9. A ferromagnetic device as in claim 8 wherein said means for selectively switching said remanent circumferential D.C. magnetization includes a plurality of D.C. magnetizing current conductors each wound through the bore of its associated cylindrical element and each having a source of current pulses of positive and negative polarity coupled thereto.

10. A ferromagnetic device as in claim 9 wherein an outer conductive sheath encloses the helically wound cylindrical elements for modifying the RF magnetic field configuration therein.

11. A ferromagnetic device for applying a controllable phase shift to RF energy propagating through said device comprising:

- (a) a ferromagnetic element,
- (b) means for selectively applying within said element a controllable remanent D.C. magnetization, and
- (c) a conductor having coupled thereto said RF energy, said conductor being wound along said element so as to produce in response to said RF energy a rotating RF magnetic field within said element disposed in orthogonal spatial relationship with said remanent D.C. magnetization, said RF energy being of sufficiently high frequency capable of supporting interaction between said RF magnetic field and precessing electron spins of said ferromagnetic element, the applied remanent D.C. magnetization being employed to provide selective interaction between said RF magnetic field and said precessing electron spins so as to vary the RF permeability of the ferromagnetic element and accordingly control the phase delay of the propagating RF energy.

12. A ferromagnetic device as in claim 11 wherein said ferromagnetic element is cylindrically shaped and said

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conductor is in the form of a helix wound about the outside of said element.

13. A ferromagnetic device for applying a controllable phase shift to RF energy propagating through said device comprising:

- (a) a cylindrically shaped ferromagnetic element,
- (b) means, including a pulse generator coupled to a D.C. magnetizing current conductor, for selectively applying within said element a controllable remanent D.C. magnetization, and
- (c) a conductor having coupled thereto said energy, said conductor being wound along the ferromagnetic element so as to produce in response to said RF energy a rotating RF magnetic field within said element disposed in orthogonal spatial relationship with said D.C. magnetization, said RF energy being of sufficiently high frequency capable of supporting interaction between said RF magnetic field and precessing electrons of said element, the applied D.C. magnetization being employed to provide a selective interaction between said RF magnetic field and said precessing electron spins so as to vary the RF permeability of the ferromagnetic element and accordingly control the phase delay of the propagating RF energy.

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