

Jan. 28, 1969

M. C. MOHR  
 RECIPROCAL DIGITAL LATCHING FERRITE PHASE SHIFTER  
 WHEREIN ADJACENT FERRITE ELEMENTS  
 ARE OPPOSITELY MAGNETIZED

3,425,003

Filed Jan. 27, 1967

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FIG. 1

PRIOR ART

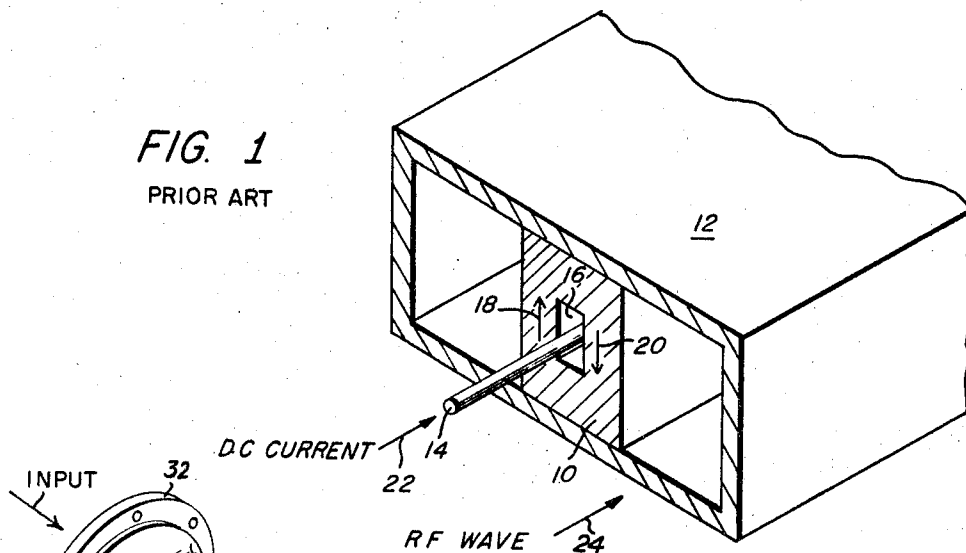


FIG. 2

PRIOR ART

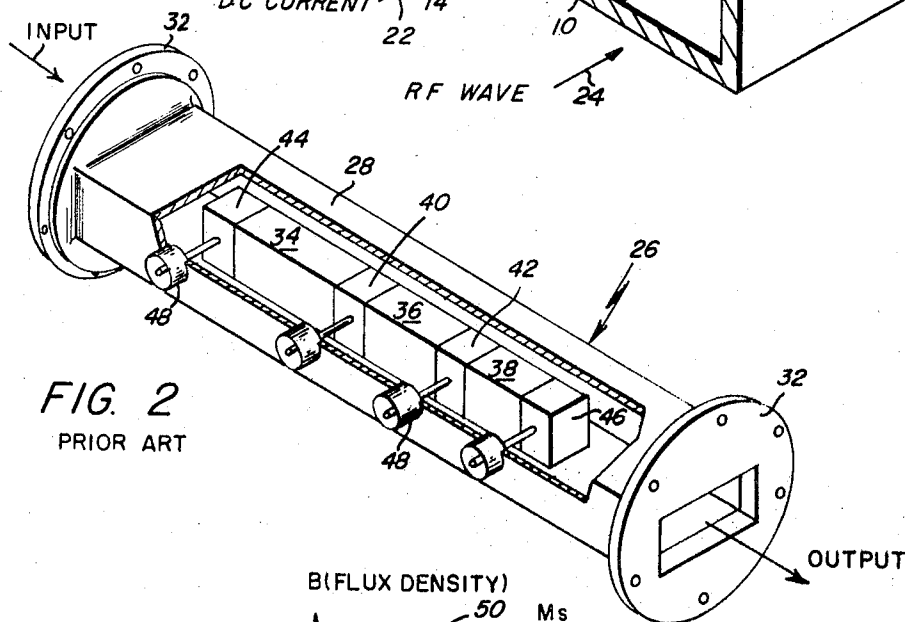
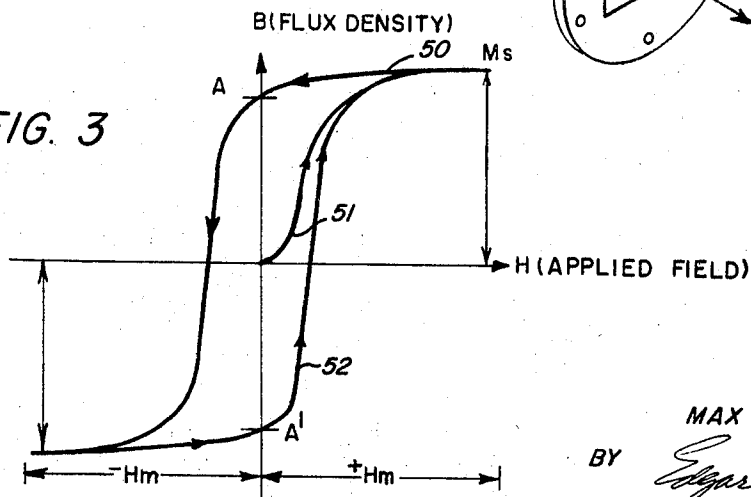


FIG. 3



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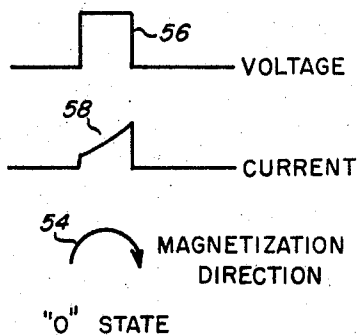


FIG. 4A

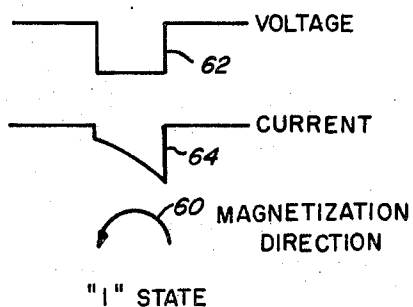
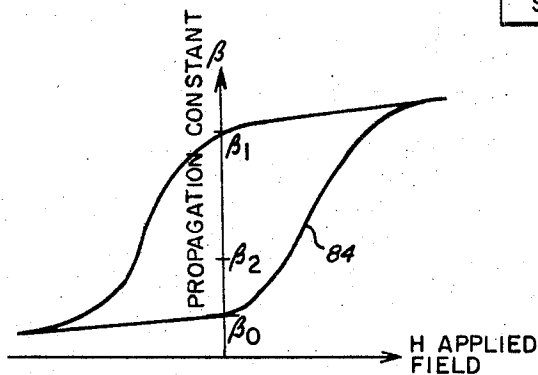
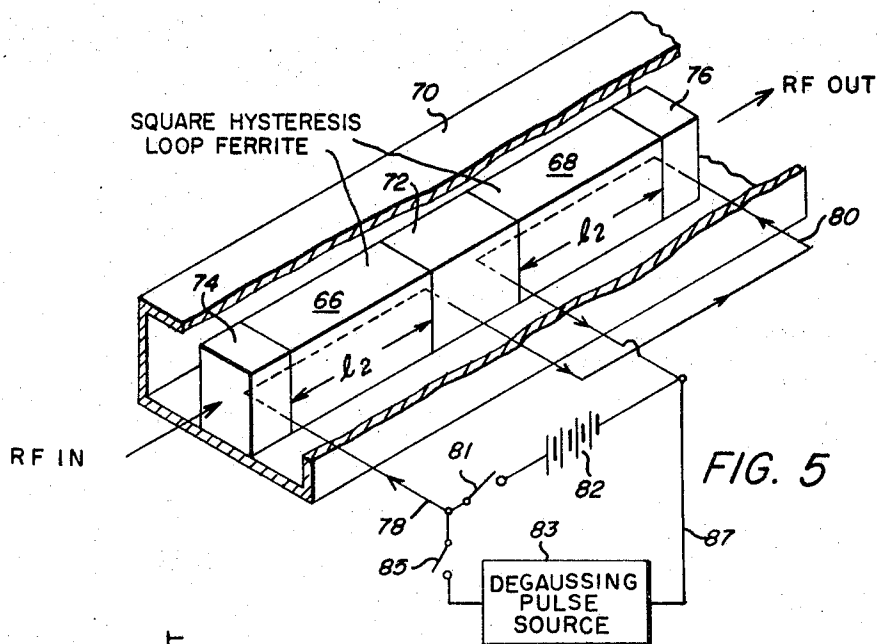


FIG. 4B



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FIG. 7

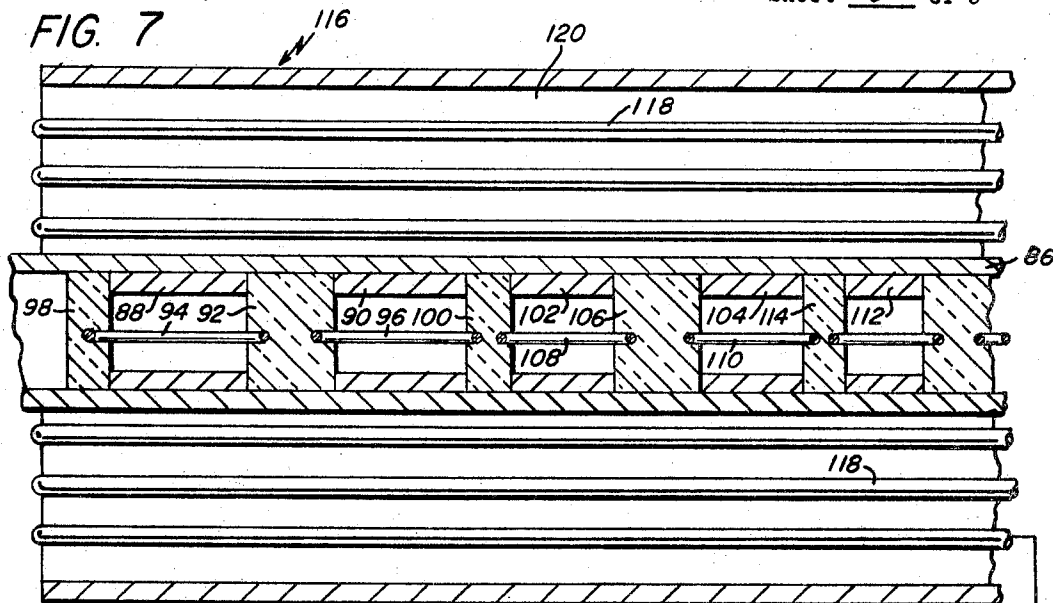


FIG. 8A

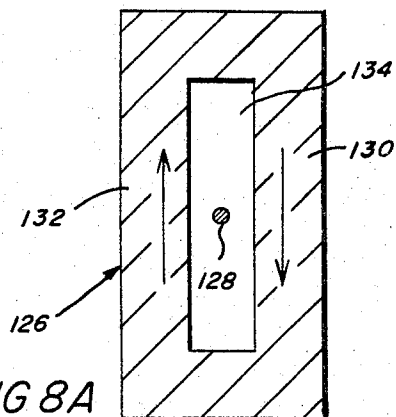


FIG. 8B

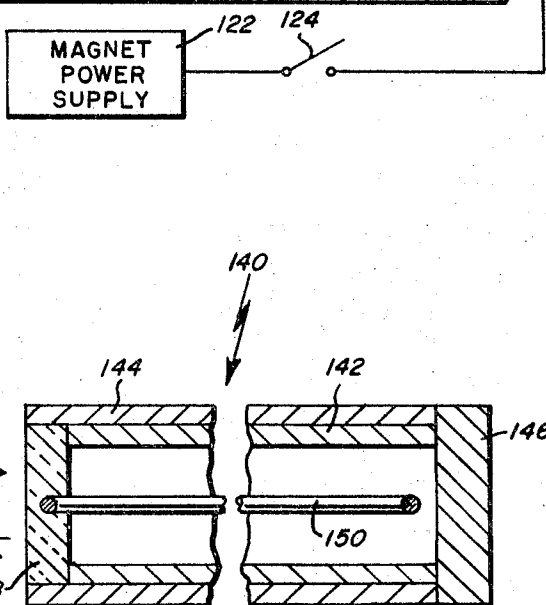
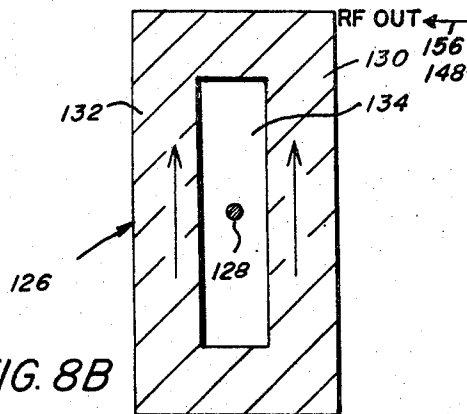


FIG. 9

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## RECIPROCAL DIGITAL LATCHING FERRITE PHASE SHIFTER WHEREIN ADJACENT FER- RITE ELEMENTS ARE OPPOSITELY MAG- NETIZED

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Filed Jan. 27, 1967, Ser. No. 612,157

U.S. Cl. 333-31

Int. Cl. H03h 7/18

5 Claims

### ABSTRACT OF THE DISCLOSURE

A phase shifter device for microwave frequency energy employing a plurality of ferromagnetic elements defining closed magnetic circuits and having a high degree of remanent magnetization achieved by passage of intermittent current pulses through wires centrally disposed in each element. Paired elements of equal length are provided in tandem within rectangular waveguide propagating structures with the elements separated by a matching transformer. Current pulses in each of the tandem elements are directed in a series opposing manner to result in opposite directions of magnetization and a similar differential phase shift of electromagnetic waves traversing the device in either direction. Means are also provided to achieve a second magnetization condition or bit position for each of the ferromagnetic elements to render the device readily adaptable to digital current control techniques in phased array antenna applications. The invention may be utilized as a transmission or reflective type of device.

### Background of the invention

The present invention relates to the field of microwave transmission devices and more particularly to such devices employing permanently magnetized ferromagnetic elements having binary states of remanent magnetization which may be induced by means of the passage of a direct current pulse through a wire centrally disposed within each element. Such devices are now commonly referred to as "latching" ferrite devices which readily lend themselves to the application of digital techniques. Electronically scanned antennas have in recent years achieved considerable notoriety in the communication as well as radar detection fields. In such antenna systems mechanical rotation of a conventional transmitting and receiving antenna is now replaced by the radiation of a complete wave front with appropriate phase shift or time delays introduced across the entire antenna surface by means of a plurality of phase shifting devices. Antennas which are now a fixed structure may be envisaged several stories in height and many hundreds of feet in length incorporating many thousands of individual phase shifting elements.

A class of devices of interest for the accomplishment of the requisite phase shift or time delays across the radiated wave front of electronically scanned antennas utilize the variable microwave permeability of magnetized ferromagnetic materials. For the purposes of this description the term "ferromagnetic" shall include metallic or insulating materials known as "ferrites" as well as the garnet types of materials and generically such devices are commonly referred to as "ferrite phase shifters." In the known types the ferrite slab or rod of predetermined electrical length is positioned within a section of hollow pipe waveguide and a magnetizing coil is externally disposed around the waveguide. In operation a substantial electric holding current is required to achieve a reasonable phase shift value and the weight

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and bulkiness of such coils introduce many problems for a systems designer.

In recent years a new type of ferrite phase shifter has evolved wherein the ferrite bodies are in the shape of a toroid to thereby provide closed magnetic flux loops. The toroid bodies have binary remanent states of magnetization and for purposes of switching a direct current conductor is centrally disposed within the body. Because the magnetic path is entirely closed the toroid bodies are latched in the desired remanent state of magnetization by appropriate current pulses and the value of differential phase shift is determined by the properties and geometry of the ferrite bodies. The latching toroid configuration then readily lends itself to digital techniques desired for computerized current control of the electronically scanned phased array antennas. The term "differential phase shift" refers to the difference in phase shift that results when the direction of current in the latching conductor is reversed to yield the two remanent states of magnetization. In present day devices, multi-toroid bodies, sometimes referred to as "bits," of various lengths are disposed in series with a separate latching conductor provided for each of the toroid bodies. Latching ferrite phase shifters, however, are inherently non-reciprocal, and therefore the phase shift values through a given section of transmission line is different for propagation in opposite directions. Such nonreciprocal characteristics impose additional requirements on the systems designer where a common antenna is desired for transmission as well as reception of electromagnetic microwave energy.

### Summary of the invention

In accordance with the teachings of the present invention a latching ferrite phase shifter is disclosed which is completely reciprocal. The device as will be hereinafter described in further detail embodies a plurality of discrete toroid bodies of appropriate ferrite material arranged in tandem pairs. Each pair comprises toroid bits of substantially identical electrical length separated by matching transformers or other nonmagnetic spacers. Direct current conductors extend through axial passages in each of the toroid bodies with the state of the induced magnetic field in one body being set in series opposing relationship with respect to the companion body. Linearly polarized electromagnetic waves traversing the phase shifter in a particular direction, illustratively during the transmission cycle, are subject to a propagation constant  $\beta_0$  in the first body and a propagation constant  $\beta_1$  in the second similar body of the array. The combined phase of the signal output therefore becomes equal to  $\beta_0 + \beta_1$  multiplied by the length of each of the toroid bodies. Propagation in the opposite direction, illustratively during the reception cycle, will provide the same phase shift value. The ferromagnetic bodies may be defined to provide zero degrees of phase shift for the waves propagated in this first total condition of latched series opposing states of remanent magnetization of the ferrite bodies. For digital purposes this first condition may be correlated with binary code techniques.

A second magnetization condition may be illustratively achieved by the passage of a degaussing current pulse through each of the latching current conductor means. Both of the toroid bodies in the degaussed condition will then produce a new phase shift value in the transmission characteristic of the electromagnetic waves. A differential phase shift will then be produced reciprocally in either the transmission or reception cycle. A plurality of tandem bodies may be utilized with each pair having differential phase shift values of illustratively 180°, 90°, 45°, 22.5°, etc. The present invention is considered to be novel and unique by reason of the reciprocal opera-

tion which eliminates the need for magnetic control field switching between transmit and receive modes of operation in radar systems utilizing the heretofore known non-reciprocal phase shifters.

#### *Brief description of the drawings*

The invention as well as the details of the construction of a preferred embodiment will be readily understood after consideration of the following detailed description and reference to the accompanying drawings in which:

FIG. 1 is a partial perspective view of a toroid body element of a prior art latching ferrite phase shifter;

FIG. 2 is an elevational view of a prior art latching ferrite phase shifter embodiment for a 3-bit differential phase shifter with a portion of the outer envelope broken away;

FIG. 3 is a plot of the magnetization curves referred to in the art as a hysteresis loop of a typical ferromagnetic material;

FIGS. 4A and 4B are diagrammatic plots of current and voltage pulse waveforms for the switching of the ferromagnetic elements between remanent states of magnetization;

FIG. 5 is a schematic representation of a portion of a preferred embodiment of the invention;

FIG. 6 is a plot of the propagation constant values related to the applied magnetic field;

FIG. 7 is a longitudinal cross-sectional view of an embodiment of the invention;

FIGS. 8A and 8B are diagrammatic representations of the directions of the magnetization within a ferrite toroid body in an alternative embodiment for the reciprocal latching ferrite phase shifter; and

FIG. 9 is a schematic representation of a reflective one port type device as still another embodiment of the invention.

#### *Description of a prior art embodiment and theoretical consideration*

Referring now to FIG. 1, a latching toroid body 10 is shown disposed along the longitudinal axis of hollow pipe waveguide 12. A direct current conductor 14 extends through a rectangular passageway 16 in the toroid body. The magnetic closed loop is indicated by arrows 18 and 20 with the direction representing the magnetization induced by the passage of a direct current pulse in the direction designated by the arrow 22. Due to the fact that the magnetic path is closed, demagnetizing effects are relatively absent and the ferrite material is said to be at a remanent magnetization state symbolically represented as  $4\pi M_r$ . Advantageously, the toroid geometry should provide a reasonably square hysteresis loop. Reversal of the direction of the current pulse will result in the induction of another remanent magnetization state with the directions of the magnetic flux lines being reversed and directed in a counterclockwise manner. The phase shift of electromagnetic wave energy propagated through the waveguide 12 is determined by the properties and geometry of the ferrite material and the orientation of the direct current magnetization with respect to the direction of the RF magnetic field. RF interaction occurs between the spin dipoles in the ferrite material and the RF waves for clockwise direct current magnetization and RF propagation in what will be referred to as the forward direction indicated by the arrow 24. The interaction is opposite for direct current counterclockwise magnetization and the differences between these interactions result in different phase shift values. It is now well known in the art that the interaction phenomenon is directly related to the opposite signs of the off-diagonal components of the ferrite permeability tensor as described in the article "The Elements of Nonreciprocal Microwave Devices" by Hogan, Proceedings of the IRE, October 1956, pp. 1345-1368.

If the direction of the microwave magnetic field is in a plane perpendicular to the magnetization path within the toroid body and the polarization of the electric field is linear then the effective permeability ( $\mu$ ) is equal to:

$$(1) \quad \mu_{\text{eff}} = 1 - \frac{4\pi\gamma M_r^2}{\omega}$$

where  $4\pi M_r$  is the remanent magnetization,  $\gamma$  is the gyromagnetic ratio = to  $2\pi \times 2.82 \times 10^6$  radians per oersted and  $\omega$  is the microwave frequency. It will be noted, then, that the effective permeability of ferrite materials is dependent upon the degree of magnetization, the frequency of the energy propagating through the material and a change in this parameter is proportional to the magnitude of the remanent magnetization.

The foregoing description assumes passage of the microwave energy in only the forward direction or from left to right in the illustration. In view of the inherent non-reciprocal behavior of this device the phase shift values are entirely different in the reverse direction of propagation and it is to this end that the present invention offers an attractive solution.

In FIG. 2 an illustrative embodiment of a prior art nonreciprocal latching ferrite phase shifter is disclosed as indicated generally by the numeral 26 comprising a section of rectangular waveguide 28 having waveguide mounting flanges 32 at opposing ends thereof. Full waveguide height toroid bodies 34, 36 and 38 are axially disposed within the waveguide and the complete embodiment as shown is referred to in the art as a three bit phase shifter. The individual toroids are separated by spacers 40 and 42 of any appropriate dielectric material and matching stub means 44 and 46 are positioned at the input and output ends of the embodiment. The latching conductors 48 are provided for each of the toroid bodies and the conductors disposed within the dielectric spacers 40 and 42 are provided with leads to alter the magnetization states within the toroid bodies. Toroid body 34 has an electrical length selected to illustratively provide a 180° phase shift in one remanent state and 0° phase shift in the second remanent state. In a similar manner the electrical length of bodies 36 and 38 will be designed to provide illustratively a 90° or 45° latch and any combination of toroid bodies may be employed to provide the desired total phase shift characteristics.

The properties of the ferromagnetic materials desired for the toroid body members will now be described with reference being directed to FIG. 3 showing the hysteresis loop plot of an idealized material. The flux density is plotted along the vertical axis (B) along with H or the applied magnetic field along the horizontal axis. If a large positive current pulse is passed through the conductor the flux density in the material increases to a point of saturation designated  $M_s$ . The material will then retain a positive residual induction indicated by the point designated A which is the remanent magnetization state along the curved plot 50 after passage of the pulse. The amount of current necessary is designated  $+H_m$  and the accepted designation of value is of amperes per meter. The initial magnetization curve is designated 51 in accordance with the well known principles of electromagnetics. A large negative reset pulse of sufficient amplitude and designated  $-H_m$  may be transmitted through the latching conductor to assure saturation in the opposite direction. Curve 52 then indicates an approximation of the induced field with point A' designating the second remanent state of the ferrite material. It is therefore evident that reversal of the voltage pulses in a latching conductor disposed within a body of ferrite material provides a binary mode of operation involving two remanent magnetization states, A and A'. Relatively small amounts of current, in the order of a few amperes, are required for switching between the respective states with each of the two states providing a different value of phase shift. Further de-

scriptive information relative to the hysteresis loop may be obtained in the text "Electromagnetics" by John D. Kraus, McGraw-Hill Book Company, Inc., 1953, pages 232-238.

In FIG. 4A the latching pulses are indicated to produce illustratively a clockwise magnetic field flux path 54 by means of a positive voltage pulse designated by the waveform 56. The current is gradually increasing during application of the latching pulse as schematically illustrated by curve 58. The second state with the flux path directed in a counterclockwise manner is indicated by arrow 60 in FIG. 4B. This state may be realized by a negative reset pulse 62 of sufficient amplitude and current designated by waveform 64. While the positive and negative polarities have been indicated for the clockwise and counterclockwise magnetization direction, respectively, such polarity designations are merely exemplary. Those skilled in the art, therefore, may utilize any combinations of polarities desired to set the ferromagnetic material in the bistable states.

#### Description of the preferred embodiment

Referring now to FIG. 5 an embodiment of the invention will be described. Toroid bodies 66 and 68 having the preferred reasonably square hysteresis loop magnetization characteristics are disposed in-line within waveguide 70 with a dielectric spacer 72 therebetween. In accordance with the teachings of the invention both toroid bodies have an identical over-all length calculated to give a predetermined value of phase shift. The symbol  $l_2$  in the illustration is a representation of the length. Matching dielectric stubs 74 and 76 are disposed at each end of the tandem pairs in the well known manner. The direction of propagation in one mode of operation is indicated by the arrows designated RF in and RF out. This direction of propagation may illustratively be the transmission cycle of operation of a phased array antenna system. The toroid body 66 is provided with latching conductor 78 while toroid body 68 is provided with an individual latching conductor 80. Following the direction of the arrows it will be noted that toroid body 66 is provided with a current pulse in a direction from left to right in the illustration while the current pulse through latching conductor 80 is directed in an opposite manner to define a series opposing circuit. A suitable pulsed voltage source 82 together with switch 81 is connected to the respective latching conductors 78 and 80. The direction of magnetization in toroid body 66 then will be in a clockwise manner while the direction of magnetization in the adjacent component of the array, specifically toroid body 68, has a counterclockwise direction of magnetization. It will therefore be evident that toroid body 66 may be considered to be in the "0" remanent state while toroid body 68, which has the current pulse in the opposite direction, is in the "1" remanent state.

We next consider the calculation of phase shift through ferrite bodies which has been described by Hogan in the previously referenced article as being determined by microwave scalar permeabilities  $\mu' - K'$  and  $\mu' + K'$ . It is possible to determine by appropriate selection of ferrite materials and the applied magnetic field (H) the value of material magnetization ( $4\pi M$ ) desired to yield a propagation constant ( $\beta$ ) from the following equations for the lossless infinite medium case:

$$(2) \quad \beta_0 = \omega [\epsilon'(\mu' - K')]^{1/2} = \omega \left[ \epsilon' \mu_0 \left( 1 + \frac{4\pi\gamma M}{\omega} \right) \right]^{1/2}$$

and

$$(3) \quad \beta_1 = \omega [\epsilon'(\mu' + K')]^{1/2} = \omega \left[ \epsilon' \mu_0 \left( 1 - \frac{4\pi\gamma M}{\omega} \right) \right]^{1/2}$$

In the phaser diagram shown in FIG. 6 an idealized plot of propagation constant related to applied field (H) indicates that the curve 84 follows the material square hysteresis characteristics. In the case of the prior art latching

toroid bodies of the nonreciprocal phase shifter the point  $\beta_0$  then could be the remanent state yielding a phase shift of zero degrees. Point  $\beta_1$  similarly could yield a predetermined phase shift in the one direction of propagation. In view of the proportional relationship of phase shift to the propagation constant a simplified equation to follow in the design of the device parameters is:

$$(4) \quad \Phi = \beta l$$

In the present embodiment ferrite body 66 is adjusted to exhibit a propagation constant of  $\beta_0$  and the adjacent body 68 is latched in the opposite state yielding the  $\beta_1$  value. The phase of the output signal therefore is as follows:

$$(5) \quad \Phi = (\beta_0 + \beta_1) l_2$$

for propagation in one direction. If a signal is propagated in the opposite direction we note that the propagation constants for the respective bodies are interchanged; however, the same total phase change will result. The reciprocal behavior of the device is therefore readily evident. The magnetization condition obtained from the first arrangement thus described together with the phase shift value may be correlated to binary techniques since the total latched states are "0, 1" or "1, 0" depending on the direction that the propagated signal is being transmitted through the device.

The second magnetization condition may be readily achieved by degaussing the toroid bodies to result in a net induction field within the ferrite material of zero value. A useful current pulse waveform that is ideal for degaussing is one that exhibits a damped oscillation after the pulse is turned off. Such a pulse waveform may now be provided by a degaussing pulse source 83 coupled through switch 85 to branch circuit 87 which is connected in turn to conductors 78 and 80. The degaussed state then becomes the binary magnetization condition which may be symbolically represented as  $\beta_2$ . Both toroid bodies are in a similar state and consequently the total phase change becomes:

$$(6) \quad \Phi = 2\beta_2 l_2$$

For binary control purposes we may refer to this second state for the paired toroid bodies as a digital code "2," "2."

The over-all toroid length to yield any desired phase shift value in a reciprocal manner then is derived between the two magnetization conditions from the equation:

$$(7) \quad \Delta\Phi = (\beta_1 + \beta_0 - 2\beta_2) l_2$$

In the actual operative embodiment then a plurality of tandem pairs of ferrite bodies arranged similar to bodies 66 and 68 in FIG. 5 will be disposed within a waveguide envelope. Each pair of ferrite bodies will provide a predetermined value of phase shift in the binary condition of being latched in series opposing relationship to yield opposing remanent states and the degaussed state. The lengths of the ferrite paired bodies will differ with the longer bodies providing the higher phase shift values.

Referring next to FIG. 7, an embodiment incorporating plural tandem pairs of ferrite bodies is illustrated together with an alternative structure for achieving the second magnetization condition referred to herein as the "2, 2" state. Waveguide section 86 houses in-line a first pair of toroid bodies 88 and 90 separated by a dielectric spacer 92. Latching conductors 94 and 96 extend within the respective bodies to conduct current pulses in the series opposing manner and are supported by spacer 92 together with dielectric members 98 and 100. Well known external digital control and voltage supply means are coupled to the conductors and have not been illustrated in the interest of clarity. The first paired bodies may have an over-all length to provide a differential phase shift of illustratively  $180^\circ$  in the latched remanent states.

The next pair is disposed in-line and along the longitudinal axis of the waveguide section. Bodies 102 and 104 together with the dielectric spacer 106 may have an illustrative length to provide a lesser phase shift value, illustratively 90°. The conductors 108 and 110 provide for conduction of the latching current pulses.

In a similar manner, another pair is partially illustrated with a smaller toroid body 112 of another length to provide an additional phase shift value. Dielectric spacer 114 separates the ensuing pair. In this fashion any combination of ferrite toroid bodies may be digitally controlled to provide the desired total phase shift characteristics in the magnetized condition with the latched states of "0, 1" and "1, 0."

Now in this embodiment the second magnetization condition or "2, 2" state which yields another propagation characteristic may be realized in an alternate manner. Rather than degaussing the magnetized toroid bodies another magnetic field may be superimposed on the bodies in the latched magnetic state and the direction of the magnetization paths within the ferrite material thereby altered. For this purpose a solenoid magnet 116 having a plurality of turns of a wire 118 on a metallic core 120 is externally disposed relative to the toroid bodies within waveguide 86. The magnet power supply 122 is either intermittently or continuously activated by a switching circuit diagrammatically indicated at 124 connected to the magnetic field producing means.

This alternative embodiment will be understood more fully, reference being now directed to FIGS. 8A and 8B. In FIG. 8A the direction of magnetization of toroid body 126 in the clockwise latched state is indicated as produced by a current pulse through conductor 128. In analyzing the behavior of such magnetized bodies the parallel longer segments 130 and 132 closely resemble two ferrite slabs separated by a dielectric medium 134 with said slabs oppositely magnetized as indicated by the arrows. It is the oppositely latched remanent states with magnetic field vectors disposed parallel to the electric vector E of linearly polarized waves which results in the phase shift characteristics for the latched states "0" or "1." In the present invention, therefore, another body with the direction of the latched state reversed would be disposed in-line behind body 126. The combined oppositely magnetized bodies in each tandem pair separated by the dielectric matching transformer now leads to reciprocal operation easily adapted to digital control techniques.

The embodiment illustrated in FIG. 7 with the magnetic field producing means 116 turned on will impose magnetic lines of force on the internal magnetic field to result in the direction of the arrows now extending in the same direction. As seen in FIG. 8B, the magnetic field may be considered to be parallel in the respective segments 130 and 132 while the previous state indicated in FIG. 8A is exemplary of the anti-parallel disposition of the lines of force. This parallel field distribution then represents an alternative method of establishing the "2, 2" binary condition of the ferrite toroids with the accompanying differential phase shift values.

FIG. 9 introduces still another variation in the practice of the present invention. In this embodiment a reciprocal phase shifter is disclosed which may be employed as a reflective device wherein energy from the transmitter enters the device and is propagated through a single port. In phased array antenna systems it has now become desirable to spatially position the high power transmitter with respect to the array containing many thousands of phase shifting devices in what may be referred to as a "non-corporate feed" arrangement. The phase shifter illustrated in FIG. 9 and designated by numeral 140 includes a toroid ferrite body 142 of predetermined length to yield a desired phase shift value. The toroid body 142 is intended in this application to represent one-half of the tandem paired arrangements previously described in

FIGS. 5 and 7. Rectangular waveguide 144 is short circuited at one end by a conductive plate 146. Transformer 148 is provided at the open end to match the propagation characteristics of the waveguide with the ferrite body to free space and any quartz or dielectric material having a  $\lambda/4$  wavelength dimension is preferred. Latching conductor 150 extends through the ferrite toroid and a side wall of waveguide 144 as well as dielectric transformer 148. A current pulse will latch the toroid in either the "0" or "1" remanent magnetization state. An RF signal transmitted to device 140 will enter the waveguide as indicated by arrow 154 and the electromagnetic energy will be shifted in phase as determined by the orientation of the magnetic field within the ferrite material.

Reflection of the signal at the short circuit end 146 now results in another phase shift since the disposition of the magnetic field as seen by the reflected signal is reversed. Passage in one direction and return results in a reciprocal phase shift with one ferrite toroid body which is comparable to that obtained with two bodies in the transmission type of device. The accompanying savings obtained with the reflective one port device will then be evident since one body provides twice the ferromagnetic material volume. The reflected RF signal then exits through the single port as indicated by arrow 156.

The second or "2, 2" magnetization condition would then be provided by degaussing ferrite body 142 or any other auxiliary magnetic field variation means desired. Passage of the signal in both directions would then yield twice the  $\beta_2$  propagation constant value.

This completes the description of several embodiments of the present invention. Numerous modifications and alternate embodiments may be evident to those skilled in the art and are to be considered within the scope of the invention as set forth in the accompanying claims.

What is claimed is:

1. A reciprocal microwave energy phase shifter comprising:

means defining a propagation path for linearly polarized electromagnetic waves at microwave frequencies;

at least one pair of discrete toroid bodies of a ferromagnetic material having binary remanent magnetization states of substantially equal length separated by a dielectric spacer disposed in axial alignment along the center plane of said propagation path;

each of said bodies defining spaced parallel wall portions between the center plane and outer walls of said propagation means;

direct current conduction means extending through said toroid bodies in a series opposing circuit arrangement;

and means energizing said conduction means to thereby establish one state of magnetization in a first toroid body of said pair with the opposite state established in the remaining toroid body of said pair and the directions of magnetization in each of the toroid wall portions is antiparallel with respect to its companion wall member.

2. A reciprocal microwave energy phase shifter comprising:

a section of hollow rectangular waveguide having broad and narrow sidewalls for propagating electromagnetic waves;

at least one pair of discrete toroid bodies of a ferromagnetic material having binary remanent magnetization states of substantially equal length separated by a dielectric spacer disposed in axial alignment along the center plane of said waveguide;

each of said bodies defining spaced parallel wall portions between the center plane and narrow sidewalls; direct current conduction means extending axially through said toroid bodies in a series opposing circuit arrangement;

means energizing said conduction means to thereby

latch a first toroid body of said pair in one remanent magnetization state while the next toroid body of said pair disposed in line is latched in the opposite magnetization state with the directions of magnetization in each of the toroid wall portions being antiparallel with respect to its companion wall portion; said latched magnetized bodies establishing a predetermined value of phase shift of microwave energy transmitted through said waveguide;

and means for producing a second magnetized condition in said bodies to yield a different value of phase shift of said waves within said waveguide.

3. A reciprocal microwave energy phase shifter comprising:

a section of hollow rectangular waveguide having broad and narrow sidewalls for propagating electromagnetic waves;

at least one pair of discrete toroid bodies of a ferromagnetic material having binary remanent magnetization states separated by a dielectric spacer disposed in axial alignment along the center plane of said waveguide;

each of said bodies defining spaced parallel wall portions between the center plane and narrow sidewalls; each of said toroid bodies being of substantially similar length and magnetized in a series opposing condition with the directions of magnetization in each of the toroid wall portions being antiparallel with respect to its companion wall portion to yield a predetermined value of phase shift of electromagnetic waves within said waveguide;

and means for degaussing said toroid bodies to thereby provide a second magnetization condition and corresponding predetermined value of phase shift of said microwave energy.

4. A reciprocal microwave energy phase shifter comprising:

a section of hollow rectangular waveguide having broad and narrow sidewalls for propagating electromagnetic waves;

a plurality of discrete toroid bodies of a ferromagnetic material arranged in tandem pairs along the center plane of said waveguide with the bodies in each pair having a substantially similar length and being separated by a dielectric spacer;

electrical current conduction means extending axially through said bodies with the current direction in one body being in series opposing relationship to the current direction in its paired counterpart to yield opposite remanent states of magnetization with an accompanying value of phase shift of waves transmitted through said waveguide in either direction and the directions of magnetization in each of the toroid wall portions being antiparallel with respect to its companion wall portion;

and means for producing a second magnetization condition in said toroid bodies comprising external magnetic field producing means of sufficient magnitude to alter the magnetic flux line directions within the wall portions of said bodies to be parallel and thereby yield a different value of phase shift of waves transmitted through said waveguide in either direction.

5. A reciprocal microwave energy phase shifter comprising:

a section of hollow rectangular waveguide having broad and narrow sidewalls for propagating electromagnetic waves;

tandem pairs of discrete ferrite bodies of a toroid configuration disposed along the center plane of said waveguide and separated by a dielectric spacer;

each of said bodies defining spaced parallel wall portions between the center plane and narrow sidewalls; latching current pulse conduction means extending axially through said bodies to yield an induced magnetic state having a direction of magnetization which is opposite in one body of each pair with respect to the other body to yield a first magnetization condition consisting of the combined total states with the directions of magnetization in each of the toroid wall portions being antiparallel with respect to its companion wall portion;

means for producing a second magnetization condition comprising degaussing each ferrite body to yield a substantially zero net internal magnetic field magnetism;

and means for selectively and intermittently energizing said latching pulse and degaussing means to render the ferrite bodies in the first and second magnetization conditions with accompanying differential values of phase shift of electromagnetic waves transmitted through said waveguide.

#### References Cited

##### UNITED STATES PATENTS

|           |         |                  |            |
|-----------|---------|------------------|------------|
| 3,100,287 | 8/1963  | Scharfman et al. | 333—24.1   |
| 3,277,401 | 10/1966 | Stern            | 333—24.1   |
| 3,317,863 | 5/1967  | Ngo              | 333—24.2 X |
| 3,332,042 | 7/1967  | Parris           | 333—24.2 X |

##### OTHER REFERENCES

Tech-Briefs, The Microwave Journal, April 1965, p. 43.

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U.S. Cl. X.R.

333—24.1