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LATCHING-TYPE DIGITAL PHASE SHIFTER EMPLOYING
TOROIDS OF GIROMAGNETIC MATERIAL
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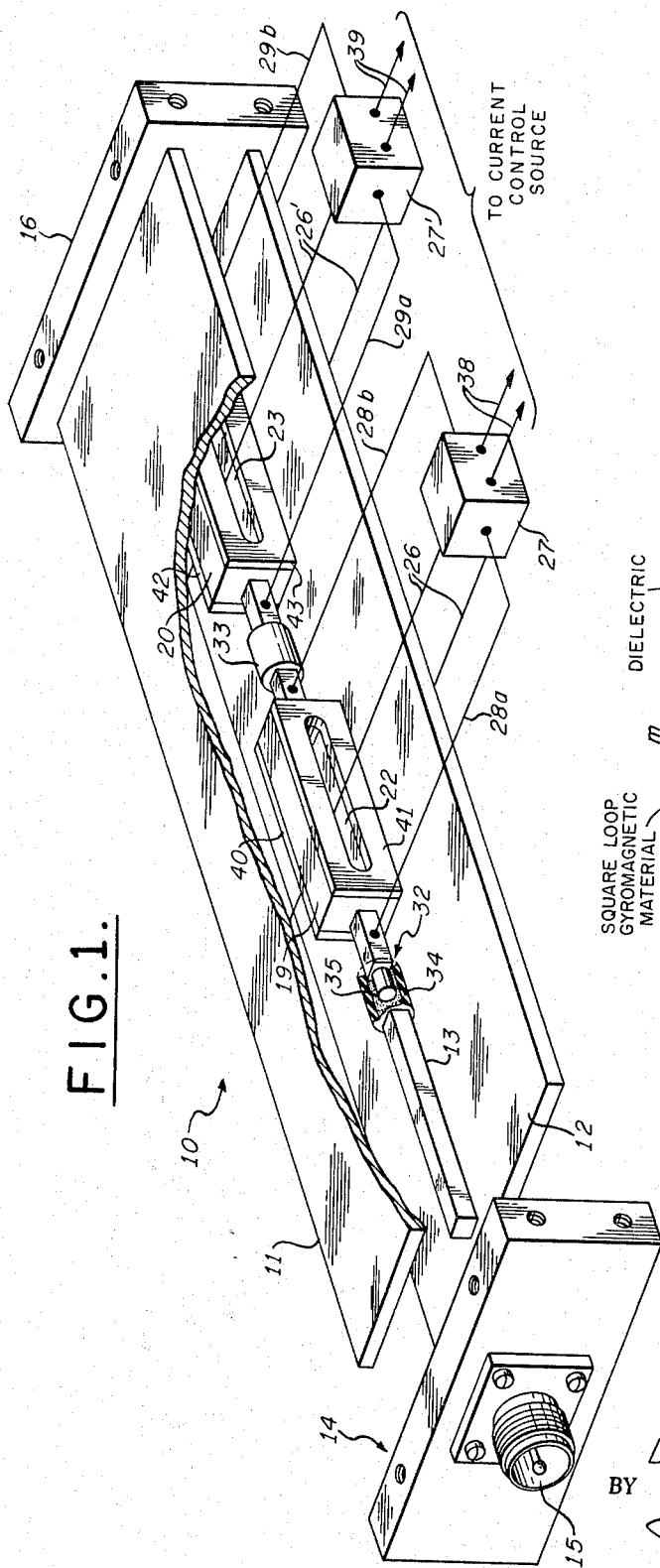


FIG. 1.

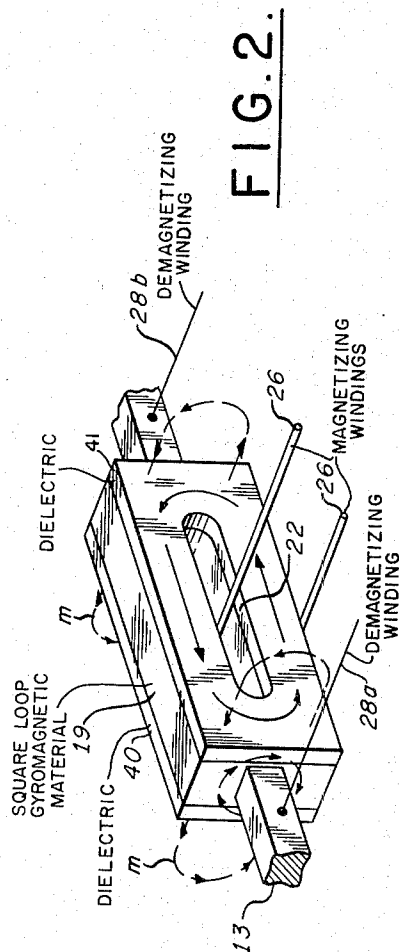


FIG. 2.

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LATCHING-TYPE DIGITAL PHASE SHIFTER EMPLOYING TOROIDS OF GYROMAGNETIC MATERIAL

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ABSTRACT OF THE DISCLOSURE

A microwave, digital, reciprocal phase shifting apparatus comprising a gyromagnetic member disposed symmetrically within a wave propagating medium in a region where the magnetic field of the electromagnetic wave is linearly polarized, the gyromagnetic member being oriented such that an axis of symmetry passing through an aperture in the member is transverse to the direction of wave propagation. Current alternately applied to an electrical conductor threading the aperture and another conductor traversing the gyromagnetic member in the direction of wave propagation establishes orthogonal magnetic fields which cause the member to present two discrete values of permeability to the electromagnetic wave.

This invention relates to electromagnetic wave phase shifting devices and more particularly relates to small and efficient reciprocal latching-type digital phase shifters that utilize toroids of gyromagnetic material whose magnetization states may be selectively switched to provide different values of phase shift, and which require no external magnetizing energy to maintain either value of phase shift. In the present invention the toroids are so positioned in the magnetic field of the electromagnetic waves and their magnetization states are chosen so as to assure optimum interaction with the linearly polarized magnetic field components when magnetized in one state and to provide minimum interaction with said components when magnetized in their second state, thus providing large differential phase shifts.

Phase shifters constructed in accordance with the present invention are particularly useful in the so-called "digital" phase shifters that have been proposed for use in radar systems whose antenna beams are to be electronically scanned. Electronic scanning is achieved by providing a plurality of wave radiating elements whose relative physical arrangement, together with their amplitude and phase of excitation, are so proportioned that the composite radiation pattern of all the elements is a shaped beam whose direction in space may be changed in a controlled manner. A rather complex waveguide network having a plurality of wave propagating paths connects the microwave transmitter to the various radiating elements and establishes the required amplitude and phase relationships at the elements. The beam is continuously scanned in small angular increments by changing in discrete steps the phase shift of the waves through the various paths of the waveguide network. It is obvious that in order to effectively cover a large volume of space with a rapidly scanned antenna beam, the phase shifting means in the waveguide network must be capable of rapidly changing in discrete steps the phase of the electromagnetic waves through the various paths of the network. Further, because a large beam-scanning radar system may employ hundreds or thousands of phase shifting devices in the waveguide network, the switching power that is required to effect phase changes in all of the phase shifting devices is a matter of primary concern and must be held to a minimum.

In designing the waveguide networks for use in these types of radar systems, considerable attention has been

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given to the use of phase shifters that employ gyromagnetic materials. These phase shifters of the digital type employ several members of gyromagnetic material, each member having its own independent magnetizing source. Most commonly, a magnetizing source functions to magnetize each gyromagnetic member to one or the other of two magnetization states. The individual members of gyromagnetic material introduce different values of phase shift by themselves, and by selectively magnetizing various combinations of the individual members to one or the other magnetization state, different values of phase shift may be selected. In order to reduce the power requirements of the magnetizing sources, gyromagnetic members in the shape of toroids, and having two remanent magnetization states, have been used. This then requires magnetization power only during the switching operation, and no source power is required to hold a toroid in a given one of its remanent magnetization states. Phase shifters operating in this manner sometimes are called "latching" phase shifters because the toroids of gyromagnetic material always are used in one or the other of their magnetization states.

When used in beam scanning radar systems it is desirable that the phase shifters be reciprocal, or bilateral, in their operation because in order for the antenna to receive reflected waves from the same direction in which they were radiated during transmission, the various paths of the waveguide network must be the same electrical length for both the transmitted and received waves. To achieve bilateral operation, the toroids of ferrimagnetic material should be positioned in the transmission lines of the waveguide network in regions where the magnetic fields of the transmitted and received waves are linearly polarized. In magnetizing toroids of ferrimagnetic material to obtain different values of phase shift from each toroid, it will not be possible to switch the magnetization states between the two remanent magnetizations of a square hysteresis loop magnetization characteristic because this would result in the same magnitude of phase shift for both magnetizations. Consequently, other combinations of magnetization conditions must be utilized in switching the toroids to produce different values of bilateral phase shift.

It therefore is an object of this invention to provide an electromagnetic wave reciprocal phase shifter employing gyromagnetic material whose magnetization may be switched between two states that provide substantially optimum and substantially minimum interaction between the material and the waves.

Another object of this invention is to provide in an electromagnetic wave reciprocal phase shifter means for selectively magnetizing a toroid of gyromagnetic material in either one of two orthogonal directions, whereby the material introduces different values of reciprocal phase shift when magnetized in the different directions.

In accordance with the present invention a reciprocal latching type phase shifter is constructed in a double ground plane strip transmission line by providing a plurality of toroids of gyromagnetic material each of which is disposed symmetrically within the transmission line with the center axis of its aperture extending transversely to the center conductor of the line and parallel to the ground plane conductors. Each toroid has a square hysteresis loop magnetization characteristic that includes two opposite remanent magnetization states. The center strip conductor of the transmission line extends through each toroid from front-to-back and thus transversely to the axis of the toroid aperture. A magnetizing winding threads each toroid aperture and serves to magnetize the toroid in a circumferential direction to one of its remanent magnetization states. Because the toroid is located in a region where the magnetic field components

of the electromagnetic waves are linearly polarized, and because the toroid is everywhere magnetized transversely to those magnetic field components, the gyromagnetic material interacts optimally with the electromagnetic waves and produces a relatively large value of phase shift. To obtain a different value of phase shift from each toroid, a magnetizing current pulse is passed through the portion of the center strip conductor that extends through the toroid. The toroid then is magnetized in a circular direction that is orthogonal to its first direction of magnetization. In this second condition of magnetization the magnetic moments of the material are substantially parallel to the direction of the linearly polarized magnetic field components of the electromagnetic waves and there is minimum interaction between the material and the waves, thus resulting in a minimum value of phase shift to the waves. Each individual toroid produces a different value of maximum phase shift and the magnetization state of each toroid is independently controllable. By selecting different magnetization states for various toroids different values of phase shift may be produced. Because the material interacts optimally with the electromagnetic waves when magnetized in one condition and interacts minimally when magnetized in the other state, a minimum amount of material need be utilized in the toroids. This feature, together with the requirement for magnetizing current only during the switching of magnetizations, provides small and efficient reciprocal latching-type phase shifters.

The invention will be described by referring to the accompanying drawings wherein:

FIG. 1 is a simplified illustration of a latching-type digital phase shifter constructed and operated in accordance with the present invention; and

FIG. 2 is a sketch showing a toroid of gyromagnetic material and is used to explain the different magnetization states of the toroid.

Referring now in detail to FIG. 1, a double ground plain strip transmission line 10 is comprised of the broad conductive ground planes 11 and 12 and the narrow center strip conductor 13 which is disposed symmetrically between said ground plane conductors. A strip transmission line-to-coaxial transmission line transition member 14 provides means for coupling strip transmission line 10 to a coaxial input connector 15. A similar arrangement is provided at the opposite end of the device by a transition member 16. Strip transmission line 10 propagates electromagnetic waves in a TEM mode in which the electric field extends transversely between the center strip conductor 13 and the respective ground planes 11 and 12. The magnetic field lines of this TEM mode are in the form of ellipses that extend circumferentially about center strip conductor 13, and the components of this magnetic field are substantially linearly polarized in the region about center strip conductor 13.

Center strip conductor 13 extends longitudinally and symmetrically through the two toroidally shaped members 19 and 20 of gyromagnetic material. The toroids 19 and 20 of gyromagnetic material are positioned within strip transmission line 10 so that axes of symmetry passing through their toroidal apertures 22 and 23 are transverse to the longitudinal axis of strip transmission line 10 and parallel to the ground plane conductors 11 and 12. The toroids 19 and 20 have square hysteresis loop magnetization characteristics and may be comprised of any of the suitable ferrimagnetic materials that are known to those skilled in the art. In a practical latching-type digital phase shifter intended for use in electronically scanned radar systems more than two toroids most likely would be used, but for simplicity of illustration and description, just two toroids have been illustrated in FIG. 1. The magnetizing windings 26 and 26' thread the respective apertures 22 and 23 in toroids 19 and 20 and serve to magnetize the toroids in a circumferential direction around their toroidal shape as illustrated

in FIG. 2. Pulses of magnetizing currents are supplied to the windings 26 and 26' by the respective magnetizing current sources 27 and 27'. The conductors 28a and 28b each contact the portion of center strip conductor 13 that passes through toroid 19 and thereby establishes a second magnetizing current path which will be referred to hereinafter as the demagnetizing winding. The conductors 29a and 29b are similarly connected and serve the same purpose with respect to toroid 20.

In order to provide D.C. isolation for the two demagnetizing windings just described, appropriate D.C. blocking capacitors are provided in center strip conductor 13. Two of these capacitors are illustrated by the members 32 and 33. As may be seen from the cut-away view of the member 32, an outer cylindrical shell 34 is conductively secured to the left end of center strip conductor 13 and is provided with an insulating sleeve 35 about its inner surface. The portion of center strip conductor 13 within the sleeve 35 is fashioned to make a snug fit within the sleeve and nowhere contacts the conductive cylinder 34 on the left end of center strip conductor 13. Thus, an open circuit is established for D.C. currents but a relatively large A.C. capacitance is formed so as to provide negligible disturbance to A.C. currents propagating on the strip transmission line. The magnetizing current sources 27 and 27' apply appropriate magnetizing and demagnetizing current pulses to the respective windings associated with each of the toroids 19 and 20 so as to change the magnetization states of the toroids in response to command signals on the respective lines 38 and 39 which may be coupled to a current control source whose operation may in turn be controlled by logic or computer apparatus which programs the magnetization states of the toroids of all of the phase shifters of a radar system to achieve the desired scanning of an antenna beam. In practice, each phase shifting device 10 may include four toroids which respectively produce differential phase shifts of 22.5°, 45°, 90° and 180°. By selectively choosing different magnetization states of the four toroids, differential phase shifts in increments of 22.5° may be selected from 0° to 360°.

In the operation of a digital phase shifter it is required that the ferrimagnetic material produce two different values of phase shift when in two different magnetization states. The different values of phase shift result from the fact that the ferrimagnetic materials present different values of permeability to the electromagnetic waves when in the two different magnetization states. To assure that the phase shifter functions in a reciprocal manner the magnetic field components of the electromagnetic waves that propagate in opposite directions through the ferrimagnetic material must be linearly polarized. To add assurance that this condition is in fact achieved in the device of FIG. 1, slabs 40, 41 and 42, 43 of a low loss, non-magnetic dielectric material having a relative dielectric constant substantially the same as that of the toroids of ferrimagnetic material are respectively positioned along the sides of the toroids 19 and 20. The function served by the slabs 40-43 of dielectric material is to present at the sides of the toroids 19 and 20 a medium having the same dielectric constant so that the magnetic field lines of the electromagnetic waves are not disturbed at the side boundaries and thus the field in this region will be substantially purely linearly polarized rather than tending to become elliptically polarized at the boundaries as they would if a different dielectric constant medium were present. Further, for the ferrimagnetic material to interact in an optimum manner with the magnetic field of the electromagnetic waves, it is necessary that the material be magnetized in a direction transverse to the direction of the magnetic field components of the waves. Should the material be magnetized parallel to the direction of the magnetic field components of the electromagnetic waves, the magnetic susceptibility of the material will be substantially zero and there will be minimum interaction between the ferri-

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magnetic material and the waves. These two facts are taken advantage of in the construction and operation of the phase shifter illustrated in FIG. 1, as will be explained in more detail with the aid of FIG. 2.

The linearly polarized magnetic field components of the electromagnetic waves are illustrated in FIG. 2 by the ellipses *m* formed by the broken lines. To achieve one magnetization state of the toroid 19, a magnetizing current pulse is passed through winding 26 which establishes a magnetization flux in a circumferential direction about the toroid aperture 22 and magnetizes toroid 19 to a remanent magnetization state. The direction of magnetization of toroid 19 is illustrated in FIG. 2 by the solid arrows about aperture 22. It may be seen that the magnetic field components of the waves are everywhere transverse through the toroid 19 and are everywhere transverse to the direction of magnetization of the toroid. Therefore, optimum interaction will take place between the ferrimagnetic material of toroid 19 and the magnetic field components of the electromagnetic waves. Because the magnetic field components of electromagnetic waves are linearly polarized, the same interaction will take place irrespective of the direction of propagation of the waves through the toroid 19 and the resulting phase shift will be bilateral. To obtain a different value of phase shift from the toroid 19, a magnetizing current pulse is passed through the demagnetizing circuit comprised of the leads 28a, 28b and the portion of center strip conductor 13 that extends through toroid 19. The D.C. current pulse through the portion of center strip conductor 13 establishes a magnetizing flux that magnetizes toroid 19 in a circumferential direction around center strip conductor 13, as illustrated by the curved solid arrows on the front face of toroid 19. With this condition of magnetization the ferrimagnetic material is magnetized in directions substantially parallel to the directions of the magnetic field components of the electromagnetic waves. With this condition existing, the permeability of the ferrimagnetic material is essentially a scalar of value 1 and the magnetic susceptibility is nearly zero. Therefore, the interaction between the magnetic moments of the ferrimagnetic material and the magnetizing field component of the electromagnetic waves will be substantially minimum and the interaction may be considered essentially the same as if the ferrimagnetic material were demagnetized. Again, the conditions for reciprocal operation exist and the two different conditions of magnetization would produce two different values of phase shift for waves propagating through the device. In a practical latching-type digital phase shifter which employs four toroids of ferrimagnetic material in the manner mentioned above, each toroid would produce a different magnitude of differential phase shift, and by appropriate energization of the magnetizing and demagnetizing windings of each toroid, different combinations of total phase shift may be selected.

It will be understood that the teachings of the present invention also may be adapted for use in a coaxial transmission line. In such a device, the inner conductor of the coaxial line would pass longitudinally through each one of the successively positioned toroids. In such a device the toroids may have circular shapes in planes taken transversely to the longitudinal axis of the coaxial transmission line.

While the invention has been described in its preferred embodiments, it is to be understood that the words which have been used are words of description rather than limitation and that changes within the purview of the appended claims may be made without departing from the true scope and spirit of the invention in its broader aspects.

What is claimed is:

1. In an electromagnetic wave device employing a member of gyromagnetic material and operating to have the magnetization state of said member switched between two different magnetization states to effect differential inter-

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action with linearly polarized electromagnetic waves when in the two different magnetization states, the combination comprising:

electromagnetic wave propagating means for propagating electromagnetic waves along a given direction in a mode in which the magnetic field component is linearly polarized in a given region,

a member of gyromagnetic material that exhibits gyromagnetic effects to said waves,

said member being positioned in said given region such that an axis of symmetry of said member is transverse to said given direction and substantially coincident with the axis of an aperture in said member, first means for magnetizing said member in a first direction around said axis, whereby said member presents a first value of permeability to said waves, and

second means for magnetizing said member in a second direction orthogonal to said first direction so that said member presents a second value of permeability to said waves,

said first and second means being actuated alternately to switch the magnetization of said member between said first and second directions.

2. The combination claimed in claim 1 wherein:

said means for magnetizing said member in said first direction is a first current conductor that threads said member in the direction of said axis of symmetry, and wherein,

said means for magnetizing said member in said second direction is a second current conductor that threads said member in a direction orthogonal to said axis of symmetry.

3. The combination claimed in claim 2 wherein said electromagnetic wave propagating means is comprised of a TEM mode transmission line having at least first and second conductors extending in said given direction, said second conductor extending through said member and serving as said second current conductor.

4. The combination claimed in claim 3 wherein said TEM mode transmission line is a coaxial transmission line and said second conductor is the inner conductor of said coaxial transmission line.

5. The combination claimed in claim 1 wherein said member has a rectangular cross-section and further including:

low loss, non-magnetic dielectric material disposed along said member of gyromagnetic material on the sides thereof oriented transverse to said axis of symmetry, said material having a dielectric constant substantially the same as that of the gyromagnetic material, thereby to assure that said magnetic field component is linearly polarized throughout the entire region occupied by said member.

6. An electromagnetic wave phase shifter comprising: a strip transmission line comprised of a narrow strip conductor and a pair of broad conductive ground plane conductors spaced from and extending parallel to said strip conductor,

a plurality of longitudinally disposed members of gyromagnetic material located entirely between said ground plane conductors with respective axes of symmetry passing through an aperture in each of said members being transverse to said strip conductor, and with said strip conductor extending successively through each of said members,

means for magnetizing each of said members in a first direction around its respective axis of symmetry, and

means for magnetizing each of said members in a second direction around said strip conductor, said members being alternately magnetized in either of said first and second directions.

7. An electromagnetic wave device comprising:

a longitudinally extending strip transmission line com-

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