July 25, 1967 W. J. PARRIS 3,333,214

RECIPROCAL LATCHING GYROMAGNETIC SWITCH HAVING ORTHOGONALLY CROSSING CONDUCTORS EXTENDING THROUGH THE GYROMAGNETIC MATERIAL

Filed Sept. 14, 1964

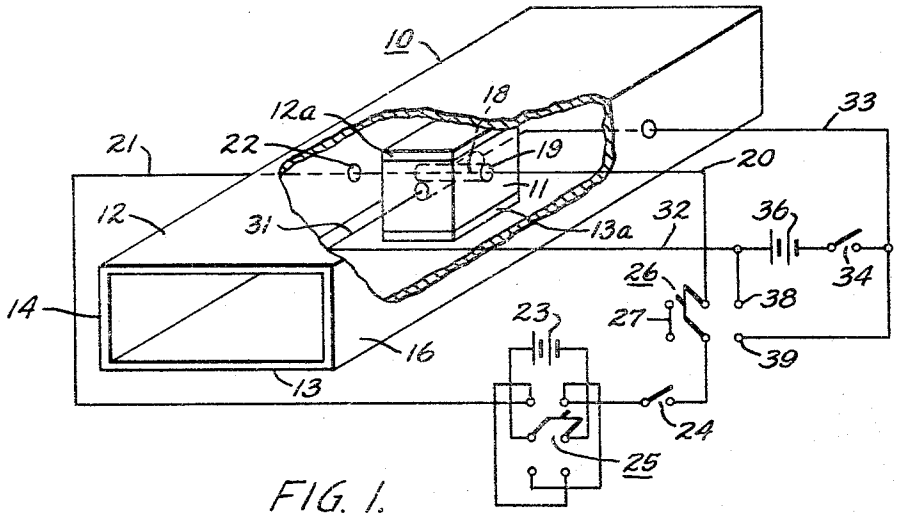
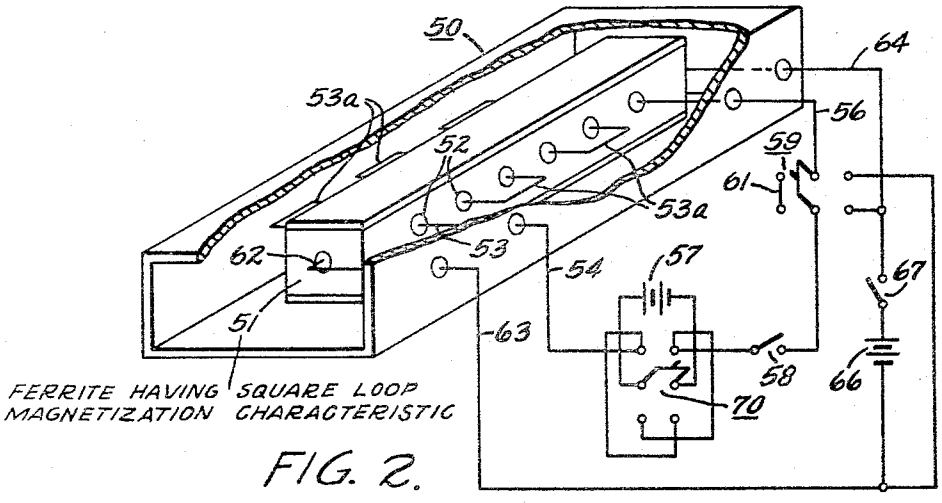


FIG. 1.



FERRITE HAVING SQUARE LOOP MAGNETIZATION CHARACTERISTIC

FIG. 2.

United States Patent Office

3,333,214

Patented July 25, 1967

3,333,214

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Filed Sept. 14, 1964, Ser. No. 396,120
9 Claims. (Cl. 333—24)

This invention relates to electromagnetic wave apparatus and particularly to an improved latching microwave gyromagnetic switch. The residual magnetism of a gyromagnetic material is utilized to provide latching action so that no holding current is required to maintain the switch in the on or off condition. The device is reciprocal in its operation.

An object of the invention is to render selectively a section of microwave transmission line transparent to impressed electromagnetic wave energy or reflective to such waves under electronic control.

Another object is to provide a microwave ferrite switch in which novel and improved means are provided for switching the magnetic state of the gyromagnetic element from a condition of transparency to the electromagnetic waves to a condition of high reflective impedance and which has minimum inductance and therefore can be operated at a very fast rate.

It is still another object to provide a novel and improved latching microwave gyromagnetic switch which is responsive to a signal pulse of one polarity to put the switch in one condition and responsive to signal pulse of the opposite polarity to switch it to the opposite condition.

The use of gyromagnetic materials to obtain both reciprocal and non-reciprocal effects in microwave transmission lines is rather widely known and has found numerous and varied applications. In applicant's copending applications case No. 36,226 entitled Reciprocal Microwave Apparatus Ser. No. 396,119, filed Sept. 14, 1964, and case No. 36,509 entitled Non-reciprocal Microwave Apparatus Ser. No. 396,121, filed Sept. 14, 1964, there are described and claimed two novel and improved microwave transmission systems involving applications of such gyromagnetic devices. In case No. 36,226 a brief outline and a cross reference to a more complete treatise of the basic fundamentals of the behavior of gyromagnetic materials are set forth. Also most of the basic fundamentals are known for making such devices reciprocal, non-reciprocal and for determining whether the device will be a phase shifter or an attenuator. However, there are still some permutations and combinations which can be found to provide new and unobvious results. The present invention represents one such novel permutation.

It is known that when gyromagnetic materials are immersed in D-C magnetic biasing fields of such density as to produce a gyroresonant condition with the propagated microwave that the gyromagnetic material will absorb the microwave energy in accordance with the mechanism which is well understood and is briefly outlined in the aforementioned case 36,226. In such prior devices, the gyromagnetic material is usually always biased at or beyond the saturation condition so that the material will be an efficient attenuator. Such devices when used under those conditions are usually called isolators and are non-reciprocal as they will permit energy to be propagated in only one direction while absorbing energy propagated in the other direction.

As distinguished from such prior devices, the present invention utilizes a body of gyromagnetic material, which although biased near the saturated state to produce the

stop-signal condition it is not biased to the gyroresonant condition and, instead of absorbing microwave energy, produces a highly reflective impedance. This is a wholly unobvious result obtained from gyromagnetic materials in microwave transmission systems and is not understood although it has been demonstrated and is being put to use.

To facilitate an understanding of how the present invention distinguishes from some of the prior devices, although its exact operation is not known, a very brief statement of the principles of gyromagnetic materials is made below to facilitate an understanding of the invention. The present invention has been reduced to practice using ferrite materials having gyromagnetic properties. By gyromagnetic is meant a class of magnetic polarizable materials having unpaired electron spins which involve portions of the material. They are capable of being aligned with an external D-C biasing magnetic field and exhibit a significant precessional motion when subjected to transverse magnetic forces while immersed in the biasing field. In the gyromagnetic microwave transmission systems the transverse magnetic force is usually that applied by the propagated electromagnetic wave. It is in this manner that there is interaction between certain of the electrons of the gyromagnetic material and the electromagnetic wave. These unpaired electron spins constitute magnetic dipoles. Since electrons have mass and an electric charge and are constantly spinning on their axis they can be considered as tiny gyroscopes and the en masse action of the unpaired electron spins of the gyromagnetic material may be considered as a single gyroscope for purposes of analysis.

Ferrites have gyromagnetic properties and at the same time have high resistivity and moderately high dielectric constants. At the same time they have numerous unpaired electron spins acting as magnetic dipoles and this gives them pronounced gyromagnetic properties so that their gyromagnetic interaction with electromagnetic waves causes their apparent permeability to electromagnetic wave energy to be readily changed by changing the internal magnetic flux. Since the gyromagnetic properties are essential to the operation of this invention, hereinafter ferrites will be used synonymously with gyromagnetic materials.

Because of the characteristics of ferrites mentioned above, microwave energy can enter and pass through substantial amounts of ferrites without excessive attenuation or phase shift, but because of the strong interaction between the electromagnetic wave and the spinning electrons the apparent permeability, attenuation and, in accordance with the present invention the apparent reflective impedance of ferrites, can be electronically varied at very high rates by changing the internal flux.

Because ferrite materials have numerous spinning electrons distributed throughout their mass, when these materials are immersed in a direct current magnetic field the magnetic dipoles align themselves parallel to the internal magnetic field. From what has previously been said, it is apparent that if such materials are disposed in a wave transmission system so that it is also subjected to the linearly or circularly polarized electromagnetic field of an electromagnetic wave the precessional movement of the dipoles will be dependent upon where they are located in the electromagnetic wave field. When the precessional (angular) velocity of the dipoles about the magnetic lines of force of the applied magnetic field is substantially equal to and in the same direction as the rotating magnetic field portion of the electromagnetic wave the phenomena known as gyroresonance occurs. Since this precessional motion in gyromagnetic materials is highly damped there is a tendency for the magnetic moment vector to gradually spiral in and come into align-

ment with the magnetic field. Since the electron always precesses about the D-C field in a direction determined by its fixed direction of spin the direction in which one end of its axis precesses about the D-C field is called the positive circular component and that rotating in the opposite direction is termed the negative circular component. Regardless of where the block of ferrite material is located in the microwave guide it can always be considered that there is a circular component present in the case of linearly polarized waves since the alternating magnetic field of the linearly polarized wave may be resolved into two counter rotating circularly polarized components. During any infinitesimal rotation of all of these vectors about the biasing field work is done on the electron by the positive circular component of the electric field. Accordingly, there is a net transfer of energy from the positive circular polarized alternating field to the electron. This causes the moment vectors of the electrons to "fan out" so that it makes a larger and larger angle with the direction of the D-C magnetic field. Thus a circularly polarized component can act to maintain the precessional motion of the electron at some constant amplitude, even though this motion is heavily damped. The energy fed into the electron by the rotating magnetic field just makes up for the energy dissipated by the damping. This is the gyroresonant condition for which the gyromagnetic material absorbs the microwave energy.

If an analysis is made for the negative circular component of the alternating field it will be apparent that there is no net transfer of energy from the rotating field to the electron since the torque reverses twice each cycle. It will be readily apparent that for that portion of the magnetically biased gyromagnetic material which is displaced from the center line near one side of the wave guide the positive circularly polarized component will predominate whereas in that portion of the gyromagnetic material on the opposite side of the center line the negatively circular polarized component will dominate to provide directional characteristics. On the other hand, for that portion of the biased gyromagnetic material on the center line, or adjacent the center line, the positive and negative circularly polarized components will be substantially equal and therefore the gyromagnetic microwave device will have reciprocal characteristics.

It is not known how the gyromagnetic mechanism outlined above effects the present invention although it is believed that the gyromagnetic properties are responsible for the apparent opacity of the gyromagnetic material arranged in the microwave guide when it is subjected to a magnetic flux intense enough to approach the saturated condition but not sufficient enough to produce the gyromagnetic resonant condition. Since the device of the present invention is frequency sensitive, that is, its change from transparent to opaque characteristics over a narrow band of frequencies depends upon the dimensions of the gyromagnetic material, it presents the appearance of a resonant condition but this should not be confused with the absorptive gyromatic resonant condition of the prior devices previously discussed.

In Patent 2,798,205, dated July 2, 1957, issued to C. L. Hogan, there is described a gyromagnetic microwave device in which the microwave permeability of ferromagnetic material is varied by the application of an external magnetic field to a section of wave guide applied parallel to the electric vectors to make the material selectively transparent or reflective to microwave energy of a selected frequency. In that device the material is biased beyond saturation and above the gyroresonant condition. That patent distinguishes from prior devices where it is known to produce variable attenuation by absorption in the material when the material is biased in the vicinity of gyroresonance. That patent does not disclose the use of square loop material and therefore there is no self-latching effect.

The present invention provides a microwave switch for microwave transmission systems utilizing a gyromagnetic element in the form of a ferrite having a square loop magnetization characteristic of dimensions which appear to be a function of the frequency band to which it is opaque and in which there is a novel means for establishing closed path magnetization in a ferrite element of critical volume, the plane of the magnetization of the ferrite element being switched in direction to change from a reflective to a transparent state. As distinguished from the Hogan patent here, the element is biased selectively in either direction to produce the respective "go-signal" and "stop-signal" conditions. The "go-signal" condition corresponds to the transparent state while the "stop-signal" condition is synonymous with opaque, or reflective impedance, state of the ferrite element. The ferrite element will "latch" in its residual magnetization state after magnetization to saturation in either direction. With material having a substantially square loop magnetization curve the residual magnetization state is very near saturation.

The invention itself, however, both as to its organization and method of operation as well as its additional objects and advantages will best be understood from the following description when considered in connection with the accompanying drawing in which:

FIGURE 1 is an isometric view of an illustrative embodiment of a microwave device in accordance with the present invention, with a section broken away; and

FIG. 2 is a modified form of the invention.

The illustrative embodiment of the invention in FIG. 1 comprises a section of microwave guide **10** of rectangular cross section and has suitably secured within its cross section an element of ferrite material **11** which is suitably secured, as by adhesive, between the upper and lower broad side walls of the guide **10**. The dimension of the guide walls **12** and **13** is substantially equal to one half wavelength of the electromagnetic wave energy desired to be propagated through the guide. However, as understood in the art, due to high dielectric loading by the ferrite this dimension may be appropriately reduced. The narrow side walls **14** and **16** are preferably substantially half the dimension of the broad faces for maximum capacity, as is well known in the art. Such a microwave guide of rectangular section will then propagate microwave energy in the dominant TE_{10} mode, wherein the plane of the magnetic field of the electromagnetic wave is parallel to the broad side walls. The invention is also applicable to H-type guide.

In the illustrated embodiment the ferrite element **11** does not extend all the way between the top and bottom broad faces of the guide but instead is interposed between two metal conducting plates **12*a*** and **13*a***, respectively secured to the upper and lower broad faces. However as is well understood in the art, the dimensions of the narrow faces **14** and **16** can be reduced in the event that it is not desired to operate the guide at the maximum capacity and the element **11** may be connected directly to the upper and lower broad faces.

For the purpose of producing internal magnetic flux in closed paths within the ferrite element **11**, a suitable conductor **18** extends through a central transverse opening in the element in which is inserted an insulating bushing **19**. Through conductors **20** and **21**, which may be covered with insulation or are otherwise insulated from the narrow side walls by insulating bushings, one of which is illustrated at **22**. Conductor **18** is connected in a control circuit which includes a source of control signal power, represented symbolically by the battery **23**, switches **24** and **25** and a second switch **26** of the double-pole double-throw type for purposes hereinafter described. The switch **26** has a shorting bar **27** so that when the switch is in the left-hand position the circuit through the conductors **18**, **20** and **21** will be closed when the switch **24** is closed.

In accordance with the discovery of this invention it has been found that a current of sufficient amplitude passed through the transverse conductor **18**, in the ferrite element **11** to magnetize the latter with magnetic flux in paths closed upon themselves in the ferrite, produces a substantially non-absorptive reflective impedance condition in the wave guide for a selected band of frequencies. The direction of flow of current through the conductor **18** is immaterial as far as this reflective impedance is concerned when switch **25** is in one of its closed positions. This is called herein a resonant reflection condition for want of a better term because of the frequency selective characteristics of the reflection. This should not be interpreted as a gyroresonant condition in the ferrite material.

In addition to the transverse conductor **18** through the ferrite body **11**, a longitudinal conductor **31**, extending at right angles to the transverse conductor **18** and insulated therefrom, is adapted to be energized through conductors **32**, **33** and a switch **34** by a second source of control signal energy symbolically represented by the battery **36**. In accordance with the findings of this invention current in either direction through the longitudinal conductor **31** of sufficient magnitude to magnetize the ferrite body **11** in closed circular paths in the ferrite about the conductor **31** and below that necessary to produce gyroresonance will make the ferrite element **11** substantially transparent to microwave energy in the guide and will pass the microwave energy with little attenuation or reflection.

Further, in accordance with the discovery of this invention it has been found that when the two wires **18** and **31** are connected in series so that they are energized by the same current of an amplitude sufficient to produce magnetization in circular paths around the respective conductors, flow of current in one direction will put the ferrite element **11** in a transparent condition while the similar flow of current in the opposite direction will place the element **11** in an opaque or reflective condition. The exact reason for the reflective switch action of this invention is not understood although the prior art is aware of the reciprocal and non-reciprocal phase shifting action that is present when the microwave energy is propagated. Also the absorptive attenuation that accompanies a gyroresonant condition is understood by the art but that has no bearing on the present invention. One possible explanation is offered based on the fact that closed path magnetization in planes transverse to the direction of propagation gives a non-reciprocal characteristic. Closed path magnetization in planes parallel to the propagation gives a reciprocal characteristic. Simultaneous energization by current in one direction gives a resultant closed path magnetization on an inclination of 45° with respect to propagation and energization by current flowing in the opposite direction gives net closed path magnetization inclined in the other direction. One inclination of the closed path magnetization makes the gyromagnetic element opaque and the other inclination makes the element transparent. Means for so connecting the conductors **18** and **31** in series include the double-pole double-throw switch **26**, which in addition to the contacts in the circuit which includes the battery **23** and the conductor **18**, has additional contacts **38** and **39** connected to the conductors **32** and **33**. When the switch **26** is thrown to the right-hand position it will be seen from the circuit diagram that the transverse wire **18** is connected in series with the longitudinally extending wire **31** and when the switch **24** is closed (assuming that switch **34** is open) the two conductors **18** and **31** will be energized from the battery source **23** when switch **25** is in one of its closed positions. As previously mentioned, when current flows in one direction through these two conductors when connected in series circuit the microwave device will be turned on ("go signal" condition) and when current flows in the opposite direction the device will be switched off ("stop-signal" condition). Means for selectively controlling the direction of current flow is provided by the double-pole double-throw switch **25**.

A specific example of a microwave guide switch which successfully operated in the manner described above comprised a cube of ferrite .375 inch on a side. The material was a magnesium manganese ferrite with aluminum substitution. This material is identified as type TT1–105 manufactured by the Trans-Tech, Incorporated, Box 457, Gaithersburg, Maryland. A body of this ferrite material placed in a rectangular wave guide of such dimension as to propagate in the dominant TE_{10} mode electromagnetic wave energy at 5600 megacycles produced the so-called resonant reflective condition when the ferrite body was saturated with a short pulse of 15 amperes.

It should be understood that a cascaded plurality of the above described units, preferably contiguous to each other, may be associated together to produce an increased rejection bandwidth. Such a cascaded arrangement is illustrated in the modified form shown in FIG. 2. In this embodiment a longer wave guide section **50** of rectangular cross section, and similar to wave guide section **10** of FIG. 1 has mounted within its cross section an elongated ferrite element **51**. The length of element **51** corresponds to six ferrite elements of the size of element **11** of FIG. 1.

For the purpose of producing internal magnetic flux in closed paths in the territe, the latter is provided with a plurality of spaced transverse holes **52** through which a conductor **53**, preferably with an insulated cover or otherwise insulated from the element **50** by insulating bushings, is threaded back and forth. The holes **52** are in the center of respective volumes that correspond to an element of the size of element **11**. Therefore they are spaced apart a distance equal to one side of the cubic element **11**. The loops **53***a* are spaced from the element **50** so that magnetic flux encircling them when energized does not interfere with the flux encircling the straight transverse portions in the holes **52**.

The conductor **53** is connected by leads **54** and **56**, extending through the side wall of the guide, in a control circuit including a source of control voltage, represented by the battery **57**, a suitable single pole switch **58** and a double-pole double-throw switch **59**. Switch **59** has a shorting bar **61** so that when the switch is in the left-hand position the circuit through the conductor **53** will be closed when switch **58** is closed, all in a manner similar to that of the first embodiment. Also, as in the previous embodiment, means are provided for connecting conductor **53** in a series control circuit including a longitudinal conductor **62** extending through a central bore in the ferrite element **51**.

To this end, conductor **62** is connected through leads **63** and **64** in a control circuit including a battery **66** and a single pole switch **67**. This control circuit can be energized separately by battery **66** by closing switch **67** or can be energized by battery **57** (when switch **67** is open) when it is connected in series with the conductor **53** when switch **58** is closed and switch **59** is in the right-hand position, in a manner similar to the first embodiment. The operation of this embodiment is substantially identical to that of the first embodiment, except as mentioned above, the rejection frequency band is a multiple, proportional to the ratio of the volume of element **50** to that of element **11**, of the frequency band of the first embodiment of FIG. 1. Through a double-pole double-throw switch **70** the current through the series control circuit can be caused to flow in either direction. The length of the element **50** with appropriately additional transverse portions of conductor **53** can be extended to any practical limit to increase the rejection frequency band. The cross sectional dimensions and the length of the ferrite combined with the number and spacing of the transverse portions of conductor **53**

determine the operating frequency, bandwidth and switching action.

Variations and changes will be apparent to those skilled in the art without departing from the spirit or scope of the invention.

I claim as my invention:

1. Electromagnetic wave apparatus comprising a wave guide structure having at least first and second parallel elongated conductive members of such transverse dimension as to support propagation of electromagnetic wave energy of selected frequency with said electromagnetic wave having a magnetic field pattern forming closed loops parallel with said elongated conductive members, an element of gyromagnetic material having a square loop magnetization curve between said conductive members, means for selectively providing closed loop magnetic flux paths of magnetization in said element in planes parallel to the direction of propagation, and in planes transverse to the direction of propagation, the resulting net closed loop magnetic flux paths lying in a volume symmetrical about an axis inclined with respect to the direction of propagation, the aforesaid structure cooperating so that for one position of the inclined closed loop magnetic flux paths of said element no substantial attenuation or reflection is presented to the propagation of microwave energy through said wave guide structure and the opposite inclination of the net closed loop magnetic flux paths produces non-dissipative high reflective impedance to microwave energy in said wave structure.

2. Microwave guide switch apparatus comprising a section of microwave guide of rectangular cross section of such size as to support electromagnetic wave propagation in the dominant TE_{10} mode, an element of gyromagnetic material having a square loop magnetization curve arranged within said section, and means for simultaneously establishing closed loop magnetic flux paths in said element about one axis transverse to the direction of propagation and about a second axis parallel to the direction of propagation.

3. Microwave guide switch apparatus comprising a section of microwave guide of rectangular cross section of such dimension as to support electromagnetic wave propagation of a selected frequency in the TE_{10} mode, an element of gyromagnetic material having a square loop magnetization curve arranged within said section, means for inducing simultaneously in said element closed loop magnetic flux path magnetization in planes disposed at right angles to each other, said element being cubical in shape, the simultaneous magnetization in closed loop magnetic flux paths in planes at right angles to each other produces a net closed loop magnetic flux path magnetization in a portion of said element symmetrically disposed about an axis at substantially 45° with respect to the direction of propagation, the aforesaid structure cooperating so that the net magnetization of one inclination causes said gyromagnetic element to be substantially transparent to microwave energy in said guide and magnetization of the opposite inclination causes said element to be substantially opaque to microwave energy in said guide.

4. Microwave guide switch apparatus comprising a section of microwave guide of rectangular cross section of such dimension as to support microwave energy of a selected frequency band, an element of gyromagnetic material having a square loop magnetization curve arranged within said section, and means wholly within said section for establishing closed loop magnetic flux paths in said element in planes transverse to the direction of propagation and in planes parallel to the direction of propagation, said gyromagnetic element being cubical in shape and of such dimension that when it is simultaneously magnetized by closed loop magnetic flux path magnetization of substantially the same magnetizing force in both the transverse and longitudinal vertical planes said cubical element will become substantially opaque to microwave energy in said guide for one direction of magnetization and will become substantially transparent for the opposite direction of respective magnetizations.

5. Microwave guide switch apparatus comprising a section of microwave guide of such shape and dimension as to support microwave propagation of a selected frequency band in a dominant mode having a concentrated electric field symmetrically disposed along its longitudinal axis, an element of gyromagnetic material having a square loop magnetization curve arranged within said section, a conductor extending transversely through the center of said gyromagnetic element, as viewed along a direction transverse to the axis of propagation, a second conductor extending longitudinally through the center of said element as viewed along a direction parallel to the axis of propagation, and means for energizing said conductors to produce closed loop path magnetization in said element around each of said conductors.

6. A microwave switch comprising a section of microwave structure having at least first and second parallel elongated conductive members of such transverse dimension as to support propagation of electromagnetic wave energy of selected frequency in the TE_{10} mode with the electromagnetic wave having a magnetic field pattern forming closed loops parallel with said elongated conductive members, an element of gyromagnetic material having a square loop magnetization curve extending longitudinally of said wave guide and constituting a plurality of contiguous elements extending longitudinally of said structure, said element having a substantially square cross section and being of a length substantially equal to a multiple of the cross sectional dimension to optimize performance at a selected frequency band, said element having a pluarity of holes extending transversely through said element and spaced longitudinally of said wave guide structure a distance substantially equal to the cross sectional dimension of said element, said element also having a hole extending longitudinally thereof substantially in the center of said element when viewed in a direction parallel to the axis of propagation, a first conductor having a plurality of portions threaded back and forth through said transverse holes, a second conductor in said longitudinally extending hole, and means for selectively energizing said conductors to establish closed loop path magnetization in said element about said conductors.

7. Electromagnetic wave apparatus comprising a wave guide structure of such shape and dimension as to support propagation of microwave energy in a selected frequency band in a dominant mode having a concentrated electric field symmetrically disposed along its longitudinal axis, an element of gyromagnetic material having a square loop magnetization curve arranged within said wave guide structure, a first conductor extending transversely through said gyromagnetic element in a direction transverse to the direction of propagation, a second conductor extending longitudinally through said element in a direction parallel to the direction of propagation and means for selectively energizing each conductor separately, energization of one winding at a value below that necessary to produce gyroresonance producing no substantial attenuation or reflection, and energization of the other winding at a value below that necessary to produce gyroresonance producing substantially non-dissipative substantially total reflection of said microwave energy.

8. The combination as set forth in claim 7 wherein energization of said transverse conductor at a value below that necessary for gyroresonance produces substantially non-dissipative substantially total reflection and energization of said longitudinal conductor at a valve below that necessary for gyroresonance produces substantially no attenuation or reflection of said microwave energy.

9. Electromagnetic wave apparatus comprising a wave guide structure of such configuration and dimension as to support propagation of microwave energy in a selected frequency band in a dominant mode having a concen-

trated electric field symmetrically disposed along the longitudinal axis of said wave guide structure, an element of gyromagnetic material having a square loop magnetization curve arranged within said wave guide structure, a conductor extending transversely through said gyromagnetic element in a direction transverse to the direction of propagation, a second conductor extending longitudinally through said element in a direction parallel to the direction of propagation, means for connecting said conductors in series and means for energizing said conductors to produce closed loop path magnetization in said element around each of said conductors whereby current in one direction at a value below that necessary to produce gyroresonance through said conductors in series causes substantially total non-attenuative reflection of said microwave energy and energization of said conductors in the

opposite direction at a value below that necessary to produce gyroresonance produces substantially non-dissipative high reflective impedance to said microwave energy in said wave guide structure.

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