

Nov. 21, 1961

H. SEIDEL
MICROWAVE ISOLATOR

3,010,084

Filed Oct. 4, 1960

2 Sheets-Sheet 1

FIG. 1

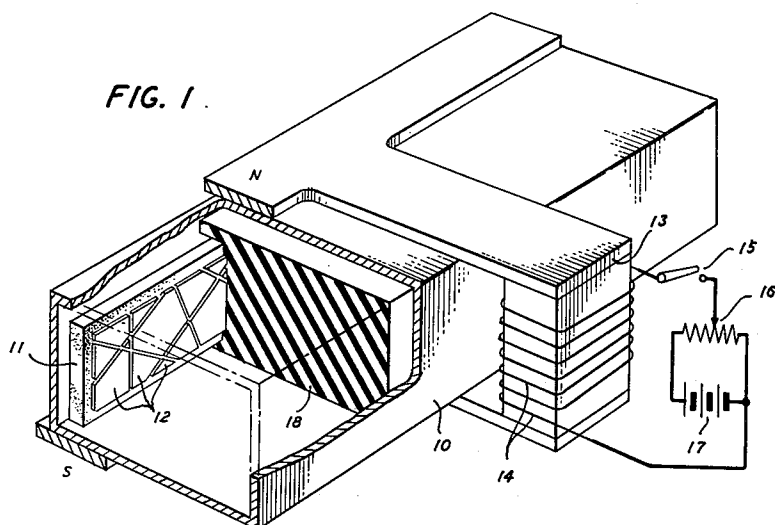


FIG. 2

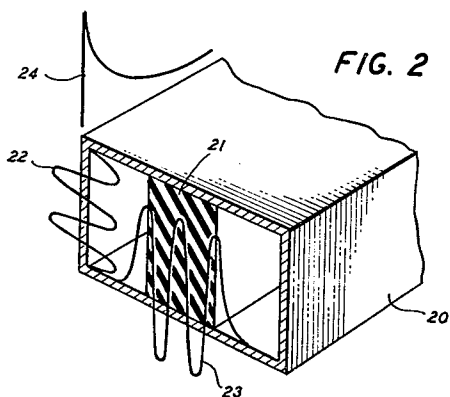


FIG. 1A

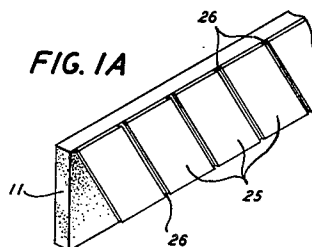


FIG. 3

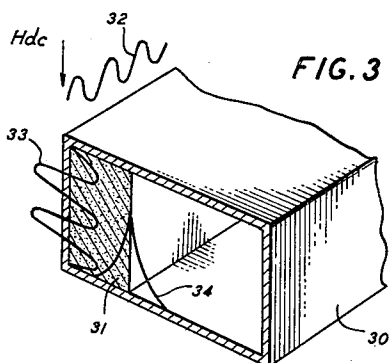
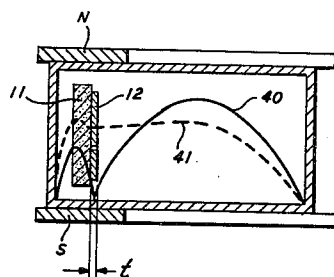


FIG. 4



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FIG. 5

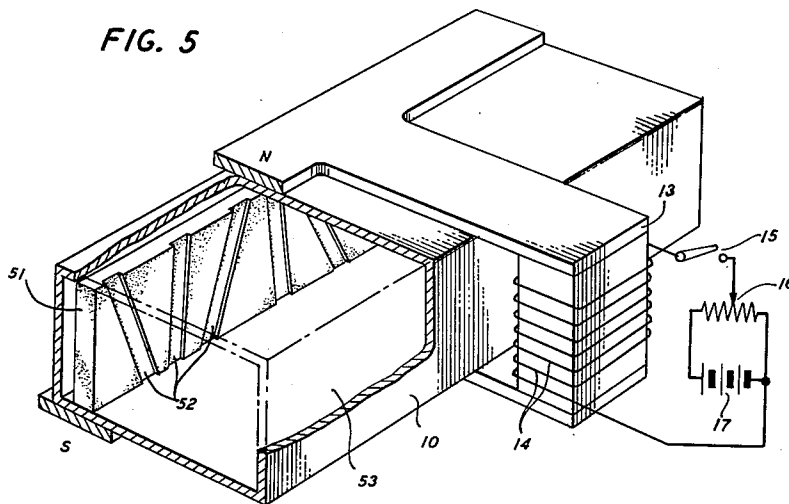


FIG. 5A

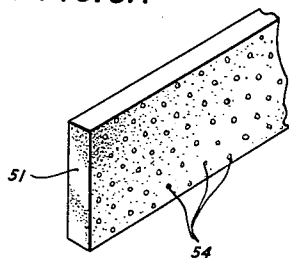
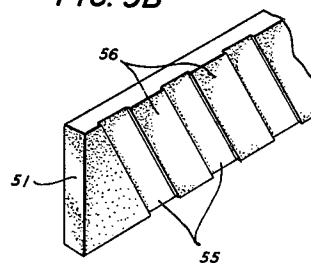


FIG. 5B



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3,010,084

MICROWAVE ISOLATOR

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Filed Oct. 4, 1960, Ser. No. 60,439

10 Claims. (Cl. 333-24)

This invention relates to electromagnetic wave transmission systems and more particularly to transmission structures having nonreciprocal attenuating properties for use in such systems.

This application is a continuation-in-part of my copending applications Serial No. 774,496 and Serial No. 774,548, both of which were filed on November 17, 1958.

The use of materials having gyromagnetic properties to obtain both reciprocal and nonreciprocal effects in microwave transmission circuits is widely known and has found numerous and varied applications in propagation structures of both the waveguide and the transmission line types. A résumé of early work done in this field is contained in an article entitled "The Behavior and Application of Ferrites in the Microwave Region" by A. G. Fox, S. E. Miller and M. T. Weiss, Bell System Technical Journal, January 1955, pages 5-103. The Proceedings of the I.R.E., Vol. 44, No. 10, October 1956 is devoted in major part to a more recent survey of the uses and characteristics of ferrites.

Included among the new transmission components that have found widespread use in the microwave art is the so-called "isolator." The isolator may be defined as a circuit element which is transparent to electromagnetic waves propagating therethrough in one direction, designated the forward direction, whereas electromagnetic waves propagating in the opposite, or reverse, direction are attenuated by the isolator to the extent required by the system.

Among the isolators described in the above-mentioned article by Fox, Miller and Weiss is the so-called "field displacement" isolator. In accordance with the simple theory of the prior art field displacement isolator, a null in the electric field configuration is made to exist at an interface of a gyromagnetic element for the forward direction of propagation while a finite, and preferably large, electric field is caused to exist at that face for the reverse direction of propagation. Resistive material for producing loss in the reverse direction is placed upon this face in the null field region with the effect that substantially no attenuation results for a wave propagated in the forward direction, whereas substantial attenuation is produced in the reverse direction by virtue of the large electric field existing in the region of the dissipative material. However, as is well known, the power handling capability of this class of isolator is unduly limited by the restricted volume and correspondingly small heat dissipating capabilities of the thin film of lossy material.

It is therefore an object of this invention to increase the power handling capabilities of field displacement isolators.

Applicant has recognized that in the presence of gyromagnetic materials, the waveguide modes differ radically in almost every essential detail from the propagating modes normally associated with the conventional unloaded waveguide. It is now proposed to utilize these different, or so-called, "anomalous modes" to produce new and useful results. In particular, it is proposed to utilize that certain class of higher order modes for which the energy tends to concentrate about an interface or boundary of the gyromagnetic medium. This concentration about the boundary produces extremely large radio frequency magnetic field densities in a relatively small portion of the gyromagnetic materials. Within this region

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of the material there is induced, by this class of modes, highly turbulent electron spin systems having extreme variations in the alignment of the magnetization vectors associated with such spin systems. In this nonuniformly induced state of alignment of the magnetic spins there is a greater tendency for the material to absorb radio frequency energy, resulting in what may be referred to as a "self-loss, nonresonant attenuator." It is "self-loss" in the sense that power absorption takes place in the gyromagnetic medium itself rather than in some external lossy material, and it is "nonresonant" in that it operates at a direct-current magnetic biasing field intensity far below that required to induce the usual resonance conditions. This mode of operation is in marked contrast to the arrangement of the spin systems as they exist in the usual resonance attenuators wherein substantially all the magnetization vectors are aligned parallel to the direct-current biasing field.

While it is recognized that imperfections in any practical transmission system will tend to induce higher order modes of the type herein considered, the prior art has arduously sought to minimize this tendency by appropriately shaping and proportioning the gyromagnetic materials. Attenuation of microwave energy has been achieved by either using external lossy materials in association with the gyromagnetic material or by resonantly biasing the gyromagnetic material itself. By contrast, it is the purpose of this invention to produce maximum disruption of the normal propagating modes by inserting essentially reactive discontinuities in the waveguide path in the region of the gyromagnetic material and thereby to convert substantially all of the wave energy to higher order mode energy. These higher order modes, being bound very tightly as surface waves to the interface of the gyromagnetic material, are then highly attenuated due to the very inefficient use of said material as a transmission medium. A crude analogy of the operation of an attenuator in accordance with the present invention would be to compare the loss induced in this type of attenuator to that induced in the conventional conduction system when large currents are caused to flow through conductors having extremely small cross-sectional dimensions.

It is therefore a more specific object of this invention to introduce attenuation in electromagnetic wave systems by inducing a high degree of nonuniformity in the electron spin systems of gyromagnetic materials.

It is a further object of this invention to induce such nonuniformity by concentrating, into a restricted region, the radio frequency magnetic fields of the higher order turbulent modes associated with such materials.

It is also an object of this invention to use scattering techniques to couple wave energy between modes of propagation having different propagating characteristics.

In accordance with the broad principles of the invention, the intensity and distribution of the higher order turbulent modes, characteristic of the propagating modes in gyromagnetic media, are greatly enhanced by means of scattering elements longitudinally distributed along the gyromagnetic medium. The transmission path and the gyromagnetic material are so shaped and oriented with respect to each other so as to minimize the effect of the scattering elements for one direction of propagation and to enhance it for propagation in the reverse direction.

In a preferred embodiment of the invention scattering is induced by means of a substantially lossless distribution of conductively insulated metallic elements disposed along the inner face of an element of gyromagnetic material.

For the direction of wave propagation for which the electric field has a null at the inner face, the metallic elements are ineffective and the propagating wave is completely transmitted. However, for the reverse wave, having a substantial electric field at the inner face, the wave

energy must either be scattered into another system of modes or be reflected. It can be shown from thermodynamic considerations, however, that for a structure that is perfectly transmitting in one direction, the reverse wave cannot be reflected. Consequently, it must be scattered into a system of higher order modes. As has been indicated above, the magnetic fields associated with these modes tend to concentrate at the boundary of the gyromagnetic material, producing a highly non-uniform condition therein, and are absorbed. It is to be noted that this power absorption takes place under a condition of applied static field for which the gyromagnetic element is in an intrinsically low loss, nonresonant, state and that none of the absorption takes place in the metallic elements themselves.

In a second embodiment of the invention, scattering is induced by means of changes in the dielectric constant of the wave path. Such changes can be produced by means of a plurality of indentations distributed along the inner surface of the gyromagnetic material or by the insertion of separate dielectric material along the region of the electric field null.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a perspective view of the present invention employing the field displacement principle and using randomly distributed metallic scattering elements;

FIG. 1A shows a ferrite vane with periodically disposed metallic scattering elements;

FIG. 2 shows, by way of illustration, the field distribution of a dielectric loaded waveguide in a cut-off state;

FIG. 3 shows, by way of illustration, the field distribution in an anisotropic wave transmission path;

FIG. 4 shows, by way of illustration, the variation in the electric field intensity over the cross-section of the waveguide for both directions of propagation;

FIG. 5 is a perspective view of a second embodiment of the invention employing the field displacement principle and using randomly distributed dielectric scattering elements;

FIG. 5A shows an alternate arrangement of random dielectric scattering elements; and

FIG. 5B shows a ferrite vane with periodic scattering means.

In FIG. 1, there is shown an attenuator in accordance with the invention using the field displacement effect to establish nonreciprocal operation. The attenuator comprises a length 10 of bounded electrical transmission line for guiding electromagnetic wave energy which may be a rectangular waveguide of the metallic shield type having a wide internal cross-sectional dimension of at least one-half wavelength of the wave energy to be conducted thereby and a narrow dimension substantially one-half of the wide dimension. So constituted, this waveguide operates in the dominant mode known in the art as the TE_{10} mode, in which the electric lines of force extend from the bottom to the top of the waveguide, perpendicular to the wide guide walls. The intensity of the electric field in the unloaded guide varies sinusoidally along the wide dimension, having a maximum at the center of the guide and being substantially zero at the narrow walls.

Extending longitudinally within guide 10 and transversely offset from the center line thereof is an element 11 of material capable of exhibiting gyromagnetic properties over a range of operating frequencies of interest. The term "gyromagnetic material" is employed here in its accepted sense as designating the class of magnetic polarizable materials having unpaired spin systems involving portions of the atoms thereof that are capable of being aligned by an external magnetic polarizing field and which exhibit a significant precessional motion at a frequency

within the range contemplated by the invention under the combined influence of said polarizing field and an orthogonally directed varying magnetic field component. This precessional motion is characterized as having an angular momentum and a magnetic moment. Typical of such materials are ionized gases, paramagnetic materials and ferromagnetic materials, the latter including the spinels such as magnesium aluminum ferrite, aluminum zinc ferrite and the garnet-like materials such as yttrium iron garnet.

Element 11, as shown, is in the shape of a thin vane or septum of ferrite material positioned to be parallel to the narrow walls of guide 10. Element 11 is biased by a steady magnetic field at right angles to the direction of propagation of the wave energy in guide 10. As illustrated in FIG. 1, this field may be supplied by a single solenoid structure comprising a magnetic core 13 having pole pieces N and S bearing against the top and bottom wide walls, respectively, of guide 10. Turns of wire 14 on core 13 are connected through switch 15 and rheostat 16 to a source of magnetizing current 17. The biasing field, however, may be supplied by an electric solenoid with a magnetic core of other suitable physical design, by a solenoid without a core, by a permanent magnet structure, or element 11 may be permanently magnetized if desired. The vane of ferrite is held in position in guide 10 by means of a holder 18 composed of low dielectric, low-loss material such as, for example, foamed polystyrene. Any other suitable material may be used.

The heart of the present invention, as embodied in the structure of FIG. 1, resides in the plurality of contiguously insulated metallic segments 12 distributed along the height and length of the inner face of element 11.

In applicant's paper entitled "Character of Waveguide Modes in Gyromagnetic Media" published in the Bell System Technical Journal, volume 36, March 1957, pages 409-426, the transmission of wave energy in isotropic and in anisotropic waveguides is considered. In this article it is shown that in the presence of gyromagnetic materials the waveguide modes differ radically in almost every essential detail from the propagating modes normally associated with the conventional unloaded or isotropic waveguide.

When it is stated that the higher order modes of a guide of restricted size are in a cut-off state, it means that there is a longitudinally decaying field associated with the cut-off modes, but that the transverse cross-section of the guide has associated with it waves of an harmonic nature, at least over restricted regions. Such a field distribution is shown in FIG. 2 in which there is shown a waveguide 20 partially filled with dielectric material 21. Here, at least over the dielectric filled section, there are observed transverse harmonic energy distributions. These are represented by vertical variations 22 and horizontal variations 23. The longitudinally decaying field normally associated with the cut-off state is shown by means of curve 24.

In an anisotropic wave transmission path, the wave energy distribution may be inverted. That is, cut-off may be induced with respect to one or both of the transverse dimensions of the path, while retaining the harmonic character of the wave in the longitudinal distribution. In contradistinction to the conventional guide, the energy associated with these higher order modes propagates within the path. This situation is illustrated in FIG. 3 in which there is shown a waveguide 30, partially filled with some gyromagnetic material 31. The vertical harmonic variation is given by curve 33, and the longitudinal harmonic variation, representing a propagating wave, is given by curve 32. The cut-off horizontal transverse distribution is represented by the exponentially decaying wave 34.

There remains, however, one degree of comparison or similarity between the modes of the two differently loaded guides. This similarity resides in the fact that cut-off,

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whenever induced by the higher order mode distribution, becomes progressively sharper the greater the order of the modes present. This relates equally to the horizontal transverse distribution 34 of FIG. 3 irrespective of the fact that it is a transverse rather than a longitudinal distribution. Thus, with increasing mode order, the energy is more tightly bound to the interface of the gyromagnetic material. Since this energy is propagating, the transmission of these higher order modes becomes increasingly inefficient as a consequence of the highly restricted portion of the guide through which the energy is being channeled.

It is the function of the metallic segments 12 to produce the higher order modes of the type discussed and to make possible the interchange of energy between the incident wave mode in the isotropic waveguide which, in the illustrative embodiment is the dominant TE_{10} mode, and the more complex wave modes capable of existing in the anisotropic waveguide. Because of the large differences in phase velocities between the two systems of modes, there tends to be no interaction between them. This stable situation, however, may be altered very effectively by a scattering technique which both modifies the spatial symmetry of the incident wave mode by creating a spectrum of space harmonic modes, and simultaneously provides the coupling means whereby these modes are capable of exchanging energy with the corresponding compatible ferrite modes which propagate at substantially lower transmission velocities.

In a broad-band system, the segments are randomly distributed over the face of the gyromagnetic material as in FIG. 1 and have cross-sectional areas which are also randomly varied both as to size and shape. The random nature of both the distribution and the configuration of the scattering elements is intended to avoid specific space harmonic selection which might create excessive frequency sensitivity. Hence, the discontinuities or interruptions of whatever nature are made aperiodic. On the other hand, in a narrow-band system, the attenuation per unit length of ferrite may be increased by careful design of the discontinuities to favor scattering at the frequency of the wave energy. In the narrow-band situation, the scattering elements, as shown in FIG. 1A, are uniformly distributed to provide periodic interruptions of the incident wave. Thus, in FIG. 1A, conductive segments 25, of equal size and shape are longitudinally distributed along element 11. The segments are physically separated and conductively insulated from each other by the longitudinal intervals 26. The periodic spacing of segments 25 tends to favor the space harmonics associated with a relatively narrow band of frequencies, thus making the attenuator more frequency sensitive than the random arrangement of FIG. 1. In either arrangement, however, the scattering elements operate most efficiently when they themselves are lossless. This requirement creates no conflict since the operation of the isolator does not depend upon dissipation within the metallic segments themselves. Hence, they are preferably made of a low resistivity material, as, for example, those having specific resistivities of the order of one ohm per square or less. To maintain this low resistivity at the higher radio frequencies, it is necessary that the segments have a thickness equal to or greater than the skin-depth thickness for the lowest operating frequency of interest. The maximum thickness of the segments, however, is limited by other considerations that will be explained in greater detail below.

The attenuator, in accordance with the invention, achieves nonreciprocal properties as a consequence of the field displacement effect which results from the presence of the gyromagnetic material in guide 10. Field displacement effects are disclosed and discussed in detail in Patent 2,834,945, issued on May 13, 1958, to S. Weisbaum. Briefly considered, the field displacement effect is a consequence of the opposite sense of the circularly polarized

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magnetic field produced at the gyromagnetic material for oppositely directed propagating energy. This results in a shift of the energy density and the associated electric field to one side of the center line for propagation in one direction and to the other side of the center line for propagation in the opposite direction. This effect is shown in FIG. 4. In this figure, curves 40 and 41 show the approximate variation of the electric component of field intensity along the width of the waveguide in the presence of element 11. For one direction of propagation, a null may be caused to occur at the inner face of the gyromagnetic material. Theoretically, in the absence of an electric component of field intensity, no electromagnetic energy impinges upon the metallic elements 12 and hence they are totally ineffective. For the reverse direction, however, there is a substantial electric field component at the inner face of the gyromagnetic material as shown by curve 41. For this direction of propagation, the metallic elements have a pronounced effect upon the wave energy. The discontinuities in the transmission path presented by these elements must either scatter the wave energy into another system of modes or reflect it. It can be shown from thermodynamic considerations that in a system that is perfectly transmitting in one direction, the reverse directed wave cannot be reflected. Consequently, it must be scattered into another system of transmission modes, as was explained above.

To minimize the tendency for the scattering elements to interfere with the forward traveling wave, the elements are confined to the null region of the electric field distribution as shown by curve 40 in FIG. 4. If the width of the null is arbitrarily defined as the transverse distance t over which the electric field intensity is less than one-tenth the maximum electric field intensity, then the thickness of the scattering elements is made equal to or less than t . In practice, they would be made as small as possibly consistent with the other requirement that they be greater than the skin-depth thickness of the lowest operating frequency of interest.

A convenient way of making the scattering elements has been to cement a strip of metal foil to the surface of the ferrite vane and to score it with a sharp instrument. By varying the number and direction of the scoring, the attenuation of the isolator may be readily varied over a considerable range.

In a second illustrative embodiment of the invention, scattering is produced by means of dielectric discontinuities in the wave path instead of the conductive discontinuities utilized in the embodiment of FIG. 1. Such an arrangement is shown in FIG. 5 in which the gyromagnetic element 11 of FIG. 1 and the metallic elements 12 attached thereto are replaced by gyromagnetic element 51 along which there is distributed a plurality of discontinuities represented by the indentations 52. As illustrated in FIG. 5, these discontinuities are distributed along the height and length of element 52 and would be confined to the null region of the electric field.

Dielectric changes in the wave path result from the intrusion of the surrounding dielectric material 53 (in this embodiment, air) into the indentations 52. Because of the large difference in the dielectric constants of ferrite and air, substantial local changes in the effective dielectric constant of the wave path are established over the region coextensive with at least a portion of the gyromagnetic material. The over-all effect is to create, by means of such indentations, a plurality of dielectric scattering elements along the inner surface of element 51. Obviously, the choice of dielectric material 53 used must be considered in relationship to the type of gyromagnetic material used in order to produce the desired local changes in the dielectric constant of the wave path over the region of interest.

The operation of the isolator of FIG. 5 using dielectric scattering elements is essentially the same as the isolator of FIG. 1. It is the function of the dielectric scattering

elements 52 formed by the discontinuities to produce the higher order modes of the type discussed and to make possible the interchange of energy between the incident wave mode in the isotropic waveguide which, in the illustrative embodiment is the dominant TE₁₀ mode, and the more complex wave modes capable of existing in the anisotropic waveguide.

In a broad-band system, the discontinuities are randomly distributed over the face of the gyromagnetic material, as in FIG. 5, and have cross-sectional areas which are also randomly varied both as to size and shape. The random nature of both the distribution and the configuration of the scattering elements is intended to avoid specific space harmonic selection which might create excessive frequency sensitivity. Hence, the discontinuities or interruptions of whatever nature are made aperiodic.

In FIG. 5 the discontinuities are shown as a series of indentations distributed along the ferrite surface inclined at different angles and of random depths and widths. In FIG. 5A, the discontinuities 54 are randomly distributed over the entire surface of element 51 in the form of indentations as might be produced by sand blasting or the like. In the narrow-band situation, the scattering elements, as shown in FIG. 5B, are preferably uniformly distributed to provide periodic interruptions of the incident wave. Thus, in FIG. 5B, the discontinuities 55 are of equal size and shape and are longitudinally distributed along element 51. The indentations are physically separated from each other by equal longitudinal intervals 56. The periodic spacing of the indentations 55 tends to favor the space harmonics associated with a relatively narrow band of frequencies, thus making the attenuator more frequency sensitive than the random arrangements of FIG. 5 and FIG. 5A. In either arrangement, however, the dielectric scattering elements operate most efficiently when they themselves are lossless. This requirement, as indicated above, is not inconsistent with the operation of the device as an attenuator since such operation does not depend upon dissipation within the dielectric material itself. Hence, the dielectric material is preferably one having a very high resistivity. The thickness of the indentations is limited by the width of the electric field null. Thus, to minimize the tendency for the scattering elements to interfere with the forward traveling wave, the elements are confined to the null region of the electric field distribution as shown by curve 40 in FIG. 4. If the width of the null is arbitrarily defined as the transverse distance t over which the electric field intensity is less than one-tenth the maximum electric field intensity, then the thickness of the scattering elements (i.e., the indentations 52) is made equal to or less than t . In practice, the indentations would be made as large as possible consistent with the maximum tolerable forward loss.

The illustrative embodiments of FIGS. 1 and 5 have been characterized as isolators and, as such, the loss in the reverse direction for each is preferably made as large as possible. This means that substantially all of the incident wave energy is coupled by means of the reactive scattering elements from the incident mode to the higher order ferrite modes of the type hereinbefore described. By suitably fashioning the scattering elements, however, the amount of attenuation can be controlled and less than total attenuation realized. As indicated above, the number and shape of the scattering elements can be varied thereby varying the attenuation. This ability to control the amount of loss arises in one of two ways. For example, the amount of loss produced for a given length of ferrite depends upon the order of the ferrite modes induced. The higher the mode order, the greater is the resulting attenuation per unit length of gyromagnetic material. Thus, by suitably shaping the scattering elements, the energy content of the lower order ferrite modes may be increased in preference to that of the

higher order ferrite modes, thereby producing less loss per given length of ferrite. Conversely, the scattering elements can be proportioned to favor the generation of the higher order ferrite modes in preference to the lower order ferrite modes of the type hereinabove described. per unit length.

The order of the modes generated is, in general, a function of the number of scattering elements per unit of distance in the direction of wave propagation and the abruptness of the change in the propagation characteristics of the wave path produced by the scatterers. That is, the greater the number of discontinuities per unit length, the greater is the energy content of the higher order modes generated. Similarly, the more abrupt the change produced by the discontinuities, the greater is the energy content of the higher order modes. Conversely, fewer scatterers per unit length or more gradual changes will favor the lower order modes.

A second method of controlling the loss produced is to control the amount of energy converted from the incident mode to the higher order modes. Since the proportion of the total energy thus converted is related to the total number of discontinuities presented, the greater the total number of scatterers, the greater is the resultant mode conversion.

In all cases it is 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 these inventions. For example, the null region may be transversely displaced a distance from the inner surfaces of the gyromagnetic material and the reactive scattering elements placed in the region of the null and independently supported there. In such an arrangement the surface of the gyromagnetic material itself is smooth since the scattering mechanism has been disassociated therefrom. In addition, the use of reactive scattering to produce mode conversion for other purposes is clearly indicated. Thus, numerous and other varied 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:

1. In an electromagnetic wave transmission system, means for producing attenuation comprising a section of transmission line adapted for propagating electromagnetic wave energy in respectively opposite directions, an element of gyromagnetic material magnetically biased transverse to the direction of propagation disposed within said section and extending longitudinally therein, and means for scattering substantially all of said wave energy into a system of highly turbulent modes in a region of said section coextensive with at least a portion of said element, said means and said element being in substantial coupling relationship to dissipate within said element the energy associated with said modes for only one direction of propagation.
2. In an electromagnetic wave transmission system, means for producing attenuation comprising a section of transmission line adapted for propagating electromagnetic wave energy in respectively opposite directions, means for applying wave energy to said line in a given mode of wave propagation having a first velocity of propagation, an element of gyromagnetic material magnetically biased transverse to the directions of propagation disposed within said section and extending therein over a given longitudinal interval, said element as disposed within said interval being supportive of a class of higher order modes of wave propagation having propagation velocities substantially different than said first velocity of propagation, means for coupling substantially all of said wave energy from said given mode of wave propagation to said higher order modes of said wave propagation comprising a substantially lossless distribution of electrical discontinuities extending longitudinally along

said element, said discontinuities and said element being in coupling relationship to dissipate within said element the energy associated with said higher order modes for only one direction of propagation.

3. The combination according to claim 2 wherein said electrical discontinuities comprise a plurality of conductively insulated metallic segments of random size and shape.

4. The combination according to claim 2 wherein said electrical discontinuities comprise a plurality of conductively insulated metallic segments of uniform size and shape.

5. The combination according to claim 2 wherein said electrical discontinuities comprise a plurality of irregularities of random size and shape distributed along said element.

6. The combination according to claim 2 wherein said electrical discontinuities comprise a plurality of irregularities of uniform size and shape distributed along said element.

7. In an electromagnetic wave transmission system, means for producing attenuation comprising a conductively bounded rectangular waveguide supportive of electromagnetic wave energy, a vane of magnetically polarized gyromagnetic material having pairs of parallel broad and narrow surfaces located within said guide with the parallel broad surfaces thereof extending parallel to the narrow walls of said guide, said vane being unequally spaced away from said narrow walls to produce a null within said guide along the centermost of said broad surfaces in the electric field intensity of the wave energy propagating in one direction within said guide, and a substantially lossless distribution of conductively insulated metallic elements longitudinally distributed along the length of said vane in the region of said null.

8. The combination according to claim 7 wherein the transverse dimension of said elements in a direction normal to said broad surface is greater than the skin depth for the lowest frequency of interest of said wave energy and less than the width of said null.

9. In an electromagnetic wave transmission system, means for producing attenuation comprising a wave path supportive of electromagnetic wave energy within a frequency range of interest, means comprising an element of magnetically polarized material exhibiting gyromagnetic properties over said frequency range for producing a region of substantial electric field intensity differential in said energy for opposite directions of propagation through said guide, and means for producing a succession of abrupt changes in the dielectric constant of said wave path over a longitudinally extending interval within said region.

10. In an electromagnetic wave transmission system, means for producing mode conversion comprising a section of transmission line, means for applying wave energy to said line in a given mode of wave propagation, an element of magnetically biased gyromagnetic material disposed within said section and extending therein a given longitudinal interval, said element as disposed within said section being supportive of a class of higher order modes of wave propagation substantially different than said given mode, means for coupling a given predetermined proportion of said wave energy from said given mode of wave propagation to said higher order modes of wave propagation comprising a substantially lossless distribution of electrical discontinuities extending longitudinally along said line over a region coextensive with at least a portion of said element.

No references cited.