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NONRECIPROCAL WAVE TRANSMISSION

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FIG. 1

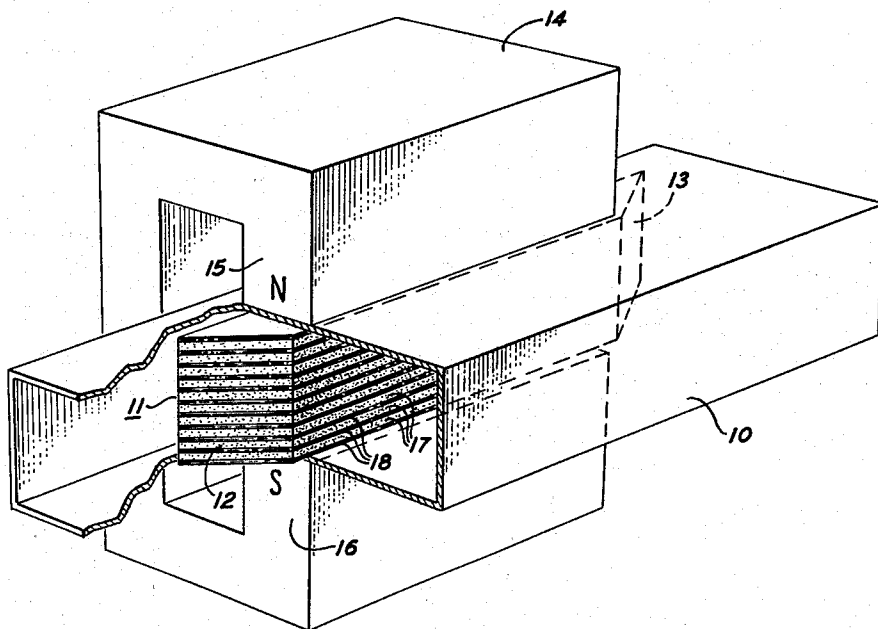


FIG. 2

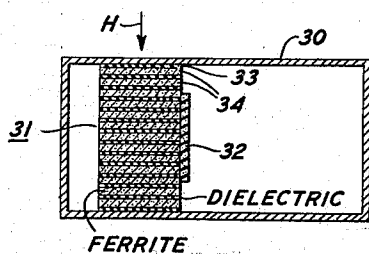
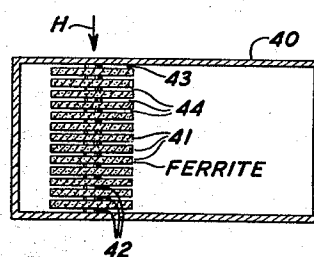


FIG. 3



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1

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1 Claim. (Cl. 333—31)

This invention relates to electromagnetic wave guide transmission systems and, more particularly, to improved gyromagnetic components for use in such systems.

It has been proposed to place an element of gyromagnetic material, such as ferrite, in the path of electromagnetic wave energy propagating within a rectangular wave guide. If this element is located asymmetrically with respect to the field pattern of the wave energy and is biased by a magnetic field at right angles to the direction of propagation, nonreciprocal transmission effects can be observed. These effects have been explained by the electron spin coupling theory whereby the individual spinning electrons within the magnetically polarized gyromagnetic material and the circularly polarized components of the magnetic field of the wave interact with one another, causing the propagated wave to encounter a different effective permeability in the ferrite material for opposite directions of propagation. For one direction of propagation, this effective permeability is greater than unity and for the other direction it is less than unity. Wave energy will therefore experience a nonreciprocal phase shift in traveling through the ferrite material. Furthermore, the higher effective permeability for one direction of propagation causes the field pattern of the wave to tend to concentrate in the ferrite material for that direction of propagation. For the opposite direction of propagation, the effective permeability is less than unity and the field pattern tends to concentrate in the region outside the ferrite element. This nonreciprocal "field displacement" can be taken advantage of by suitable placement of resistive material or coupling apertures to form useful nonreciprocal circuit components such as isolators and circulators. Similarly, symmetrical placement of the gyromagnetic element in the wave guide produces reciprocal effects which may also be useful in other applications.

The operation of gyromagnetic devices other than those utilizing gyromagnetic resonance is based upon the effective permeability presented to propagated waves. Since resonant absorption represents a loss for these applications, these devices operate in a range of applied magnetic fields between zero and that required to initiate the resonant phenomenon. In particular, the region of magnetic saturation is of primary importance since the effective permeability is greatest in this region. Unfortunately, for many materials resonance absorption begins almost as soon as saturation is achieved, leaving a small operating range in this region, or none at all. Furthermore, gyromagnetic materials, such as ferrites, have relatively high dielectric constants. Since the dielectric constant of the surrounding medium is usually unity or very close to unity, a problem arises in matching the impedance of the ferrite element to that of the unloaded wave guide. In addition, the electrical width of the ferrite element becomes a substantial portion of the guide width, and the danger of forming higher order modes of wave energy becomes increasingly great.

It is an object of the present invention to extend the

2

efficient operating range of gyromagnetic devices for use in reciprocal and nonreciprocal transmission systems.

It is a more specific object of the invention to produce large reciprocal and nonreciprocal effects in gyromagnetic materials biased far below gyromagnetic resonance.

It is another object of the invention to reduce the effective dielectric constant of gyromagnetic elements for use in reciprocal and nonreciprocal transmission systems.

It has been recognized that magnetic saturation of gyromagnetic materials occurs when the strength of the externally applied field is sufficient to align substantially all of the unpaired electron spins within the material. Gyromagnetic resonance, on the other hand, occurs when the effective internal field within the gyromagnetic material reaches a certain value. This effective internal field is dependent upon not only the applied field, but also upon demagnetizing factors acting both in the direction of the applied field and at right angles thereto. These demagnetizing factors are functions of the shape of the gyromagnetic body and result from the formation of magnetic poles on the surfaces of the body. Strong magnetic poles created at close proximity to one another give rise to a magnetic field which opposes the externally applied field, and therefore is termed a demagnetizing field.

In accordance with the present invention, gyromagnetic elements are provided in such shapes and located in such orientations that the demagnetizing factors all tend to separate the applied field value at which magnetic saturation occurs from the value at which gyromagnetic resonant absorption begins, thereby increasing the efficient operating range of reciprocal and nonreciprocal gyromagnetic elements. Such a gyromagnetic element for use in wave guide components is constructed of a series of flat plates of gyromagnetic material arranged parallel to each other and perpendicular to the direction of the applied magnetic field. The demagnetizing factors in the direction aligned with the applied field are large because of the close proximity of the surface poles formed in this direction, thereby reducing the internal field. Furthermore, the demagnetizing fields which are formed normal to the direction of the applied field are made negligible by separating the surfaces on which the normal poles are formed by a large distance, thereby reducing the additive effect of these factors on the internal field. Both of these effects tend to increase the value of external field required to achieve gyromagnetic resonance, and therefore separate the values of external field at which saturation and resonance occur. A large range of values of external fields is thereby provided between that at which saturation occurs and that at which the resonant absorption phenomena begins and a still larger range is provided between zero field and the field at which resonance begins. Thin sheets of nonmagnetic dielectric material are interposed between adjacent plates of gyromagnetic material to make possible the formation of magnetic poles at each of the broad surfaces of the gyromagnetic plates.

One obvious advantage of the laminated ferrite structure described is the increased operating range of applied fields made possible by the shifting of the gyromagnetic resonance value of the applied field. Another advantage resides in the lower effective dielectric constant of the laminated structure as compared to a solid homogeneous gyromagnetic element. The high dielectric constant of gyromagnetic materials creates a large capacitance between the opposite faces of the wave guide wall in the regions of a homogeneous element. The effect of interposing sheets of material having a lower dielectric constant between layers of gyromagnetic material is to create a number of capacitances in series between these walls. The total capacitance is then much less than the higher capacitance due to the ferrite material itself, and the effective dielectric constant of the

combination is much less than the dielectric constant of the ferrite material. This lower effective dielectric constant makes impedance matching less difficult and reduces the danger of higher moding in the ferrite region.

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

In the drawings:

Fig. 1 is a perspective view of one principal embodiment of the invention showing a laminated gyromagnetic element in a phase shifter in accordance with the principles of the invention;

Fig. 2 is a cross-sectional view of another embodiment of the invention showing a field displacement isolator in accordance with the principles of the invention; and

Fig. 3 is a cross-sectional view of an alternate embodiment of the invention showing a phase shifter in accordance with the invention.

Referring more particularly to Fig. 1, there is shown a first illustrative embodiment of the invention comprising a section of rectangular wave guide 10 having a wider internal dimension greater than a half-wavelength of the lowest frequency of wave energy to be transmitted therein and a narrower dimension substantially equal to one-half of the wider dimension. Located within guide 10 is a laminated element 11 extending between the wider walls thereof and positioned asymmetrically between the narrower walls of guide 10. Element 11 comprises a gyromagnetic medium having a composite structure to be more fully described hereafter and exhibiting gyromagnetic properties at microwave frequencies. Element 11 extends along the length of guide 10 for a distance of several wavelengths of the wave energy in guide 10 and has a width equal to some fraction of the wider dimension of guide 10. The ends of element 11 are each provided with a wedge-like taper, tapers 12 and 13, to prevent undue reflections of wave energy therefrom.

Element 11 is magnetically biased or polarized by a steady magnetic field perpendicular to the wider walls of guide 10. As shown in Fig. 1, this field may be supplied by a permanent magnet 14 having two pole-pieces 15 and 16 resting on opposite wider walls of guide 10 in the region of element 11. Magnet 14 is so magnetized that a north magnetic pole N is formed at pole-piece 15 and a south magnetic pole S is formed at pole-piece 16. A steady magnetic field therefore exists in the region of element 11 between pole-pieces 15 and 16 having a direction from pole-piece 15 to pole-piece 16. This field may be supplied by any other suitable means, for example, by an electrical solenoid wound on a magnetic core similar to magnet 14, by an electrical solenoid without a magnetic core, or by permanently magnetizing element 11 itself. In the event that an electrical solenoid is used, electrically variable phase shift effects can be obtained by varying the coil current in the solenoid.

In accordance with the present invention, element 11 is composed of a gyromagnetic medium having a composite structure such that the range of field strengths between that required to magnetically saturate element 11 and that required to produce gyromagnetic resonance is relatively large. In Fig. 1, element 11 comprises a plurality of thin rectangular shaped plates 17 of gyromagnetic material arranged with the broader faces thereof parallel to each other and to the wider walls of guide 10. Plates 17 are separated from each other and from the wider walls of guide 10 by thin sheets 18 of dielectric material having a dielectric constant substantially less than the dielectric constant of plates 17. Sheets 18 may, for example, be composed of polystyrene, polyethylene, or polyfoam. It should be noted that,

in the orientation indicated, plates 17 have one narrow dimension parallel to the direction of the applied field and two broader dimensions perpendicular to the direction of this field.

Plates 17 of element 11 in Fig. 1 are composed of a gyromagnetic material which may, for example, be any of the several ferromagnetic materials combined in a spinel structure. Specifically, they may comprise an iron oxide combined with a small quantity of one or more metallic materials, such as nickel, magnesium, zinc, or other similar material in which the metals combine with the iron oxide in a spinel structure. Such materials are known as ferromagnetic spinels or ferrites and are more completely described in the copending application of C. L. Hogan Serial No. 252,432, filed October 22, 1951, now United States Patent 2,748,353, issued May 29, 1956.

The gyromagnetic properties of ferrites may be best understood by recognizing that ferromagnetic materials contain unpaired electron spins which tend to align their axes of spin with an applied magnetic field. Displacement from such alignment causes these spins and their associated moments to precess gyroscopically about the line of the applied field. These spins tend to precess in one angular sense but to resist rotation in the opposite angular sense. The high frequency alternating magnetic field of an electro-magnetic wave propagating through the ferrite material provides a spin-axis displacement from alignment with the applied field. Furthermore, the circularly polarized components of magnetic flux associated with certain portions of the propagating wave can interact with these precessing electron spins. When the circularly polarized components of magnetic flux of the wave are rotating in the same angular sense as the preferred precessional direction of the electron spins, the wave will encounter an effective permeability less than unity, when the circularly polarized components of magnetic flux of the wave are rotating in the opposite angular direction, however, the wave will encounter an effective permeability greater than unity. This results in difference in effective permeability experienced for oppositely polarized components and, since the direction of polarization reverses with the direction of propagation, for oppositely directed waves.

The effect of making plates 17 of element 11 in Fig. 1 of such a shape can be seen by considering the magnetic effects occurring within the ferrite material. As the applied field starts to line up the unpaired electron spins within the ferrite material, this alignment tends to create magnetic poles on the surfaces of the ferrite material making up each of plates 17. These induced surface poles are magnetically opposite to the poles of magnet 14 closest to them, a south pole being created on each surface facing pole-piece 15 and a north pole on each surface facing pole-piece 16. These poles create their own magnetic fields which are directed oppositely to the field produced by magnet 14 and are therefore called demagnetizing fields. If the surfaces on which these poles are produced are separated by a sufficient length of ferrite material, the demagnetizing fields generated are small enough to be negligible. Such is the case when the ferrite elements extend unbrokenly between the walls of a wave guide. Plates 17, however, have an extremely small dimension in this direction and therefore the demagnetizing field is considerably higher. Since this demagnetizing field opposes the externally applied field, the resultant internal field in the ferrite material is substantially less than the applied field.

Another magnetic effect taking place within the ferrite material is the formation of surface poles normal to the direction of the externally applied field. If a sufficient number of electron spins have a component of their magnetic moments lying in a direction normal to the applied field, magnetic poles are formed on the surfaces of the ferrite plates 17 which are parallel to the applied field. These poles will create demagnetizing fields

5

which exert a torque on the electron spins normal to the applied field in such a phase relation that it adds to the precessional torque produced by the internal magnetic field. This added torque tends to reduce the externally applied field necessary to produce resonance, thereby reducing the range of field strengths available below resonance. In the ferrite elements heretofore used, the distance between opposite faces parallel to the applied field was made small to prevent adverse moding effects, thus making this normal demagnetizing effect large and reducing the efficient operating range. Plates 17, however, have a relatively large dimension normal to the line of the applied field and therefore the normal demagnetizing factors are small or negligible. The range of external field values below gyromagnetic resonance is thereby further increased since a larger value of external field is required to produce resonance at a given frequency.

It will be noted that the total effect of the shape of plates 17 is to reduce the internal effective field within the gyromagnetic material for any value of externally applied field. It can be seen that while the variation in effective permeability depends primarily upon the degree of magnetization of the ferrite material, the gyromagnetic resonance frequency depends upon the effective internal field. Therefore, by decreasing the effect of the externally applied field on the effective internal field, the range of applied field values between magnetic saturation and the beginning of gyromagnetic resonance absorption is extended. Since optimum nonreciprocal permeabilities occur in this region, the range of efficient nonreciprocal effects is substantially extended. Furthermore, the region up to saturation, where the rate of change of phase shift with applied field is greatest, is also extended, providing a large operating range for variable phase shift devices.

Making sheets 18 of dielectric material having a low dielectric constant gives the added advantage of reducing the effective dielectric constant of element 11 in Fig. 1. Since the laminations of element 11 are perpendicular to the electric vector in guide 10, the electric field intensity in sheets 18 is higher than that in plates 17. This causes the total effective dielectric constant to be closer in value to that of the dielectric material of sheets 18 than that of plates 17. This lower dielectric constant makes impedance matching to the ferrite region less difficult than if homogeneous ferrite were used, such materials having a relative dielectric constant on the order of ten to twenty. Furthermore, the electrical width of element 11 is much less than that of a comparable homogeneous ferrite element and therefore the danger of higher order modes of wave energy forming is considerably less.

The application of a magnetic field to element 11 of Fig. 1 causes the effective permeability of the region of element 11 to be different for opposite directions of propagation of wave energy in guide 10. This results in a nonreciprocal phase shift, the phase shift experienced by a wave passing through in one direction being different from the phase shift experienced by a wave traveling in the opposite direction. This difference in phase shift is proportional to the length of element 11 in guide 10. When this length is adjusted so that the difference in phase shift is 180 degrees, the resulting device is commonly termed a "gyrator."

The embodiment shown in Fig. 1 is described as a nonreciprocal component which is capable of introducing a different amount of phase shift into wave energy propagating in opposite directions therethrough. It is also possible, however, to adapt this embodiment to reciprocal phase shift operation. Placement of gyromagnetic element 11 symmetrically at the center of guide 10 results in a reciprocal phase shifting component which is controlled by the magnitude of the applied field. The reason for the reciprocal action in this component is the fact that at the center of guide 10 the circularly polarized components of magnetic flux of the propagating wave are equal for opposite directions of propagation. That is, for one direc-

6

tion of propagation one side of centered element 11 produces the same phase shift as the other side of centered element 11 produces for the opposite direction of propagation. It can therefore be seen that the structure shown in Fig. 1 is equally well adapted for reciprocal phase shift and nonreciprocal operation.

In Fig. 2 is shown a cross-sectional view of a field displacement isolator comprising a section of rectangular wave guide 30 in which a laminated element 31 is positioned asymmetrically between the narrower walls thereof and extends completely between the wider walls. Element 31 comprises a gyromagnetic medium substantially identical to that of element 11 in Fig. 1, having a plurality of plates of gyromagnetic material, such as plate 34, parallel to the wider walls of guide 30, each of which is separated from adjacent ones and from the walls of guide 30 by sheets of dielectric material such as sheet 33. Element 31 is biased by a steady magnetic field represented by the vector "H" which may, for example, be produced by a permanent magnet such as magnet 14 in Fig. 1. Located adjacent to element 31 and extending longitudinally within guide 30 is a member 32 of resistive material which may, for example, be carbon loaded polystyrene.

As stated above, the effective permeability of element 13 is less than unity for one direction of propagation in guide 30 and greater than unity for the other direction. Element 31 may be so proportioned and so located that an electric field null is produced at the wall of element 31 at which member 32 is located for the direction of propagation for which the wave encounters an effective permeability of less than unity. The field pattern for this direction of propagation tends to crowd away from element 31 and no electric field vector exists in member 32. For the opposite direction of propagation, however, the permeability of element 31 is greater than unity and the field pattern tends to crowd into element 31. An electric field null can no longer exist in the region of member 32 and a substantial electric vector will therefore exist there. This electric field will induce a current in member 32 which will be quickly dissipated due to the resistive properties of element 32. This dissipation represents a loss of energy to the wave, the wave being substantially attenuated. A device which nonreciprocally attenuates electromagnetic wave energy is commonly termed an "isolator" and has many significant uses, among them being to prevent reflections from a succeeding circuit element from reaching a prior element.

In Fig. 3 is shown a cross-sectional view of an alternative arrangement for providing nonreciprocal phase shift of electromagnetic wave energy. This embodiment comprises a section of rectangular wave guide 40 having positioned therein a plurality of plates, such as plate 41, of gyromagnetic material arranged in a spaced parallel array. The plates of gyromagnetic material are maintained parallel to each other and to the wider walls of guide 40 by dielectric spacers 42 interposed between adjacent plates and between the outer plates and the walls of guide 10. This arrangement leaves an air gap, such as gaps 43 and 44, between adjacent plates. These air gaps act as a layer of dielectric material between adjacent plates in much the same manner as sheets 18 in Fig. 1. These gyromagnetic plates are biased by a magnetic field represented by vector "H" in a direction perpendicular to the wider walls of guide 40 and to the broader faces of the plates.

The embodiment pictured in Fig. 3 operates in exactly the same manner as that shown in Fig. 1. The added advantage of this arrangement is the fact that air has a dielectric constant of unity while solid dielectric materials have dielectric constants which are greater than unity. This lower dielectric constant of the dielectric layers reduces the overall effective dielectric constant of the array, enhancing the impedance matching characteristics and higher moding properties of the structure. Furthermore, the gyromagnetic medium may be varied in size to fit any size wave guide merely by adding plates of gyro-

magnetic material and making spacers 42 of the correct height.

In all of the above-described embodiments of the invention as shown in Figs. 1 through 3, it is apparent that optimum effects can be obtained where the ratio of width to thickness of the ferrite elements is maximum. The larger this ratio is, the greater is the effect of the demagnetizing fields acting along the line of the applied field and the smaller is the effect of normal demagnetizing fields. While it is desirable to have this ratio as large as possible, a ratio of ten to one has been found to be satisfactory as a sufficient approximation of the optimum condition. The number and size of the ferrite lamina are chosen so as to provide the proper distribution of gyromagnetic material in the cross section. The size of the dielectric lamina determines the effective dielectric constant of the laminated element, but the size of these lamina need be only large enough to magnetically separate the ferrite plates and allow the formation of surface poles on their broad faces.

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

What is claimed is:

A nonreciprocal wave guiding structure for the transmission of electromagnetic wave energy at a given frequency comprising a composite laminated medium having a plurality of thin parallel spacers of low-loss dielectric material interposed among a multiplicity of magnetically polarizable plates of material capable of exhibiting gyromagnetic effects at the frequency of said wave energy, means for applying a magnetic field to said medium in a direction perpendicular to the wider surfaces of said plates for establishing a distribution of surface poles over the wider surfaces and the narrower surfaces of said plates, said field having an amplitude less than that to produce gyromagnetic resonance in said material at said given frequency, said dielectric material being nonmagnetic to

allow the formation of said surface poles upon the broad surfaces of each of said magnetically polarizable plates, the surface poles on said wider surfaces and the distance therebetween defining a demagnetizing field parallel to the direction of said applied field, the surface poles on said narrower surfaces and the distance therebetween defining a demagnetizing field perpendicular to said applied field, said plates having said wider dimensions at least ten times said narrower dimensions to substantially decrease the demagnetizing field normal to said applied field relative to the demagnetizing field parallel to said applied field.

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