

July 19, 1960

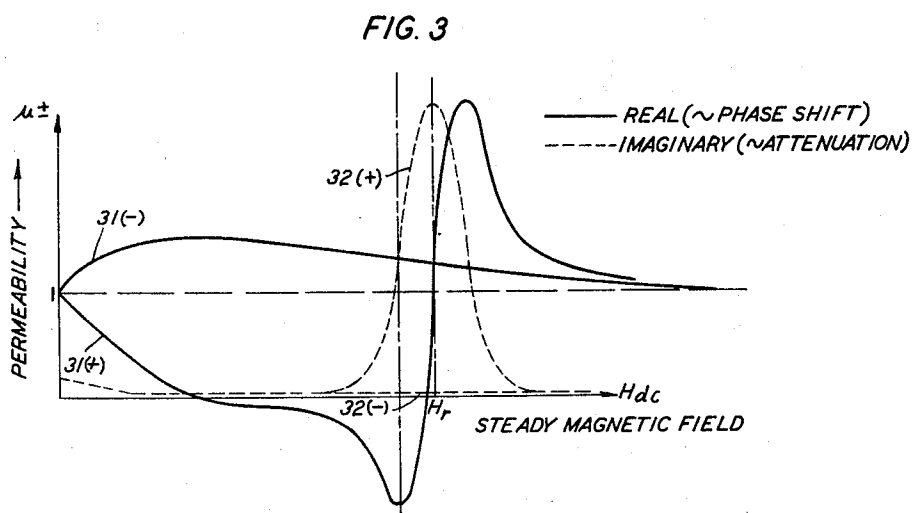
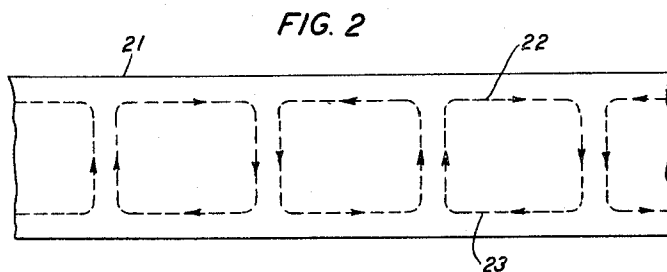
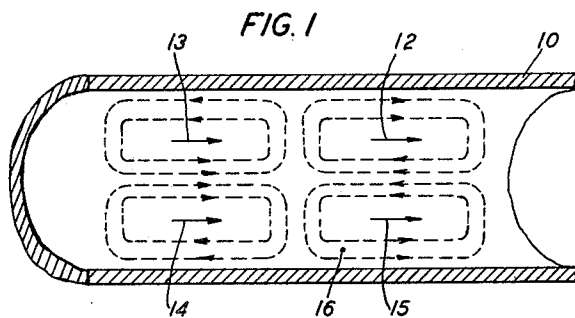
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2,946,025

NONRECIPROCAL ATTENUATOR

Original Filed June 17, 1953

4 Sheets-Sheet 1



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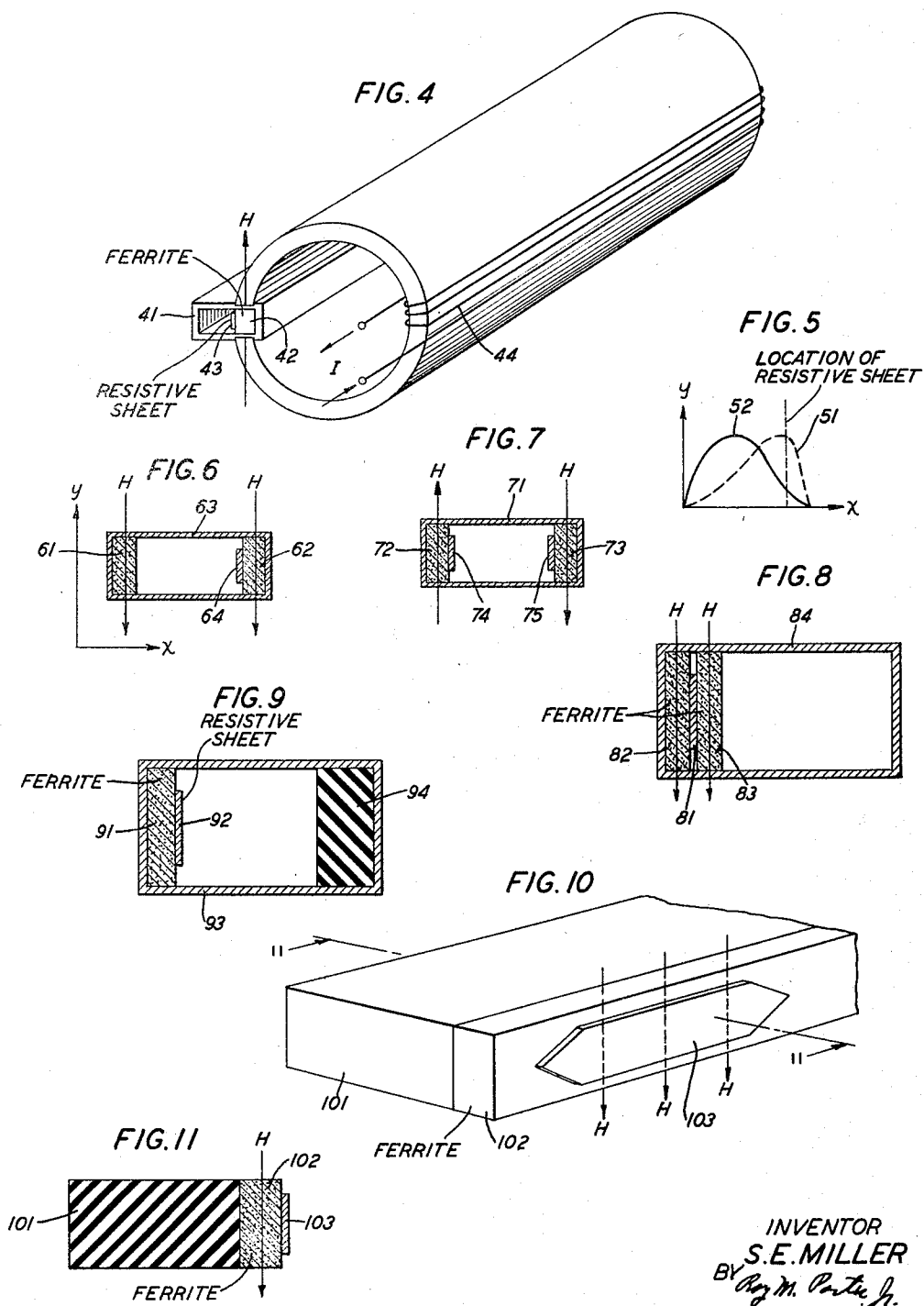
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NONRECIPROCAL ATTENUATOR

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FIG. 12

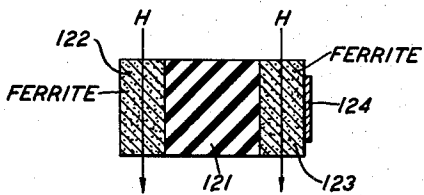


FIG. 13

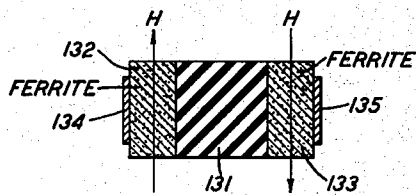


FIG. 14

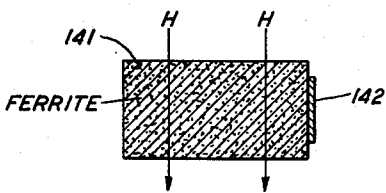


FIG. 15

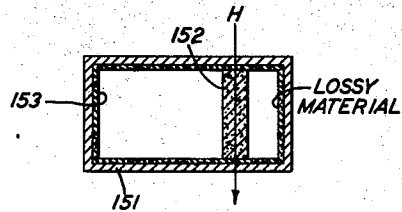


FIG. 16

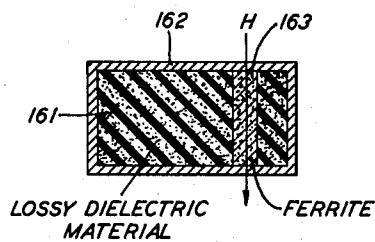


FIG. 17

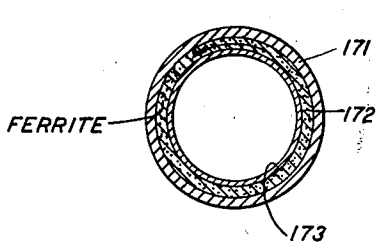
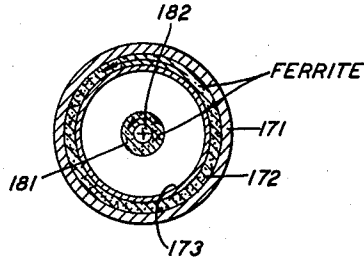


FIG. 18



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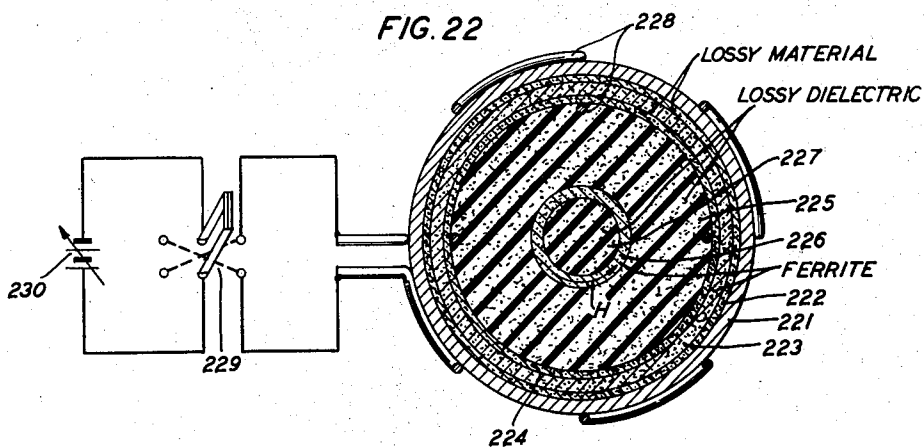
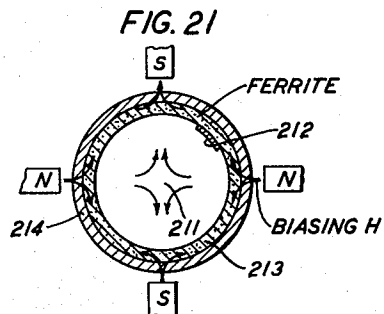
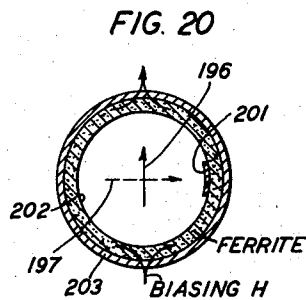
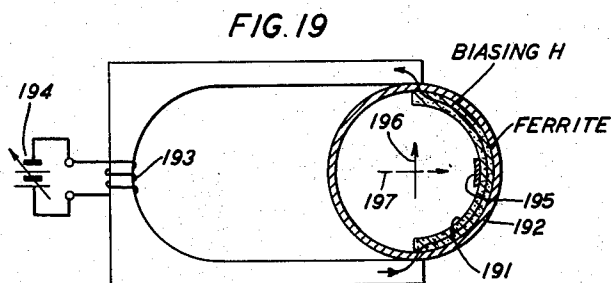
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4 Sheets-Sheet 4



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2,946,025

NONRECIPROCAL ATTENUATOR

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Original application June 17, 1953, Ser. No. 362,193. Divided and this application Dec. 17, 1956, Ser. No. 628,906

18 Claims. (Cl. 333—24)

This invention relates to nonreciprocal devices suitable for high frequency or microwave electrical systems and more particularly to electromagnetic wave isolators. This application is a division of my copending application Serial No. 362,193, filed June 17, 1953.

An isolator is defined as a device which may be employed to isolate an electromagnetic device from other portions of an electromagnetic wave system, in the sense that waves may be freely transmitted in the direction from the device through the isolator to the system, designated the forward direction, but waves originating outside of the device and traveling in the opposite direction, designated the reverse direction, are attenuated by the isolator to the extent required to prevent deleterious reaction of the system upon the device to be isolated.

An object of the invention is to obtain a large ratio of reverse loss to forward loss in a microwave component.

It is another object of this invention to produce a loss ratio characterized in a large reverse loss coupled with a small forward loss.

In a copending application of W. H. Hewitt, Serial No. 362,191, filed June 17, 1953, it has been shown that polarized elements of ferrite and other suitable gyromagnetic materials produce nonreciprocal effects when located asymmetrically with respect to the wave guide structure. Related subject-matter appears in an article by N. G. Sakiotis and H. N. Chait entitled "Ferrites at Microwaves" which appeared at pages 87 through 93 of the January 1953, Proceedings of the Institute of Radio Engineers. The isolators proposed in the above-noted prior art require relatively high magnetic fields to operate at the ferromagnetic resonance point for the gyromagnetic material involved. This has required unduly large magnets to supply the biasing field and resulted in unnecessarily bulky and expensive apparatus.

Therefore, another object of the present invention is to reduce the magnetic field strength required for directionally selective attenuation components using gyromagnetic elements.

It has been recognized that isolator action may be developed when utilizing gyromagnetic material without exciting the material to gyromagnetic resonance. Specifically it has been found that a polarized gyromagnetic element coupled to a wave guide will effect the electromagnetic field configurations of wave energy transmitted therethrough such that the electric field intensity distribution across the wave guide for one direction of propagation is different from that for the opposite direction. In one region of the wave guide the electric field intensity for the forward wave is much smaller than it would be in an unloaded guide. In the same region, the electric field intensity for the reverse wave is substantially the same as in an unloaded guide. In accordance with one aspect of the invention, resistive material is placed in this region wherein the fields of the forward and reverse waves are displaced as described. Accordingly, the forward wave is only slightly dissipated

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in the resistive material, while the reverse wave is considerably dissipated. As a result of this nonreciprocal attenuation, isolator action is achieved.

It has also been found that by employing a second gyromagnetic element which is polarized in the same sense as the first and spaced therefrom in a manner to be described in connection with the drawings, the fields of the forward and reverse waves are displaced to an even greater extent thereby resulting in the electric field intensity differential between the waves of opposite directions of propagation being substantially increased in the region of the resistive material. Accordingly nonreciprocal attenuation is enhanced by this aspect of the invention.

When either of these arrangements is utilized, as described, the electric field distribution across the guide is asymmetrical for both directions of propagation and thus there is but a single region of maximum electric field intensity differential. When, however, in accordance with another aspect of the invention, two gyromagnetic elements are utilized which are polarized in opposite senses and spaced from each other in a manner to be described hereinafter in connection with the drawings, the fields are displaced such that the electric field intensity distributions are symmetrical across the guide for both directions of propagation but differ in shape and magnitude, and result in two regions of maximum electric field intensity differential. This constitutes an improvement over the arrangement in which the single gyromagnetic element is employed since resistive material placed in both said regions substantially increases the loss that the reverse wave suffers to a much greater extent than the loss experienced by the forward wave.

When either one polarized gyromagnetic element or two gyromagnetic elements polarized in opposite senses are employed, an effect is produced, and utilized to produce an additional novel result, which is somewhat different but related to that of the nonreciprocal field distributions in the illustrative arrangements mentioned above. The wave guides loaded with gyromagnetic material in either of these two ways, exhibit nonreciprocal phase velocities. That is, the phase velocity for one direction of propagation is greater than for the opposite direction. By substantially filling a portion of the wave guide with resistive material dispersed through a dielectric binder, or by coating the walls of the guide with resistive material, the wave of greater phase velocity experiences greater attenuation than the other since the resistive material constitutes a longer electrical path for the wave of greater phase velocity.

In the embodiments to be described hereinafter in connection with the drawings these various aspects of the invention are applied to rectangular and circular hollow-conductive wave guides, and also to all-dielectric wave guides.

Other objects and certain features and advantages of the invention will become apparent during the course of the following detailed description of the specific illustrative embodiments of the invention shown in the accompanying drawings.

In the drawings:

Fig. 1 illustrates the magnetic field configuration for the circular electric TE_{01} mode in a circular wave guide;

Fig. 2 is a schematic diagram of the magnetic loops in a rectangular wave guide;

Fig. 3 is an idealized plot of the real and imaginary parts of the permeability in a polarized medium of gyromagnetic material;

Fig. 4 shows an arrangement in which a polarized element of ferrite and a resistive sheet are employed to provide a nonreciprocal microwave attenuator;

Fig. 5 is a plot employed to explain the operation of the device of Fig. 4;

Fig. 6 depicts an arrangement similar to that of Fig. 4 in which a second ferrite element is added to enhance the nonreciprocal effect;

Fig. 7 discloses a wave guide isolator in which two gyromagnetic elements respectively polarized in opposite senses and two resistive vanes are employed;

Fig. 8 shows an embodiment wherein a resistive vane is sandwiched between two elements of ferrite;

Fig. 9 illustrates a field displacement-resistance isolator in which a dielectric element has been added;

Figs. 10 through 14 illustrate the nonreciprocal attenuation effect employing ferrite and resistive material as applied to dielectric wave guiding structures;

Fig. 15 represents the cross section of a wave guide having a polarized ferrite element and wave guide walls which are lossy;

Fig. 16 is a cross sectional view of a wave guide having an asymmetrically positioned ferrite element, and lossy dielectric material filling the balance of the wave guide;

Figs. 17 through 21 illustrate the use of circularly magnetized paramagnetic elements and resistive vanes in circular wave guides for various of the common modes; and

Fig. 22 is a cross sectional view of an isolator embodying the effects of both field displacement and phase velocity differential.

Referring more particularly to the drawings, Fig. 1 shows by way of example and for purpose of illustration representative loops of the high frequency magnetic field of the circular electric TE_{01} mode in a circular wave guide at a particular instant. In this figure, the arrows 12 through 15 indicate the direction of propagation of power through the wave guide and the arrows on the individual closed magnetic loops indicate the polarity at any particular point in the guide at a given instant. On this basis, it may be noted that the magnetic field intensity vector at the fixed point 16 in the wave guide 10 will rotate clockwise as the wave propagates through the guide from left to right as indicated by the arrows 12 through 15 of Fig. 1. However, for propagation through the wave guide in the opposite direction, the circularly polarized components as seen from point 16 will rotate counterclockwise.

In Fig. 2 the pattern of the high frequency magnetic field of the TE_{10} mode at a given instant in a rectangular wave guide 21 is shown. As the electromagnetic waves propagate from left to right through the guide, it may be observed that the direction of the magnetic intensity vector seen at the fixed point 22 in the wave guide will rotate in a counterclockwise direction while that observed at point 23 will rotate clockwise.

Figs. 1 and 2 thus demonstrate the presence of negatively and positively circularly polarized magnetic components in both rectangular and circular wave guides. The plots of Fig. 3 illustrate the difference in permeability for such positive and negative circularly polarized high frequency magnetic components in a polarized medium of paramagnetic material. These plots are for radio frequency waves in which the magnetic intensity is at right angles to the steady biasing magnetic field and may be derived from a mathematical analysis of D. Polder which appeared in Volume 40, pages 99 through 115 of the January, 1949, Philosophic Magazine. In this plot of Fig. 3, the real portions of the permeability are shown by the solid lines 31(+) and 31(-) and the imaginary portions are shown by the dotted lines 32(+) and 32(-). Concerning the real portions, the negative (one which rotates counterclockwise when looking along a north-to-south pole biasing magnetic vector) circularly polarized component 31(-) has an increasing permeability as the biasing magnetic intensity is increased, and the positive circularly polarized component 31(+)

experiences a reduction in permeability for a similar increase in biasing magnetic intensity, at magnetic fields below ferromagnetic resonance, indicated at H_r on Fig. 3. More specifically, the negative component has a permeability greater than one while the positive component has a permeability less than one.

One physical explanation which has been advanced to explain this phenomenon involves the assumption that the ferromagnetic material contains unpaired electron spins which tend to line up with the applied magnetic field. These spins and their associated moments can be made to precess about the line of the magnetic field, keeping an essentially constant component of magnetic moment in the applied field direct-current direction but providing a magnetic moment which may rotate in a plane normal to the steady magnetic field direction. These magnetic moments have a tendency to precess in one angular sense, but strongly resist rotation in the opposite sense. This tendency of a spinning element to consistently precess in one angular sense is familiar to anyone who has watched a top wobble before stopping. Considering the interaction between the oppositely polarized components of high frequency magnetic intensity and the magnetic moments, it is clear that one of the circularly polarized components will be rotating in the easy angular sense of precession of the magnetic moments and the other component will be rotating in the opposite sense. When the high frequency magnetic intensity is rotating in the same sense as the preferred sense for precession of the magnetic moment, it will couple strongly with the magnetic moment and drive it into precession. When the high frequency magnetic intensity is rotating in the opposite angular sense, however, very little coupling or interaction between the high frequency magnetic intensity and the magnetic moments takes place.

While this difference in coupling and consequent difference in the real portion of the permeability for oppositely polarized components may be observed even at low values of steady polarizing magnetization, in the vicinity of ferromagnetic resonance the imaginary portion of the permeability for the positive circularly polarized component has a sharp maximum. Although attenuation varies with the imaginary portion of the permeability, phase velocity and electromagnetic field displacement vary with the real portion of the permeability. My co-pending parent application, mentioned above, deals primarily with embodiments which function with respect to the imaginary portion of the permeability. The embodiments to be disclosed hereinafter, however, operate responsively to the real portion of the permeability. Accordingly these embodiments are nonreciprocal because the real permeabilities experienced by positive and negative magnetic wave components are respectively different.

The device of Fig. 4 is a nonreciprocal attenuator or isolator utilizing the field displacement effect. Considering the device of Fig. 4, the hollow rectangular conducting section of wave guide 41 has an elongated element of paramagnetic material 42 against one of the narrower side walls. In addition a resistive strip 43 is mounted on the inner side of the paramagnetic element 42 within the wave guide 41. An electromagnet 44 magnetizes the element 42 transversely, as shown. As is illustrated in Fig. 5, the electric field distribution 51 of the electromagnetic wave which is propagated in one direction through the wave guide (shown in dashed line) is asymmetrically distorted so that it bulges toward the paramagnetic element to a substantial degree, while the field distribution 52 of the oppositely propagated electromagnetic wave, also asymmetrically distorted, is bulged away from the ferrite element to a lesser degree. The reason for this is that the transversely magnetized element of ferrite presents a permeability greater than one for wave propagation into the plane of the paper (whereby the concentration of the field distribution in the ferrite is increased) and less than one for a wave traveling out of the plane

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of the paper (whereby its field distribution concentration is decreased in the ferrite). At the position of the resistance sheet a larger field will be present for wave propagation into the plane of the paper (dotted curve of Fig. 5) than will be present for the wave propagating out of the plane of the paper (solid curve of Fig. 5). Thus the loss will be much lower for the wave propagating out of the plane of the paper than for the wave propagating into the plane of the paper.

The element 42 of the device of Fig. 4 is made from a paramagnetic material which has low conductivity. The conductivity ranges should be moderately low in order to prevent undue distortion of the electromagnetic field, and the samples should preferably have a resistance greater than 100 ohm-centimeters, although operable devices could be made with resistivities as low as 10 ohm-centimeters. Any of a number of ferromagnetic materials which each comprise an iron oxide in combination with one or more bivalent metals, such as nickel, magnesium, zinc, manganese or other similar material have proved to be satisfactory. These materials combine with the iron oxide in a spinel structure and are known as ferromagnetic spinels or as polycrystalline ferrites. In accordance with the usual practice, these materials are first powdered and then molded with a small percentage of plastic material such as Teflon or polystyrene. As a specific example, the element 42 may be of nickel-zinc ferrite of the approximate chemical formula $(\text{Ni}_3\text{Zn}_7)\text{Fe}_2\text{O}_3$ prepared as noted above. In addition, commercially available samples of ferrite, and finely powdered conducting ferromagnetic dust in an insulating binder may be employed. By way of inclusion but not of limitation, the phrase "paramagnetic material having low conductivity" is to be construed as applying to the foregoing types of materials. In addition, as employed in the present application and claims, the term "gyromagnetic medium" is intended to apply to all materials having magnetic properties of the type disclosed in the above-mentioned article by Polder, and as discussed above in conjunction with Fig. 3.

In the cross sectional view of Fig. 6 the coordinates employed in Fig. 5 are indicated, and an arrangement employing two similarly biased elements 61 and 62 of ferrite at opposite sides of the rectangular conducting wave guide 63 is set forth. In addition, a resistive vane 64 is again mounted on the inner side of one of the ferrite elements 62. With the ferrite elements located on opposite sides of the wave guide but magnetically biased in the same sense, one ferrite element exhibits a permeability greater than one for waves in one direction of propagation and the other ferrite exhibits a permeability greater than one but for waves propagating in the opposite direction. In this instance, therefore, one ferrite element distorts the field pattern for one direction of propagation in one lateral direction and the other element tends to distort the oppositely propagating wave in the opposite lateral direction. This increases the asymmetry of the field distributions and thus enhances the difference in field strengths at the resistive vane 64 for the two directions of propagation and consequently emphasizes the nonreciprocal attenuation effect.

Where a symmetrical ferrite structure is used, as in Fig. 6, the resistive material should be placed in only one of the two ferrite strips, or if it is placed in both strips the sense of the biasing magnetic field on one of the strips should be reversed. Accordingly Fig. 7 illustrates this latter arrangement. Specifically the isolator of Fig. 7 includes the wave guide 71, the two gyromagnetic elements 72 and 73 which are polarized in opposite senses, respectively, and also includes the resistive strips or coatings 74 and 75 mounted, respectively, on the gyromagnetic elements 72 and 73. The physical reason underlying the latter arrangement is that the field distribution for one direction of propagation will tend to be squared up and thus have substantial components near the side

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walls of the guide where they will be attenuated by the resistive material, while the field distribution for the opposite direction of propagation will be concentrated toward the open central portion of the guide. This may be understood by considering that with the gyromagnetic elements biased in opposite senses each of them will exhibit a permeability greater than one for the same direction of wave propagation, while each of them will exhibit a permeability less than one for waves propagating in the opposite direction. Therefore, despite the fact that both field distributions will be symmetrical across the wave guide, the field distribution of waves for one direction of propagation will be distorted differently from that for the opposite direction.

Figs. 8 and 9 are cross sectional views of arrangements representing slight variations of the general type of arrangement illustrated by the structures of Figs. 4 and 6. In Fig. 8 the resistive vane 81 is sandwiched between two thin ferrite elements 82 and 83 and the three elements are all placed at one side of the rectangular wave guide 84 to provide a nonreciprocal attenuator.

In Fig. 9 as in Fig. 4 the paramagnetic element 91 has a resistive vane 92 mounted thereon and the two elements are located at one side of a conductive wave guide 93 with a polarizing magnetic field applied to the paramagnetic element. In Fig. 9, however, a block of dielectric material 94 is provided at the opposite side of wave guide 93 to equalize some of the dielectric effect of the ferrite, to enhance the nonreciprocal loss effect.

Figs. 10 through 13, inclusive, illustrate the application of the foregoing principles of field displacement isolation to dielectric wave guides of the type disclosed in A. G. Fox application, Serial No. 274,313, filed March 1, 1952.

In Fig. 10, the dielectric guide is made up of the elongated dielectric element 101, the ferrite strip 102 and the tapered resistive vane 103 which all have the same functions as the comparable elements of Fig. 4. In the dielectric guide structures, however, because much of the electromagnetic wave energy is propagated in a field which is external to the guide, it is convenient to have the resistive vane 103 mounted on the outer surface of the paramagnetic strip 102.

Fig. 11 is a cross section taken along lines 11—11 of Fig. 10 and constitutes another view of the three component elements.

Fig. 12 is a cross sectional view of the dielectric guide equivalent of the conducting wave guide arrangement of Fig. 6. In Fig. 12, the waves are guided by the dielectric element 121 and the two matching ferrite elements 122 and 123 which are on either side of it. These ferrite strips also shift the electromagnetic field distribution in much the same manner as set forth in Fig. 5, and the resistive vane 124 attenuates waves propagating in one direction to a greater extent than the oppositely propagated waves.

Fig. 13 is a cross sectional view of the dielectric guide equivalent of the conducting wave guide arrangement of Fig. 7. In Fig. 13, the waves are guided by the dielectric element 131 and the oppositely magnetically biased ferrite elements 132 and 133 which are on either side of it. These ferrite strips also symmetrically shift the electromagnetic field distribution in much the same manner as set forth with respect to Fig. 7, and the resistive vanes 134 and 135 mounted respectively on ferrite elements 132 and 133 attenuate waves propagating in one direction to a greater extent than the oppositely propagated waves.

In the cross sectional view of Fig. 14, the dielectric material between the two ferrite elements of Fig. 12 has been dispensed with and the isolator structure comprises a simple transversely magnetized rectangular strip of ferrite 141 which guides the waves and also shifts the field patterns in the requisite manner. A resistive

vane 142 is mounted on one of the narrow outer sides of the ferrite strip 141.

The resistive vanes have been shown in the preceding arrangements illustrated by Figs. 4 through 14, inclusive, as mounted on the ferrite strips. This is merely for convenience and the resistive elements may be placed at other points in the structure. The important matter is to have the resistive vanes located at the point or points where there is greatest difference between the squares of the electric fields for the two directions of propagation. Instead of separate resistive vanes, the resistive material may be mixed with the composite ferrite and insulating material in any of the devices of Figs. 4 through 13, inclusive.

Because of the difference in phase velocities for the two directions of propagation for many of the wave guide structures disclosed in the present application, other types of isolators such as are illustrated in the cross sectional views of Figs. 15 and 16 can be constructed. The subject matter of these figures is claimed in a divisional application hereof now United States Patent 2,924,794, granted February 9, 1960. Specifically, in the vicinity of cut-off, a difference between metallic wall losses for the two directions of transmission will exist due to the fact that the wave propagating in one direction will be closer to cut-off than the other.

In Fig. 15, rectangular wave guiding structure 151 is provided with the usual asymmetrically located, transversely magnetized element of ferrite material 152, and is also provided with an internal layer 153 of relatively high resistivity, such as a painted layer of aquadag, which has a thickness approximating the skin depth. When a section of the wave guiding structure such as is shown in Fig. 15 several wavelengths long is coupled to a microwave source having a frequency slightly above the cut-off frequency of the wave guide structure, the attenuation through the unit will be much greater for one direction of transmission than for the other. In Fig. 16 the lossy dielectric material 161 in combination with the wave guide 162 and polarized ferrite element 163 serve to yield the same effect as the device of Fig. 15 when a similar length is operated in the same manner as set forth above. The dielectric material may be made up of dielectric material such as polystyrene having finely divided particles of carbon dispersed throughout its volume.

Figs. 17 through 20, inclusive, illustrate, in cross sectional views, resistance sheet field-displacement type isolators for circular wave guides, which operate on much the same principles discussed above in connection with the rectangular wave guide structures illustrated in Figs. 4 through 7, inclusive. The similarity becomes apparent on considering Figs. 1 and 2 in their relation to Fig. 3.

The structure of Fig. 17 is designed to be used with the TE_{01} mode in the circular wave guide 171. Within this wave guide, the ferrite liner element 172 shifts or displaces the electric field configuration toward the resistive sheet 173 for a first direction of propagation and away from the resistive sheet for the opposite direction of propagation, so that the resistive vane 173 attenuates wave propagating in the first direction to a substantially greater extent than the oppositely propagated waves. The circumferential field in the ferrite liner 172 of Fig. 17 may be obtained by the permanent magnetization of the core, by a coil threaded through the liner or by any other suitable method. As may be observed by correlating Figs. 1 and 17, the circularly polarized components of the high frequency magnetic field lie in radial planes which are perpendicular to the circumferential biasing magnetic field in the cylindrical ferrite liner 172. Considering electro-magnetic waves of the TE_{01} mode, propagating in opposite directions through the wave guide 171, it is clear that the circularly polarized components of the radio frequency magnetic intensity for the opposite directions of propagation will have opposite senses of

rotation with respect to the steady magnetic field and thus that the permeabilities experienced by the oppositely directed waves will differ as indicated by the plots of Fig. 3. As a consequence the above-mentioned shifts or displacements in electric field configurations result.

In the device of Fig. 18, the ferrite liner 172 and the resistive sheet 173 within the circular wave guide 171 are assisted in the field displacement action by the central hollow coaxial ferrite element 181 which is magnetized in the same angular sense as the outer ferrite core 172 by passing direct current through a centrally located conductor 182. This central ferrite element 181 acts in much the same manner as the second ferrite element in Fig. 6 to displace the field intensity toward the resistive sheet for a first direction of propagation while displacing the field intensity for the other direction of propagation away from the resistive sheet, thus cooperating with the outer ferrite element 172 to create a greater differential loss at the resistive sheet 173.

Figs. 19 and 20 illustrate resistance sheet field-displacement isolators for the TE_{11} mode.

In Fig. 19, a semicylindrical liner element 191 of ferrite overlies a portion of the inner surface of the circular wave guide 192. The electromagnet 193 provides the magnetic field for biasing the element 191 of ferrite. Electromagnet 193 is shown energized by a steady biasing current from direct-current source 194. As a consequence of resistive sheet 195 mounted on ferrite element 191, the unit provides nonreciprocal attenuation for vertically polarized electromagnetic waves 196 due to the field displacement effect, and will exhibit nonreciprocal phase displacement properties for horizontally polarized waves 197.

In the isolator of Fig. 20, a resistive sheet 201 is mounted on one internal surface of the cylindrical ferrite liner 202, which in turn is supported by the inner surface of the circular conducting wave guide 203. The biasing magnetic field for the core 202 is applied to the top and bottom of the cylindrical core 202 as illustrated by the branching arrows. When the TE_{11} mode is vertically polarized as indicated by the solid arrow 196 at the center of the wave guiding passageway, the structure of Fig. 23 bears much the same relationship to that of Fig. 19 as the structure of Fig. 6 does to that of Fig. 4, and the field-displacement is enhanced. The structure of Fig. 20 does not yield a nonreciprocal phase shifting effect with any polarization of the TE_{11} mode, and even has reciprocal loss characteristics when the TE_{11} mode is horizontally polarized as indicated by the dashed arrow 197 of Fig. 20.

Fig. 21 illustrates a resistance sheet field-displacement isolator for the TE_{21} mode having a field orientation as illustrated by arrows 211. This device, for the TE_{21} mode is analogous to the structure of Fig. 20 for the TE_{11} mode, and thus has the single resistive vane 212 mounted on the hollow ferrite cylindrical liner 213 within the conducting guide 214. The magnetic field is applied to the core at 90-degree intervals about the circumference of the liner, as shown, with the two north poles opposing one another and the two south poles also in opposition. With the foregoing geometry, the field distribution for one direction of propagation will be displaced toward the resistive element 212 and the field distribution for the opposite direction of transmission will be shifted away from it, so that the result will be the nonreciprocal attenuation feature characteristic of all of these field-displacement isolators. With the foregoing examples as a guide, other resistance sheet field-displacement isolators can readily be constructed for other modes.

In Fig. 22 a nonreciprocal attenuating device is disclosed in which both the field-displacement and phase velocity differential effects discussed above are utilized cumulatively to produce desired nonreciprocal attenuation effects.

In Fig. 22 the outer circular conducting wave guide

221 encloses a number of concentric cylinders of various materials. Specifically, proceeding inwardly there is a thin layer of high resistance material 222, a ferrite cylinder 223 of substantial thickness, a resistance sheet 224, a very thick cylinder 225 of dielectric material containing a slight amount of lossy material distributed throughout, a hollow cylinder of permanently magnetized ferrite 226 and a central cylinder of dielectric material 227 similar in composition to cylinder 225. A circumferential magnetic field is applied to the outer ferrite cylinder 223 by means of a coil 228 in the manner taught in my above-mentioned parent application. The magnetization in this outer cylinder 223 may be from a suitable source of direct current 230. The double pole double throw switch 229 facilitates reversing the polarity of the magnetization in the outer ferrite cylinder 223.

Considering the possible modes of operation of the structure of Fig. 22 when energized in the TE_{01} mode, it may be noted that with the sense of peripheral magnetization in the outer cylinder 223 the same as that of the permanently magnetized inner cylinder 226, these elements together with the lossy material 223 and the resistive sheet 224 will constitute a field-displacement isolator. With senses of the fields being the same, however, the inner cylinder will have increased permeability for one direction of propagation and the outer cylinder will have increased permeability for oppositely propagated waves, and the net nonreciprocal phase shift will not be unduly great.

When the magnetic field is reversed and the microwave energy is at a frequency just above cut-off, the non-reciprocal attenuation factors due to field-displacement and phase velocity difference are combined. Initially, it may be noted that with the inner and outer ferrite cylinders magnetized in opposite circumferential senses, they will both exhibit increased permeability for the same direction of propagation of waves of the TE_{01} mode. In the direction of increased permeability the wave guide is operating closer to cut-off and the losses due to the lossy dielectric 225, 227 and the lossy inner coating 222 of the guide 221 are increased. Simultaneously, field-displacement occurs bringing resistance sheet 224 into effect for nonreciprocal attenuation.

Although many of the devices have been disclosed specifically, as for example by stating that the paramagnetic element is of ferrite or that the applied biasing magnetic field is steady, these specific disclosures are merely exemplary and are not to be considered limiting. Specifically, other types of paramagnetic material having low conductivity such as were discussed hereinabove may be used in any of the disclosed devices. In addition it might be noted that the present isolators may involve the use of tapered transitions at the point where the nonreciprocal element is coupled to standard sections of wave guide.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention and no attempt has been made to exhaustively illustrate all possible embodiments thereof. Numerous other arrangements, obviously, may readily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, an electromagnetic wave guiding structure, means including an element of material which has low dissipation loss for propagating electromagnetic wave energy for providing a first electric field intensity distribution for wave energy propagating through a region of said wave guiding structure in one direction and for providing a second electric field intensity distribution different from said first distribution for wave energy propagating through said region of said wave guiding structure in a direction opposite to said one direction while maintaining the direction of the electric field vectors

of said wave energy in said region substantially the same for both directions of propagation, and means responsive to the difference between said first and second electric field distributions for converting said difference into a non-reciprocal attenuation of said wave energy.

2. In an electromagnetic wave guiding structure, a first means including a first element of magnetically polarizable material exhibiting gyromagnetic effects at the frequency of wave energy supported by said structure for producing an electric field intensity differential in portions of said structure for opposite directions of propagation of electromagnetic wave energy therethrough, means for magnetically polarizing said element to a point removed from gyromagnetic resonance at the frequency of said wave energy, and resistive material at least partially filling at least one of said portions, said one portion being located along a longitudinally extending region of said wave guiding structure with the ends of said region being defined by the ends of said element of gyromagnetic material.

3. A combination as recited in claim 2 wherein said means for magnetically polarizing applies a magnetic biasing field to said gyromagnetic element with the lines of force of said biasing field lying in planes transverse to the direction of propagation of wave energy through said wave guiding structure.

4. A combination as recited in claim 3 wherein said first means includes a second element of gyromagnetic material disposed in a region in said guiding structure in which the magnetic field components of said wave energy are circularly polarized in a direction opposite to the direction of circular polarization in the region in which said first element is located, and also includes means for applying a magnetic biasing field to said second element transverse to the direction of propagation of wave energy through said wave guiding structure.

5. A combination as recited in claim 4 wherein the sense of said magnetic biasing field in said first gyromagnetic element is the same as the sense of said biasing magnetic field in said second gyromagnetic element.

6. In combination, a wave guiding structure having a longitudinal axis, means for exciting electromagnetic waves having a field configuration of two or more oppositely sensed magnetic cophasal zones in said structure, low loss magnetically polarizable material exhibiting gyromagnetic effects at the frequency of said waves at least partially filling one of said oppositely sensed cophasal zones and offset from said axis, means for exciting steady polarizing magnetic fields in said gyromagnetic material below the strength required to produce gyromagnetic resonance in said material at the frequency of said waves, and high loss producing resistive material located adjacent at least one portion of said gyromagnetic material.

7. A nonreciprocal attenuator for electromagnetic wave energy comprising a wave guiding structure having a longitudinal axis, magnetically polarizable material exhibiting gyromagnetic effects at the frequency of said wave energy electromagnetically coupled to said wave guiding structure and offset from said longitudinal axis, said gyromagnetic material forming an elongated element, resistive material having a different energy absorbing characteristic from that of said gyromagnetic element electromagnetically coupled to said structure in contiguous relation to said element, and means for applying a magnetic biasing field to said element below the strength required to produce gyromagnetic resonance in said element at the frequency of said wave energy, the lines of force of said biasing field lying in planes transverse to said longitudinal axis.

8. A combination as recited in claim 7, wherein said wave guiding structure is a hollow metallic wave guide of rectangular transverse cross-section, said gyromagnetic element is a vane located within said wave guide and extending parallel to said longitudinal axis, and said re-

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sistive material is disposed contiguous to at least a portion of one face of said vane.

9. A combination as recited in claim 8, wherein a second vane comprising gyromagnetic material is located within said wave guide and wherein said vanes are disposed with respect to each other on opposite sides of the longitudinal axis of said guide.

10. A combination as recited in claim 9, wherein said resistive material is located between said second gyromagnetic vane and said other gyromagnetic vane and at least one of said vanes is transversely spaced from both narrow side walls of said rectangular guide.

11. A nonreciprocal attenuator for electromagnetic wave energy comprising a hollow, metallic, rectangular wave guide having a longitudinal axis, a vane of low loss magnetically polarizable material exhibiting gyromagnetic effects at the frequency of said wave energy located within said wave guide and extending parallel to said longitudinal axis, a vane of high loss producing resistive material located between said longitudinal axis and said gyromagnetic vane, a wide face of said resistive vane being mutually parallel to said longitudinal axis and the narrow walls of said wave guide and contiguous to at least a portion of said gyromagnetic vane, and means for applying a magnetic biasing field to said gyromagnetic vane in a direction transverse to said longitudinal axis and of a strength below that required to produce gyromagnetic resonance in said vane at the frequency of said wave energy.

12. A combination as recited in claim 11, including a second vane of gyromagnetic material within said wave guide disposed parallel to and on the opposite side of said longitudinal axis from said other gyromagnetic vane.

13. A combination as recited in claim 12 including means for magnetically biasing said second gyromagnetic vane in the same direction and sense as said other gyromagnetic vane.

14. A nonreciprocal attenuator for electromagnetic wave energy comprising a section of all-dielectric wave guide having a longitudinal axis, an elongated element comprising magnetically polarizable material exhibiting gyromagnetic effects at the frequency of said wave energy electromagnetically coupled to said all-dielectric wave guide, said gyromagnetic material being everywhere offset from said longitudinal axis, resistive material having an energy absorbing characteristic different from that of said gyromagnetic material electromagnetically coupled to said all-dielectric wave guide and disposed contiguous to said gyromagnetic element, and means for applying a magnetic biasing field to said element of a strength below that required to produce gyromagnetic resonance in said element at the frequency of said wave energy, the lines of force of said biasing field lying in planes transverse to said longitudinal axis.

15. A nonreciprocal attenuator for electromagnetic wave energy comprising a section of hollow metallic wave guide having a circular cross section, a hollow cylinder of magnetically polarizable material exhibiting gyromagnetic effects at the frequency of said wave energy coaxially disposed within said circular wave guide, resistive material located within said circular wave guide adjacent to said cylinder, and means for applying a circumferential mag-

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netic biasing field to said cylinder of a strength less than that required to produce gyromagnetic resonance in said cylinder at the frequency of said wave energy.

16. A combination as recited in claim 15 including a second gyromagnetic cylinder disposed coaxially with respect to and spaced from said other cylinder, and means for applying a circumferential magnetic biasing field to said second cylinder.

17. A combination as recited in claim 8 including an element of non-magnetic dielectric material having a dielectric constant greater than unity mounted within said wave guide along the same longitudinally extending portion of said wave guide occupied by said gyromagnetic element.

18. In combination an electromagnetic wave guiding structure, means including an element of gyromagnetic material for providing a first electric field intensity distribution for wave energy propagating through a region of said wave guiding structure in one direction and for providing a second electric field intensity distribution different from said first distribution for wave energy propagating through said region of said wave guiding structure in a direction opposite to said one direction while maintaining the direction of the electric field vectors of said wave energy in said region substantially the same for both directions of propagation, said element being magnetically polarized to a point removed from gyromagnetic resonance at the frequency of said wave energy to minimize dissipation loss introduced by said element, and means including an element of material of electrical characteristics different from said gyromagnetic element for converting the difference between said first and second electric field distributions into a non-reciprocal attenuation of said wave energy.

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