

Aug. 30, 1960

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2,951,220

WAVE GUIDE WITH POLARIZED FERRITE ELEMENT

Filed June 17, 1953

5 Sheets-Sheet 1

FIG. 1

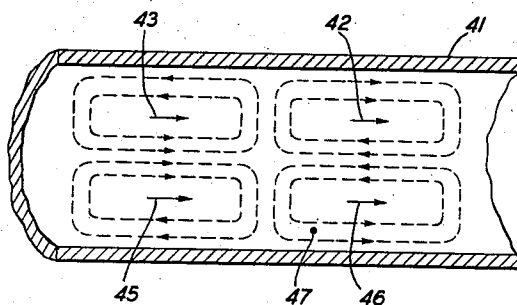


FIG. 2

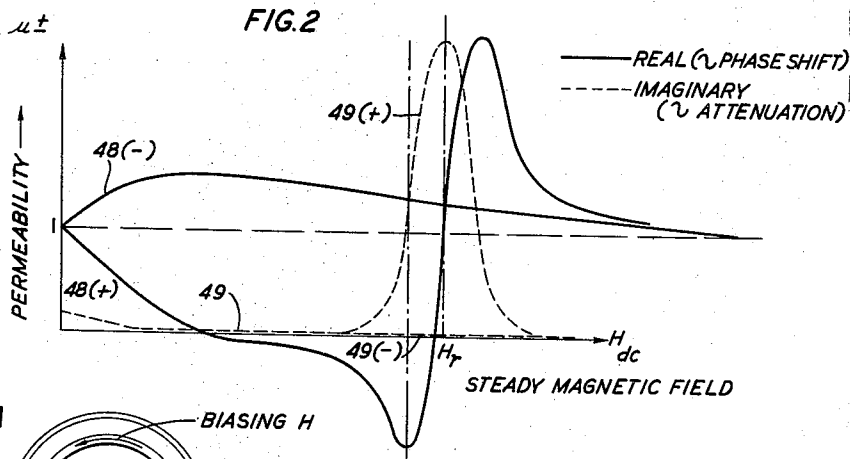


FIG. 3A

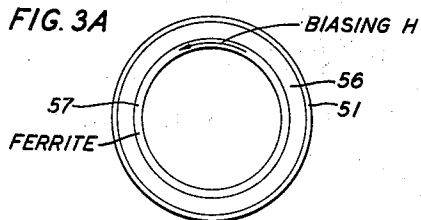
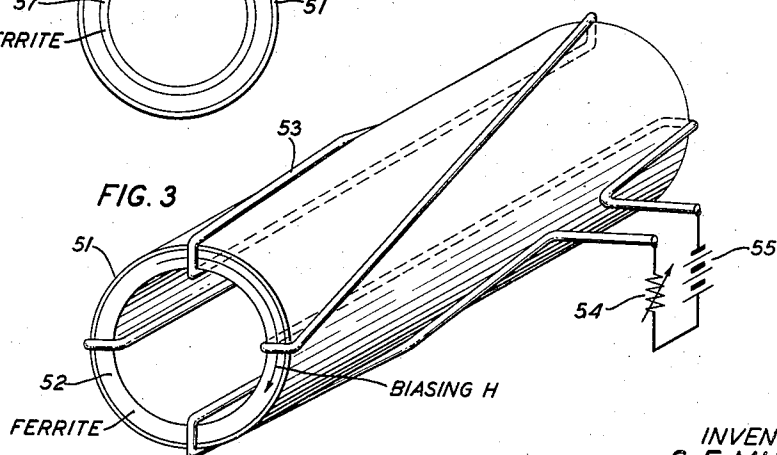


FIG. 3



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FIG. 4

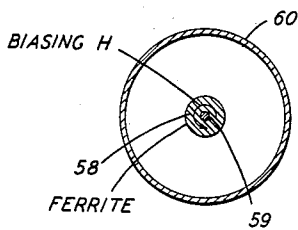


FIG. 5

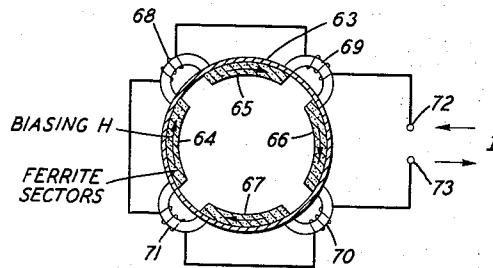


FIG. 6

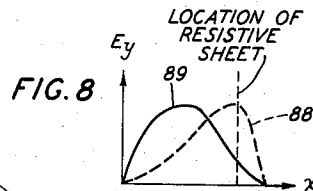
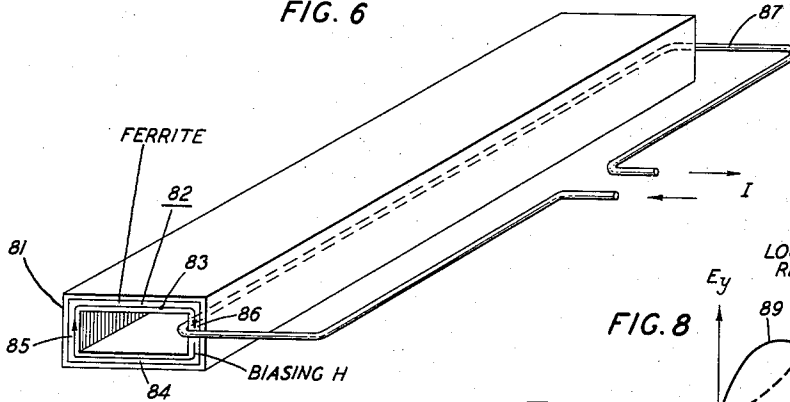


FIG. 7

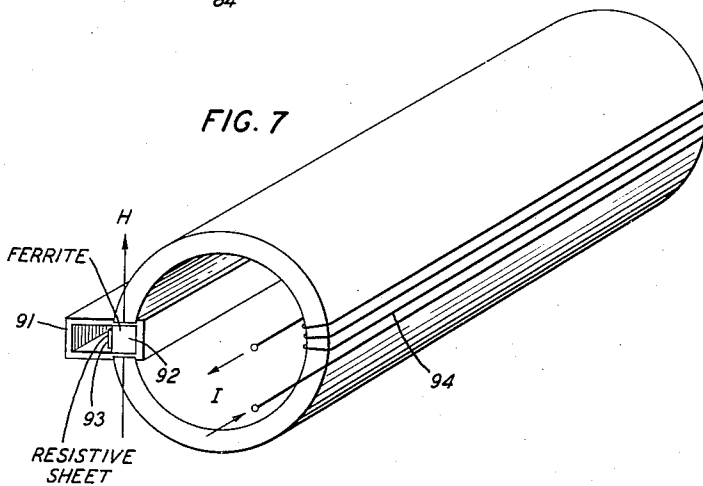
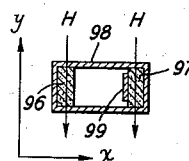


FIG. 9



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FIG. 10

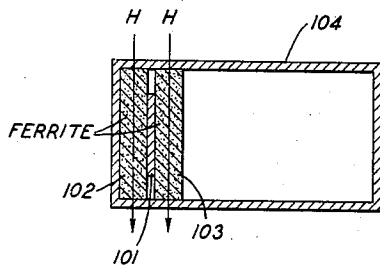


FIG. 11

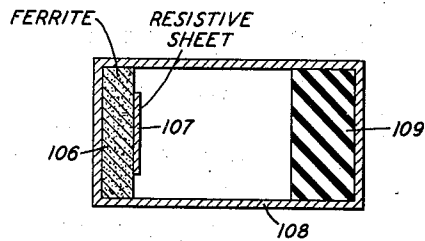


FIG. 12

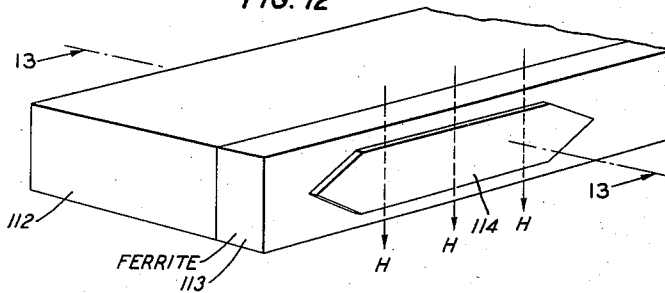


FIG. 13

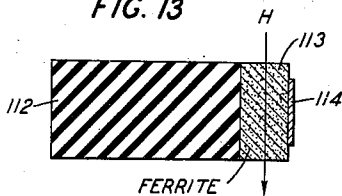


FIG. 14

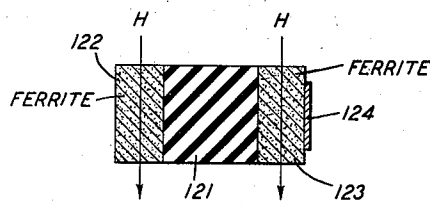


FIG. 15

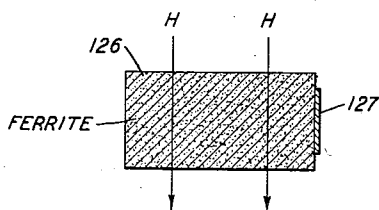
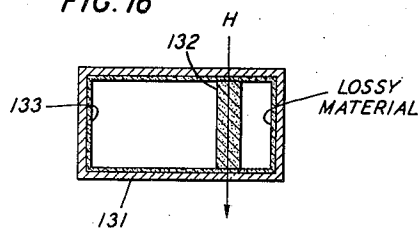


FIG. 16



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FIG. 17

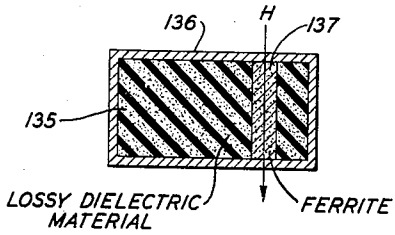


FIG. 18

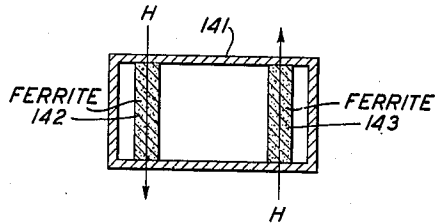


FIG. 19

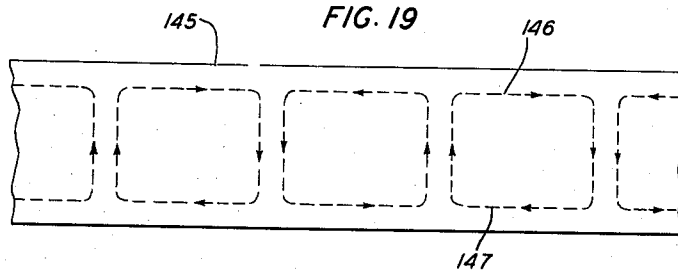


FIG. 20

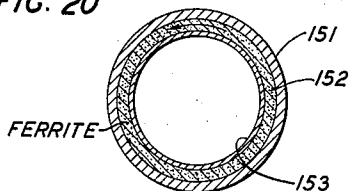


FIG. 21

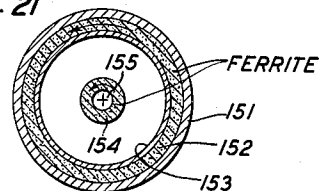


FIG. 22

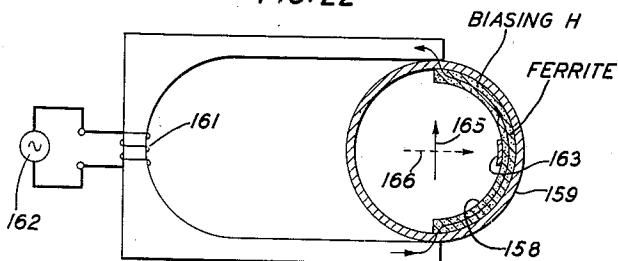
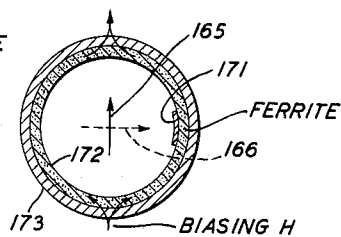


FIG. 23



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FIG. 24

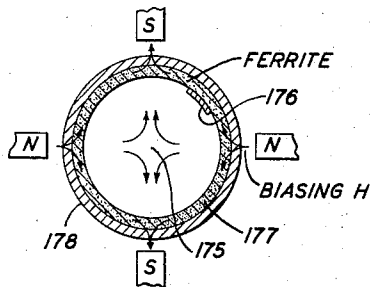


FIG. 25

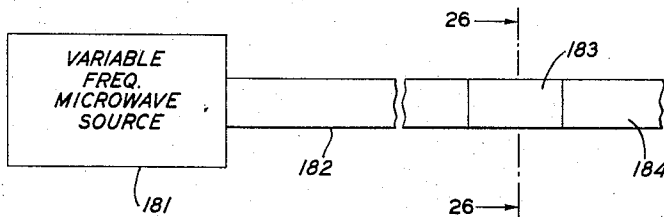
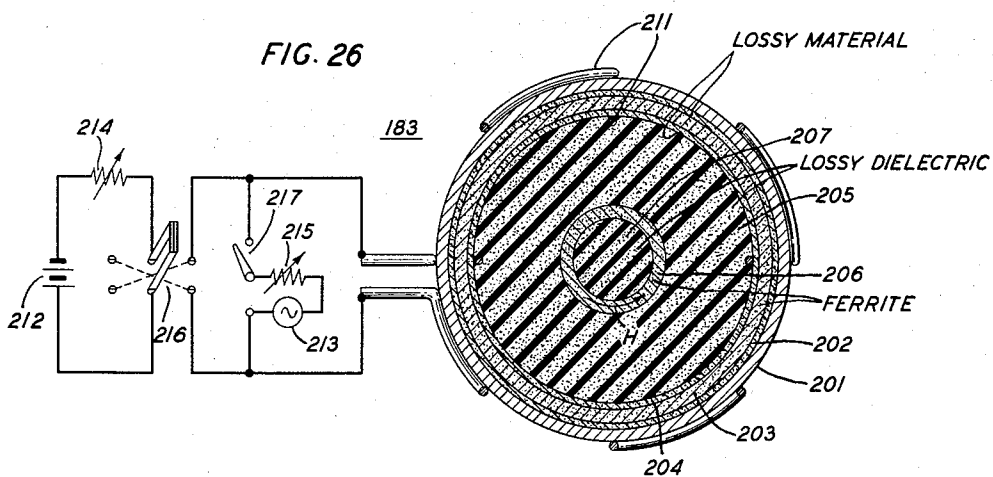


FIG. 26



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WAVE GUIDE WITH POLARIZED FERRITE ELEMENT

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Filed June 17, 1953, Ser. No. 362,193

9 Claims. (Cl. 333—24)

This invention relates to non-reciprocal devices suitable for high frequency or microwave electrical systems.

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 non-reciprocal 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 above-noted prior art, however, deals principally with rectangular wave guides. When non-reciprocal structures of rectangular configuration are employed in a circular wave guide system, costly and bulky transition elements must be employed.

Accordingly, one object of the present invention is to construct non-reciprocal phase shifting and isolating wave guide components employing polarized gyromagnetic elements for circular wave guiding structures.

In addition, 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.

In accordance with the invention, polarized gyromagnetic materials are employed to obtain non-reciprocal effects at high frequencies. From one aspect, the invention concerns the use of circular or peripheral magnetic fields in magnetic structures associated with wave guides; and from another viewpoint it involves the use of lossy material in conjunction with polarized gyromagnetic material.

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 an idealized plot of the real and imaginary parts of the permeability in a polarized medium of ferrite-like material;

Figs. 3, 3A, 4, and 5 illustrate circular wave guides having various structures for obtaining circumferentially magnetized magnetic elements in their wave guiding passageways;

Fig. 6 shows a rectangular wave guide having a peripheral or circumferential magnetic field;

Fig. 7 shows an arrangement in which a polarized element of ferrite and a resistive sheet are employed to provide a non-reciprocal microwave attenuator;

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Fig. 8 is a plot employed to explain the operation of the device of Fig. 7;

Fig. 9 depicts an arrangement similar to that of Fig. 7 in which a second ferrite element is added to enhance the non-reciprocal effect;

Fig. 10 shows an embodiment wherein the resistive vane is sandwiched between two elements of ferrite;

Fig. 11 illustrates a field displacement-resistance isolator in which a dielectric element has been added.

Figs. 12 through 15 illustrate the non-reciprocal attenuation effect employing ferrite and a resistive strip as applied to dielectric wave guiding structures;

Fig. 16 represents the cross-section of a wave guide having a polarized ferrite element and wave guide walls which are lossy;

Fig. 17 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;

Fig. 18 illustrates an isolator using two oppositely polarized ferrite elements, for comparison with Fig. 9 in which the two ferrite elements are polarized in the same sense and a resistive vane is employed;

Fig. 19 is a schematic diagram of the magnetic loops in a rectangular wave guide;

Figs. 20 through 24 illustrate the use of circularly magnetized gyromagnetic elements and resistive vanes in circular wave guides for various of the common modes;

Fig. 25 represents a microwave system in which a non-reciprocal unit is employed; and

Fig. 26 is a cross-sectional view of the non-reciprocal device of Fig. 25.

Referring more particularly to the drawings, Fig. 1 shows by way of example and for purposes of illustration representative loops of the high frequency magnetic field of the circular electric TE_{01} mode in a circular wave guide 41 at a particular instant. In this figure, the arrows 42 through 46 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 57 in the wave guide 41 will rotate clockwise as the wave propagates through the guide from left to right as indicated by the arrows 42 through 46 of Fig. 1. However, for propagation through the wave guide in the opposite direction, the circularly polarized components as seen from point 47 will rotate counterclockwise.

The plots of Fig. 2 illustrate the difference in permeability for positive and negatively circularly polarized high frequency magnetic wave in a polarized medium of gyromagnetic 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. 2, the real portions of the permeability are shown by the solid lines 48(+) and 48(−) and the imaginary portions are shown by the dotted lines 49(+) and 49(−). Concerning the real portions, the negative (one which rotates counterclockwise when looking along a north-to-south pole biasing magnetic vector) circularly polarized component 48(−) has an increasing permeability as the biasing magnetic intensity is increased, and the positive circularly polarized component 48(+) 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. 2.

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.

Furthermore, 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. Inasmuch as the attenuation varies with the imaginary portion of the permeability and the phase constant varies with the real portion of the permeability, ferrites at relatively low magnetic field strengths may be employed as non-reciprocal phase shifting devices, while ferrites at magnetic field strengths sufficient to produce resonance may be used advantageously as isolators or non-reciprocal attenuation elements.

From the plot 49(+) of the imaginary portion of the permeability as shown in Fig. 2, it may be observed that when the natural resonance frequency of the magnetic moment as determined by the strength of the applied field coincides with the driving frequency of the high frequency magnetic field components circularly polarized in the preferred sense, a large amount of power can be absorbed from the driving field. However, very little power is absorbed from the oppositely circularly polarized component at this level of magnetization.

Referring to Fig. 3 of the drawings, a hollow circular wave guide 51 is provided with a coaxial cylinder 52 of gyromagnetic material overlying its inner surface. A circumferential field is established in this cylinder of ferrite by the toroidal coil 53, which is energized by the electric source 55, and may be adjusted from low magnetic field strengths through resonance by the variable resistance 54. As may be observed by correlating Figs. 1 and 3, the circularly polarized components of the high frequency magnetic field lie in radial planes which are perpendicular to the steady peripheral biasing magnetic field in the cylindrical core 52. Considering electromagnetic waves of the circular electric or TE_{01} mode, propagating in opposite directions through the wave guide 51, it is clear that the circularly polarized components of the radio frequency magnetic intensity for the opposite directions of propagation will have opposite directions 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. 2.

At ferromagnetic resonance, therefore, the device of Fig. 3 will yield a substantial attenuation for one direction of transmission, and very low attenuation for the

opposite direction of transmission. At lower steady magnetic field strengths, the device will exhibit non-reciprocal phase shift properties, and will have a substantially greater phase shift for one direction of propagation than for the other.

For best operation as a resonance isolator, however, the structure of Fig. 3 should preferably be modified as indicated in Fig. 3A with a cylindrical dielectric liner 56 interposed between the wave guide 51 and the hollow ferrite cylinder 57. In this instance the ferrite element is placed at the point of pure circular polarization so that there will be substantially no attenuation for one direction of transmission and a substantial amount of attenuation for the opposite direction of transmission. This point will vary somewhat with frequency but will always be spaced somewhat from the wave guide wall. The circumferential magnetic field is of sufficient intensity to magnetize the ferrite element 57 to resonance.

The element 52 of the device of Fig. 3 is made from a gyromagnetic 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 52 may be a cylinder of nickel-zinc ferrite of the approximate chemical formula $(Ni_{0.3}Zn_{0.7})Fe_2O_3$ 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 "gyromagnetic 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 Figs. 2 and 3.

The structures of Figs. 4 and 5 operate on the same principle as that described in connection with the structure of Fig. 3. Specifically, Fig. 4 is a cross-sectional view of a coaxial line comprising outer cylindrical conductor 60 and inner conductor 59 with a cylinder of gyromagnetic material 58, coaxial with and mounted on the center conductor 59. The biasing magnetic field for the gyromagnetic element 58 is provided by the circumferential magnetic field associated with direct current flow in the central conductor 59. The coaxial section of wave guide illustrated in Fig. 4 may be merely interposed in a long coaxial transmission line or may be a short coaxial section interposed between two elongated hollow circular transmission lines.

The embodiment of Fig. 5 is a slight variation of Fig. 3 in which no conductors are required within the circular wave guiding tube 63. In this arrangement, the peripheral gyromagnetic ring has been subdivided into a plurality of sectors 64 through 67 for ease of magnetization by the electromagnets 68 through 71, inclusive. These electromagnets 68 through 71 are connected in series and are coupled to a suitable adjustable source of direct current (not shown) at the terminals 72, 73. The series of similarly magnetized sectors 64 through 67, inclusive, have a unitary effect which substantially duplicates that of the continuous ferrite core 52 of Fig. 3.

Fig. 6 illustrates a non-reciprocal arrangement for a section of rectangular wave guide 81 through which the TE₁₀ mode wave is to be propagated. In this arrangement, a hollow rectangular section of conducting wave guide 81 has a hollow rectangular gyromagnetic liner 82 of uniform thickness over all four internal surfaces of section 81, the liner 82 having two wider sides 83 and 84 and two narrower sides 85 and 86 making up the entire liner 82 as shown. A steady peripheral magnetic field is induced in the liner 82 by one or more conducting turns 87 which are energized by a suitable source of direct current (not shown). In the operation of this non-reciprocal device, the upper and lower portions 83 and 84 of the liner 82 serve merely to complete the magnetizing path and have substantially no non-reciprocal effect inasmuch as the biasing magnetic field in these portions is parallel to the circularly polarized radio frequency components of the magnetic field as shown in Fig. 19 discussed hereinbelow. The side walls 85 and 86, however, have the required perpendicular relationship of biasing and high frequency magnetic fields, and, because the opposite senses of magnetization (wall 85 is, for example, as indicated in Fig. 6, biased with an upwardly directed steady polarizing magnetic field, while that in wall 86 is downwardly directed) match the oppositely rotating circularly polarized components of the high frequency magnetic field on either side of the center line of the wave guide, the two narrow side walls 85 and 86 have a cumulative non-reciprocal effect. Thus, at low magnetization levels, both of the narrower sides 85 and 86 of the liner 82 will operate to shift the phase of electromagnetic waves propagating in one direction through the wave guide and neither will have an appreciable effect on oppositely propagating waves. Similarly, if the strength of magnetization is increased so that the liner 82 is at resonance, the two elements will act together to produce attenuation in one direction and substantially no attenuation in the opposite direction. In addition the operation of the structure of Fig. 6 as a resonance isolator would be improved by spacing the narrow side walls 85 and 86 of the ferrite core 82 away from the narrow wave guide walls, so that they are at the point of pure circular polarization of the high frequency magnetic field.

Instead of the rectangular ferrite liner illustrated in Fig. 6 the wave guide 81 may be provided with a central hollow cylinder of ferrite which is permanently magnetized in the circumferential direction and has its axis aligned with that of the guide. Such a ferrite core would have certain advantages over the rectangular liner 83 in that it would be a stock item and would have a low demagnetization factor.

Considering the device of Fig. 7, the hollow rectangular conducting section of wave guide 91 has an elongated element of gyromagnetic material 92 against one of the narrower side walls. In addition a resistive strip 93 is mounted on the inner side of the gyromagnetic element 92 within the wave guide 91. An electromagnet 94 magnetizes the element 92 transversely, as shown. As is illustrated in Fig. 8, the electric field distribution 88 of the electromagnetic wave which is propagated in one direction through the wave guide (shown in dashed line) is distorted so that it bulges toward the gyromagnetic element to a substantial degree, while the field distribution 89 of the oppositely propagated electromagnetic wave 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 and less than one for a wave traveling out of the plane of the paper. 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. 8) than will be present for the wave propagating out of the plane of the paper (solid curve of Fig. 8). 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.

In the cross-sectional view of Fig. 9, the coordinates employed in Fig. 8 are indicated, and an arrangement employing two similarly biased elements 96 and 97 of ferrite at opposite sides of the rectangular conducting wave guide 98 is set forth. In addition, a resistive vane 99 is again mounted on the inner side of one of the ferrite elements 97. In this instance, 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 enhances the difference in field strengths at the resistive vane 99 for the two directions of propagation and thus emphasizes the non-reciprocal attenuation effect.

Figs. 10 and 11 are cross-sectional views of arrangements representing slight variations of the general type of arrangement illustrated by the structures of Figs. 7 and 9. In Fig. 10 the resistive vane 101 is sandwiched between two thin ferrite elements 102 and 103 and the three elements are all placed at one side of the rectangular wave guide 104 to provide a non-reciprocal attenuator.

In Fig. 11 as in Fig. 7, the gyromagnetic element 106 has a resistive vane 107 mounted thereon and the two elements are located at one side of a conductive wave guide 108 with a polarizing magnetic field applied to the gyromagnetic element. In Fig. 11, however, a block of dielectric material 109 is provided at the opposite side of wave guide 108 to equalize some of the dielectric effect of the ferrite, to enhance the non-reciprocal loss effect.

Figs. 12 through 14, inclusive, illustrate the application of the foregoing principles to dielectric wave guides of the type disclosed in A. G. Fox application Serial No. 274,313, filed March 1, 1952, now Patent No. 2,794,959 issued June 4, 1957.

In Fig. 12, the dielectric guide is made up of the elongated dielectric element 112, the ferrite strip 113 and the tapered resistive vane 114 which all have the same functions as the comparable elements of Fig. 7. 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 114 mounted on the outer surface of the gyromagnetic strip 113.

Fig. 13 is a cross-section taken along lines 13—13 of Fig. 12 and constitutes another view of the three component elements.

Fig. 14 is a cross-sectional view of the dielectric guide equivalent of the conducting wave guide arrangement of Fig. 9. In Fig. 14, 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. 8, and the resistive vane 124 attenuates waves propagating in one direction to a greater extent than the oppositely propagated waves.

In the cross-sectional view of Fig. 15, the dielectric material between the two ferrite elements of Fig. 14 has been dispensed with and the isolator structure comprises a simple transversely magnetized rectangular strip of ferrite 126 which guides the waves and also shifts the field patterns in the requisite manner. The resistive vane 127 is mounted on one of the narrow outer sides of the ferrite strip 126.

The resistive vane has been shown in the preceding arrangements illustrated by Figs. 7 through 15, inclusive, as mounted on one of the ferrite strips. This is merely for convenience and the resistive element may be placed at other points in the structure. The important matter is to have the resistive vane located at the point where there is greatest difference between the squares of the electric fields for the two directions of propagation. Instead

of a separate resistive vane, the resistive material may be mixed with the composite ferrite and insulating material in any of the devices of Fig. 7 or Figs. 10 through 13, inclusive. Where symmetrical ferrite structures are used, however, as in Figs. 9 and 14, the resistive material should be placed in only one of the two ferrite strips.

Because of the difference in propagation constants 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. 16 and 17 can be constructed. 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. 16, rectangular wave guiding structure 131 is provided with the usual asymmetrically located, transversely magnetized element of ferrite material, and is also provided with an internal layer 133 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. 16 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. 17 the lossy dielectric material 135 in combination with the wave guide 136 and polarized ferrite element 137 serve to yield the same effect as the device of Fig. 16 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.

Fig. 18 illustrates a phase shifting element which operates similar to the device of Fig. 6. To better understand the operation of the wave guide component of Fig. 18, which is made up of the rectangular guide 141 and the oppositely polarized ferrite elements 142 and 143, reference may be had to Fig. 19. In Fig. 19 the pattern of the high frequency magnetic field of the TE_{10} mode at a given instant in a rectangular wave guide 145 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 146 in the wave guide will rotate in a counterclockwise sense while that observed at point 147 will rotate clockwise. Therefore, for the non-reciprocal effects produced by the two elements 142 and 143 to act cumulatively, i.e., to change the permeability in one direction, they must be oppositely polarized. The non-reciprocal effect produced by the ferrite depends on the level of magnetization, as indicated by Fig. 2. The opposite senses of the magnetization of the two elements is in contrast to the device of Fig. 9, for example, in which the senses of magnetization are the same.

Figs. 20 through 23, 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. 7 through 9, inclusive.

The structure of Fig. 20 is designed to be used with the TE_{01} mode in the circular wave guide 151. Within this wave guide, the ferrite liner element 152 shifts the electric field configuration toward the resistive sheet 153 for a first direction of propagation and away from the resistive sheet for the opposite direction of propagation, so that the resistive vane 153 attenuates waves propagating in the first direction to a substantially greater extent than the oppositely propagated waves. The circumferential field in the ferrite liner 152 of Fig. 20 may be obtained by the permanent magnetization of the core, by a

coil threaded through the liner or by any other suitable method.

In the device of Fig. 21, the ferrite liner 152 and the resistive sheet 153 within the circular wave guide 151 are assisted in the field displacement action by the central hollow coaxial ferrite element 154 which is magnetized in the same angular sense as the outer ferrite core 152 by passing direct current through a centrally located conductor 155. This central ferrite element 154 acts in much the same manner as the second ferrite element in Fig. 9 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 152 to create a greater differential loss at the resistive sheet 153.

Figs. 22 and 23 illustrate resistance sheet field-displacement isolators for the TE_{11} mode.

In Fig. 22, a semicylindrical liner element 158 of ferrite overlies a portion of the inner surface of the circular wave guide 159. The electromagnet 161 provides the magnetic field for biasing the element 158 of ferrite. While this electromagnet 161 is shown energized by the modulating signal source 162, it may alternatively be provided with a steady biasing current. In the absence of the resistive sheet 163, the semicircular ferrite element 158 will produce non-reciprocal phase shift and attenuation as indicated by Fig. 2 for a TE_{11} wave having its electric vector polarized either vertically as indicated by the solid arrow 165 in Fig. 22 or horizontally as indicated by the dotted arrow 166. With the resistive sheet 163 added to the structure, however, the unit will become an isolator for vertically polarized electromagnetic waves due to the field displacement effect, and will exhibit its non-reciprocal phase displacement properties for horizontally polarized waves.

In the isolator of Fig. 23, a resistive sheet 171 is mounted on one internal surface of the cylindrical ferrite liner 172, which in turn is supported by the inner surface of the circular conducting wave guide 173. The biasing magnetic field for the core 172 is applied to the top and bottom of the cylindrical core 172 as illustrated by the branching arrows. When the TE_{11} mode is vertically polarized as indicated by the solid arrow 165 at the center of the wave guiding passageway, the structure of Fig. 23 bears much the same relationship to that of Fig. 22 as the structure of Fig. 9 does to that of Fig. 7, and the field displacement is enhanced. The structure of Fig. 23 does not yield a non-reciprocal 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 166 of Fig. 23.

Fig. 24 illustrates a resistance sheet field-displacement isolator for the TE_{21} mode having a field orientation as illustrated by arrows 175. This device, for the TE_{21} mode is analogous to the structure of Fig. 23 for the TE_{11} mode, and thus has the single resistive vane 176 mounted on the hollow ferrite cylindrical liner 177 within the conducting guide 178. 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 176 and the field distribution for the opposite direction of transmission will be shifted away from it, so that the result will be the non-reciprocal 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 Figs. 25 and 26, a non-reciprocal device is disclosed in which several of the effects discussed above are utilized cumulatively to produce desired non-reciprocal phase

and/or attenuation effects. In Fig. 25 the variable frequency microwave source 181 energizes the wave guide 182, which is coupled by the isolator 183 to another section of wave guide 184. Fig. 26 is a cross-sectional view of the isolator 183 taken along lines 26—26 of Fig. 25.

In Fig. 26 the outer circular conducting wave guide 201 encloses a number of concentric cylinders of various materials. Specifically, proceeding inwardly there is a thin layer of high resistance material 202, a ferrite cylinder 203 of substantial thickness, a resistance sheet 204, a very thick cylinder 205 of dielectric material containing a slight amount of lossy material distributed therethrough, a hollow cylinder of permanently magnetized ferrite material 206 and a central cylinder of dielectric material 207 similar in composition to cylinder 205. A circumferential magnetic field is applied to the outer ferrite cylinder 203 by means of a coil 211 which is similar in construction to the coil 53 illustrated in Fig. 3. The magnetization in this outer cylinder 203 may be from a suitable source of direct current 212 or alternating current 213. The level of magnetization in the cylinder 203 may be controlled from zero field strength up through that required for ferromagnetic resonance by the variable resistances 214 and 215 associated respectively with the steady and alternating current sources. The double pole double throw switch 216 and the switch 217 permit applying the steady and alternating currents together or separately to the coil 211, and facilitate reversing the polarity of the magnetization in the outer ferrite cylinder 203.

Considering the possible modes of operation of the structure of Fig. 26 when energized in the TE_{01} mode, it may be noted that with the sense of peripheral magnetization in the outer cylinder 203 the same as that of the permanently magnetized inner cylinder 206, these elements together with the lossy material 203 and the resistive sheet 204 will constitute a field-displacement isolator. With angular 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 non-reciprocal phase shift will not be unduly great.

When the magnetic field is reversed and energized to a point just below resonance such as is indicated by line 221 on Fig. 2, and the microwave source 25 is adjusted to a frequency just above cut-off, several non-reciprocal attenuation factors 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 205, 207 and the lossy inner coating 202 of the guide 201 are increased. In addition, the outer cylinder 203 is biased to a magnetization level sufficiently close to resonance that it is absorbing a substantial amount of energy (note the intersection of line 221 and the positive dotted curve of Fig. 2). The cumulative non-reciprocal isolation effects noted above make the structure of Fig. 26 an excellent isolator.

Although many of the devices have been disclosed specifically, as for example by stating that the gyromagnetic 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 gyromagnetic material having low conductivity such as were discussed hereinabove may be used in any of the disclosed devices, and the biasing magnetic field may be either steady, alternating, or a superposition of an alternating on a steady magnetic field as disclosed in conjunction with Figs. 25 and 26. In this regard it may be noted that many of the structures involve very short gaps in the magnetic circuits (see Fig. 7 for example), so that high frequency alternating fields may

readily be applied to the ferrite elements, and they may, therefore, readily be employed for modulating purposes. In addition it might be noted that the present phase shifters and isolators may involve the use of tapered transitions at the point where the non-reciprocal element is coupled to standard sections of wave guide.

Many of the devices disclosed hereinabove are non-reciprocal phase shifting elements in which the difference in phase shift for the two directions of transmission is directly proportional to the length of the gyromagnetic element in question. To fabricate structures having any desired difference in phase shift for oppositely propagated waves, therefore, it is only necessary to make a measurement of the difference of phase shifts for a sample of known length, determine the difference in phase shift in degrees per unit length for that particular cross-section, and then make up a unit of identical cross-section having a gyromagnetic element of a length equal to the desired difference in phase shift divided by the factor indicating the number of degrees of non-reciprocal phase shift per unit length. Thus, to construct a gyrator, which is a two-terminal device having a 180 degree difference in phase shift for the two directions of transmission, from a sample which produced 18 degrees non-reciprocal phase shift per centimeter the length of the phase shifting element would have to be 10 centimeters. Concerning so-called "gyrators," it might be mentioned that these are one of the more important components which can be made employing the non-reciprocal phase shifting structures disclosed in the present application.

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. A non-reciprocal structure including means for introducing a non-reciprocal effect to propagating electromagnetic wave energy comprising a substantially circular wave guiding structure supportive of traveling waves, means for applying electromagnetic wave energy to said structure for propagation along the longitudinal axis of said structure, a hollow cylindrical element of low conductivity material of the type that exhibits gyromagnetic properties at the frequency of said wave energy located within said guide, and means for applying a magnetic field to said element having lines of force forming closed circles of a single polarity with the planes defined by said circles oriented perpendicularly to the longitudinal axis of said wave guiding structure.

2. A non-reciprocal structure including means for introducing a non-reciprocal effect to propagating electromagnetic wave energy comprising a hollow conductive wave guide supportive of traveling electromagnetic waves propagating in a direction along the longitudinal axis of said guide, a layer of material of low conductivity exhibiting gyromagnetic effects at the frequency of wave energy supported by said guiding structure overlying at least two opposing portions of the inner surface of said wave guide, and means for applying a magnetic field to said layer having magnetic lines of force conforming to closed loops of a single polarity, said loops being primarily enclosed by and having substantially the same shape and orientation as the conductive boundary of said wave guide with the planes defined by said loops oriented perpendicularly to the longitudinal axis of said hollow wave guide.

3. Means for introducing a non-reciprocal effect to the TE_{11} mode in an elongated wave guiding structure of substantially circular cross-section, comprising one-half of a hollow cylindrical element of material exhibiting gyromagnetic effects at the frequency of wave energy supported by said structure mounted therein con-

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tiguous to the wall of said guide, means for applying wave energy to said guide in the dominant TE_{11} mode in circular guide, and means for applying a magnetic field to said element having at least the lines of force thereof within the major portion of said element conforming to the shape of said wave guiding structure.

4. A non-reciprocal structure including means for introducing a non-reciprocal effect to propagating electromagnetic wave energy comprising a conducting wave guide of circular cross-section supportive of traveling waves, means for applying wave energy in the circular electric mode to said guide, a hollow cylindrical element of material of low conductivity exhibiting gyromagnetic effects at the frequency of wave energy supported by said wave guide located within said wave guide, and means for circumferentially magnetizing said element.

5. The non-reciprocal wave guide structure according to claim 1 including a hollow cylinder of non-magnetic dielectric material interposed between said material exhibiting gyromagnetic effects and said guide.

6. The non-reciprocal wave guiding structure according to claim 2 wherein said element overlies a major portion of the inner surface of said guide.

7. The non-reciprocal wave guiding structure according to claim 2 wherein said guide is of rectangular cross-section and wherein said layer comprises material adjacent to the inside of each of the four walls of said guide.

8. The non-reciprocal wave guiding structure according to claim 2 including a layer of non-magnetic dielectric material interposed between said layer exhibiting gyromagnetic effects and said inner surface.

9. The non-reciprocal wave guiding structure according to claim 2 wherein said guide is of circular cross-section and wherein said layer comprises a hollow cylindrical liner within said guide.

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