

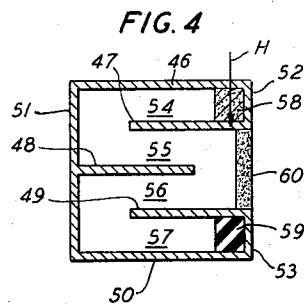
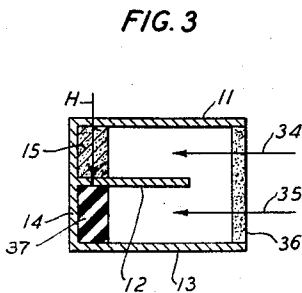
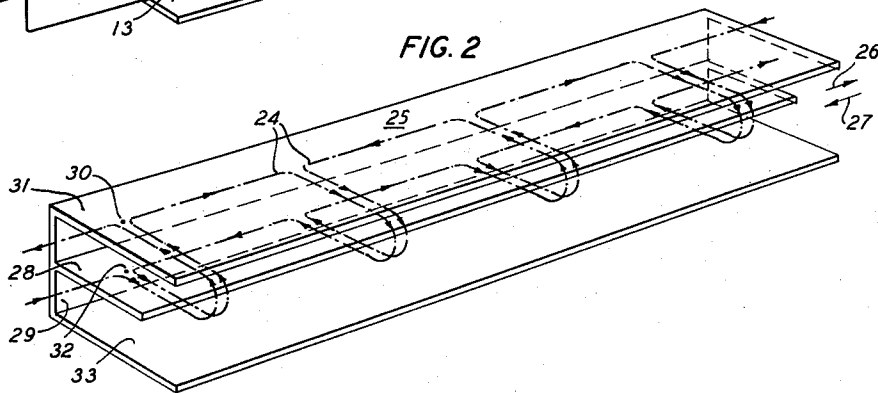
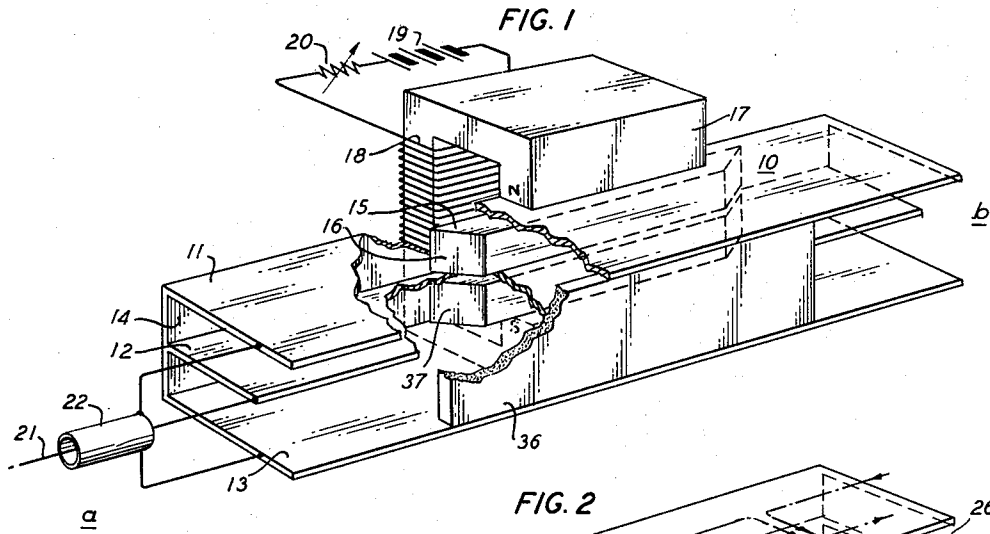
Sept. 8, 1959

S. WEISBAUM

2,903,656

NONRECIPROCAL CIRCUIT ELEMENT

Filed Dec. 22, 1955



INVENTOR
S. WEISBAUM
BY *Ray M. Porter, Jr.*

ATTORNEY

1

2,903,656

NONRECIPROCAL CIRCUIT ELEMENT

Samuel Weisbaum, Morristown, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Application December 22, 1955, Serial No. 554,883

7 Claims. (Cl. 333-24)

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

It is an object of the invention to introduce nonreciprocal attenuation into a broad frequency band of electromagnetic waves at a substantial power level.

The wave guide transmission art has been significantly advanced by making use of the nonreciprocal properties of gyromagnetic materials. It has been noted that the electromagnetic field of wave energy is displaced transversely in a rectangular wave guiding structure when a polarized element of gyromagnetic material is included within the structure. This displacement is different for opposite directions of wave propagation through the structure. Resistive material can be suitably placed within the structure to dissipate a substantial portion of the energy of a wave propagated through the structure in one direction. Because of the nonreciprocal field displacement described above, the resistive element can be placed so as to dissipate only a small portion of the wave energy for the opposite direction of propagation. A structure such as that described above which dissipates energy for one direction of propagation and freely transmits energy in the other direction is termed an "isolator."

It is a more specific object of the present invention to provide new and improved types of resistance sheet isolators.

As stated above, resistance sheet isolators have been constructed wherein energy dissipation takes place in an element of resistive material positioned within a wave guide at a point of substantially large intensity of the electric field for one direction of propagation. Since this point is displaced for the opposite direction of propagation, nonreciprocity results. However, the total amount of field displacement for opposite directions of propagation is limited by the size of the wave guide and the strength of the polarizing field. The transverse dimensions of the resistive element are therefore also limited. Accordingly, the amount of energy which can be dissipated in this element is restricted and the power capacity of the isolator relatively low.

It is therefore an object of the present invention to provide resistance sheet isolators capable of dissipating greater amounts of energy per unit of length than was heretofore possible.

Special features of the invention which permit a greater energy dissipating capacity reside in a new and improved wave guide cross-sectional shape for use in isolators of the resistance sheet type. This new cross section, comprising three parallel plates joined by a perpendicular wall at one longitudinal edge of the plates, allows the use of a much larger dissipating element for substantially smaller field strengths in the ferrite element. The dissipating element can be used as one wall of the guide opposite the perpendicular wall. This type of guide can be excited in a mode similar to rectangular guide modes and permits an entire wall of the guide to be

2

resistive material for dissipating energy in a nonreciprocal fashion. This allows the dissipation of substantially larger amounts of energy and a correspondingly higher power capacity.

Another added advantage of this cross section is its ability to transmit electromagnetic wave energy at frequencies far below those possible with conventional rectangular hollow pipe wave guides of comparable dimensions.

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

In the drawings:

Fig. 1 is a perspective view of a principal embodiment of the invention showing a ferrite loaded wave guide isolator with a resistive wall in accordance with the principles of the invention;

Fig. 2, given for the purposes of illustration, is a perspective view of a wave guide similar to that of Fig. 1 showing typical magnetic field loops within the guide at a particular instant;

Fig. 3, given for the purposes of illustration, is a cross-sectional view of the isolator shown in Fig. 1; and

Fig. 4 is a cross-sectional view of another principal embodiment of the invention showing a multicompartimented cross section having ferrite loading and resistive material in accordance with the invention.

More particularly, in Fig. 1 is shown a section of wave guide 10 having three parallel conductive members 11, 12 and 13 joined to a perpendicular conductive wall 14. Center member 12 is narrower in width than outer members 11 and 13, and outer members 11 and 13 are of the same width. Members 11 and 13 extend sufficiently far beyond center member 12, opposite perpendicular wall 14, so that guide 10 is capable of supporting wave energy with a field configuration to be described hereinafter.

Interposed within guide 10 between members 11 and 12 and extending parallel to and longitudinally along wall 14 is a rectangularly shaped element 15. Element 15 may be made of any of the several gyromagnetic materials, one of which is known as ferrite, comprising ferromagnetic materials combined in a spinel structure. It may, for example, be a combination of iron oxide and a small amount of one or more bivalent metals such as nickel, magnesium, zinc or manganese. It is necessary that these materials be combined so as to exhibit the desired gyromagnetic properties. The ends of element 15 may be provided with suitable tapers, such as taper 16, to prevent undue reflections from the ends of element 15 and thus present a better impedance match to guide 10. Opposite element 15 and between members 12 and 13 along wall 14 is dielectric counterpoise 37. Counterpoise 37 is composed of dielectric material having properties to be more fully discussed hereafter. Sheet 36, opposite and parallel to wall 14 and extending between members 11 and 13 near their outer edges is composed of resistive material suitable for dissipating electrical energy.

Element 15 is biased by a steady magnetic field at right angles to the direction of propagation of wave energy through guide 10. As shown in Fig. 1, this field may be supplied by a solenoid structure comprising magnetic core 17 having two oppositely disposed pole-pieces, one at N and the other against the lower side of guide 10. These pole-pieces bear upon opposite sides of outer members 11 and 13 of guide 10 in the region of elements 15 and 37, respectively. Turns of wire 18 are so wound on core 17 and connected to source of po-

tential 19 that they produce a north magnetic pole N at member 11 of guide 10 in the region of element 15 and a south magnetic pole at member 13 in the region of counterpoise 37. This field, however, may be supplied by any other suitable means, such as permanently magnetizing element 15, using a permanent magnet to supply the field, or using a solenoid without a magnetic core. Any means will be sufficient which will produce a magnetic field in element 15 of a strength to be hereinafter described. In Fig. 1, variable resistor 20 is connected in series with source of potential 19 to vary the strength of this biasing field.

Wave guide 10 in Fig. 1 is capable of supporting electromagnetic energy in a transverse electric mode the electric field vectors of which extend radially from center member 12 to outer members 11 and 13. Such a wave may be excited in guide 10 by a coaxial line. In Fig. 1 a coaxial line comprising center cylindrical conductor 21 and outer concentric cylindrical conductor 22 is used to excite this wave. Outer conductor 22 is connected to outer members 11 and 13 of guide 10 and center conductor 21 is terminated on the right hand end of center member 12 opposite perpendicular wall 14.

The displacement effect of element 15 upon wave energy propagated along guide 10 may most readily be understood by referring to explanatory Fig. 2. In Fig. 2 are shown, for the purposes of illustration, representative loops 24 of the high frequency magnetic field of a dominant mode wave in wave guide 25 at a particular instant. Guide 25 is similar in all respects to guide 10 of Fig. 1, comprising three parallel conductive members 28, 31 and 33 joined to a perpendicular wall 29. Center member 28 is narrower in width than outer members 31 and 33, and outer members 31 and 33 are of the same width. In Fig. 2, the arrows 26 and 27 indicate the forward and backward directions of propagation, respectively, of a wave propagated in guide 25. The arrows on the individual loops 24 indicate their polarity at any particular point in the guide at the given instant. It will be noted that the lines 24 of magnetic intensity are loops which lie entirely in curved planes which partially surround center member 28 and are parallel to center member 28 near perpendicular wall 29. It will then also be noted that at point 30 within guide 25 between members 28 and 31 and near perpendicular wall 29, and at point 32 within guide 25 between members 28 and 33 and near perpendicular wall 29, the magnetic intensity of the wave is circularly polarized as the wave propagates along guide 25. For a wave propagating in the forward direction, the direction of arrow 26, a counterclockwise rotating component of the magnetic field is presented at point 30. That is to say, as the wave propagates to the right in the figure, point 30 "sees" a magnetic field vector which appears to rotate in space in a counterclockwise sense when viewing it from above. Similarly, point 32 also "sees" a counterclockwise rotating magnetic field vector. However, for the opposite direction of propagation through guide 25, corresponding to arrow 27, the circularly polarized component of magnetic field, as seen at points 30 and 32, will appear to rotate in an opposite, or clockwise, direction. That is, points 30 and 32 will "see" a magnetic field vector which appears to rotate in space in a clockwise direction. Finally it should be noted that the intensity of the longitudinal magnetic field in guide 25 is zero at the outer or right hand edge of center member 28, and increases symmetrically to a maximum at wall 29.

One physical explanation which has been advanced to explain the nonreciprocal properties of gyromagnetic materials is the so-called "electron spin coupling theory." According to this theory, unpaired electron spins in the gyromagnetic material tend to have their axes of spin aligned with an externally applied magnetic field. The electron spins are phenomena associated with the indi-

vidual electrons within the material. If the spin axes are momentarily deflected from alignment with the externally applied field, they will not immediately realign themselves, but will precess gyroscopically about the line of the externally applied field. This precession will always be in a clockwise direction when looking along the line of the applied field.

If the deflection is caused by a periodically varying magnetic field, such as that of a transversely propagating electromagnetic wave, the resulting precession will be circular or elliptical and will produce components of magnetic flux polarized in the same angular sense as the precessing electron spins and their associated magnetic moments. If gyromagnetic material is placed in a region of circular polarization of the wave propagated within a wave guide, the high frequency magnetic intensity of the wave energy may be rotating in the same sense as the direction of precession of the magnetic moment of the electron spins. In that case, the wave energy will encounter an effective permeability less than unity. However, if the direction of propagation of the wave is reversed, the high frequency magnetic intensity of the wave energy will be rotating in a sense opposite to the direction of precession, and hence the wave will encounter an effective permeability greater than unity in the ferrite material. This results in a difference in permeability for opposite directions of propagation of electromagnetic wave energy through the gyromagnetic material.

In the cross-sectional view of Fig. 3, taken at the center portion of guide 10 in Fig. 1, it is seen that element 15 is placed in guide 10 between members 11 and 12 and near perpendicular wall 14. The nonreciprocal effect can be seen by considering the impedance presented to a propagated wave by the loaded cross section looking along arrows 34 and 35, directed into the cross section from the open end. The biasing or polarizing magnetic field is represented in Fig. 4 by the transverse vector labeled "H." It is apparent that a wave traveling out of the plane of the paper will have a circularly polarized component in the region of element 15 rotating in a clockwise sense. Since the angular sense of the precessing magnetic moments for a field applied in the direction indicated by arrow "H" will be clockwise, the wave propagating out of the plane of the paper will encounter a permeability less than unity. However, for a wave traveling into the plane of the paper, the region of element 15 will be circularly polarized in a counter-clockwise sense while the angular sense of the precessing magnetic moments will still be clockwise. Hence the wave traveling into the paper will encounter a permeability in the ferrite region greater than unity.

Element 15 is biased by the external magnetic field "H" to a point where the product of the permeability which is less than unity, and the dielectric constant of the ferrite material in element 15 is equal to the same product for counterpoise 37 for the direction of propagation out of the plane of the paper. The strength of the external magnetic field required to obtain this condition is only a small fraction of that required to produce gyromagnetic resonance in the ferrite material. It is apparent that when looking along arrows 34 and 35, the impedance presented to the waves propagated out of the plane of the paper in the regions between members 11 and 12 and between members 12 and 13 will be substantially identical, and the wave will be unable to distinguish between the two halves of line 10. The field in line 10 will therefore be uniformly distributed between these two regions and will be in a balanced condition. For the direction of propagation into the plane of the paper, however, the permeability in element 15 will be greater than unity and the product of permeability and dielectric constant will no longer be equal to the same product for counterpoise 37. The wave will therefore be unbalanced and will tend to radiate laterally from the open end opposite wall 14.

This radiating electric field will induce currents in resistive sheet 36, placed across the open end of line 10 opposite wall 14, and the resistive material of sheet 36 will dissipate this energy.

While Figs. 1 and 3 show gyromagnetic element 15 between members 11 and 12 in guide 10, this element may just as well be placed between members 12 and 13, and counterpoise 37 placed between members 11 and 12. Since the angular sense of the circular polarization is the same on both sides of center member 12, such placement of element 15 would not affect the operation of the device in any way except to interchange the bottom and top halves of guide 10. However, if the direction of the polarizing field, represented by the vector labeled "H," is reversed, the angular sense of the precession of the magnetic moments of the electron spins will also be reversed and the nonreciprocal effect will be inverted. That is, for propagation out of the plane of the paper, energy would radiate out to sheet 36 in Fig. 3, and for propagation into the plane of the paper the guide would be balanced and no radiation would take place.

Figs. 1 and 3 also show element 15 as a rectangular slab placed against perpendicular wall 14. It should be noted that element 15 may be any shape which is convenient and may be placed anywhere across the cross section so long as it is in a region of circular polarization. In the preferred embodiment illustrated in Figs. 1 and 3, the point of maximum circular polarization is found to be near to the perpendicular wall 14.

Returning again to Fig. 1, the strength of the magnetic field which biases element 15 is selected so as to produce the desired equality of $\mu\epsilon$ products for the direction of propagation from b to a . Sheet 36 of resistive material is inserted between outer members 11 and 13 of guide 10 perpendicular to and spaced away from center member 12. Sheet 36 may be composed of any energy dissipating material, for example, carbon loaded polyethylene. Any radiating electric intensity vector existing near to and parallel to sheet 36 will induce currents in the resistive material of sheet 36 which will be quickly dissipated. Obviously, sheet 36 may be of any dissipating material whatever and of a bulk many times that possible if it were to be confined within a wave guide. For the direction of propagation of a wave in guide 10 opposite to that described above, that is, from a to b of Fig. 1, the permeability would be greater than unity and there would no longer be a balance in the two halves of guide 10. In Fig. 1, counterpoise 37 is inserted in guide 10 between members 12 and 13 opposite to member 15. The material of rod 37 is chosen and rod 37 is placed so that the product of its permeability and its dielectric constant is equal to the same product for element 15 for the direction of propagation from b to a as described above. Of course, for the direction of propagation from a to b the permeability-dielectric constant product will no longer be the same and the dissipation described above will take place.

Thus, if a dominant mode microwave signal is applied to terminal a of channel wave guide 10, it will be substantially attenuated by the time it reaches terminal b . However, if a dominant mode microwave signal is applied to terminal b of channel wave guide 10, it will not be attenuated before reaching terminal a . This property of nonreciprocally attenuating a signal is the unique characteristic of the circuit component called an "isolator."

Since the cutoff wavelength of energy propagated through a rectangular wave guide is proportional to the effective width of the guide, the structure depicted in Fig. 1 has the added advantage of a lower cutoff frequency than a conventional rectangular wave guide of comparable dimensions. The effective width of guide 10 is almost twice that of a rectangular guide of the same overall width, the electrical width being measured from the upper half of perpendicular wall 14 around the end of center member 12 and back to the lower half of wall 14.

In Fig. 4 is shown a cross section of an isolator similar to the one shown in Fig. 1 but having the further advantage of even lower frequency ranges. In Fig. 4 the wave guide comprises five parallel conductive members 46 through 50 and three perpendicular conductive walls 51, 52 and 53. Together these parallel members and perpendicular walls form four inner spaces or compartments 54, 55, 56 and 57 which are simply interconnected to one another. Thus members 46 and 47, and walls 51 and 52, form a rectangular compartment 54 which is connected to another similar rectangular compartment 55 bounded on three sides by members 47 and 48 and perpendicular wall 51. Similarly compartment 55 is connected to compartment 56, and 56 to 57, but on alternate sides of adjacent compartments. Together these compartments form a continuous electrical path of an effective width many times the actual outer width of the structure. This path extends from wall 52 through compartment 54, around member 47, through compartment 55, around member 48, through compartment 56, around member 49, and through compartment 57 to wall 53.

As shown in Fig. 2, a point of circular polarization exists in the guide shown in Fig. 4 near wall 52 and near wall 53. Polarized element 58 of gyromagnetic material is placed at this point near wall 52 and dielectric counterpoise 59 near wall 53. The magnetic field represented by vector "H" causes the permeability difference resulting in a net resultant electric vector radiating to the right of member 48 for the direction of propagation out of the plane of the paper. Sheet 60 of resistive material dissipates the energy represented by this net resultant electric vector. For the direction of propagation into the plane of the paper counterpoise 59 has a $\mu\epsilon$ product exactly equaling that of element 58 and no net resultant electric vector exists at sheet 60. The structure shown in Fig. 4 is therefore also capable of exhibiting isolator properties.

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

What is claimed is:

1. A nonreciprocal electromagnetic wave guiding structure for waves within a given frequency range of interest comprising at least three conductively connected conductive plates extending longitudinally parallel to each other, at least one magnetically polarized element of material which exhibits the gyromagnetic effect at frequencies within said given range positioned within said structure, a sheet of resistive material mounted between two alternate ones of said plates and spaced away from the intermediate one of said plates, and at least one member of dielectric material positioned within said structure electrically opposite to said magnetically polarized element, said member having a dielectric constant and a permeability the product of which is substantially equal to the product of the dielectric constant and the permeability of said magnetically polarized element for one direction of propagation of said waves through said structure.

2. A nonreciprocal attenuator for electromagnetic waves within a given frequency range of interest comprising an elongated section of bounded wave guide of rectangular transverse cross section having first and second pairs of opposed parallel walls, said first pair and one wall of said second pair being conductive, said remaining wall being at least in part resistive, at least one elongated plate of conductive material mounted within said section of wave guide parallel to the two oppositely disposed conductive walls of said section of wave guide, said conductive plate extending from a conductive portion of said second pair of opposed parallel walls and being of sub-

stantially the same length as said section of wave guide and of width substantially less than said parallel conductive walls, at least one element of magnetically polarizable material which exhibits the gyromagnetic effect at frequencies within said given range mounted between said one plate and one wall of said pair of conductive walls, means for establishing a magnetic field in said element, and at least one element of dielectric material mounted between said one plate and the other wall of said pair of conductive walls, said dielectric material having a dielectric constant and a permeability the product of which is substantially equal to the product of the dielectric constant and the permeability of said magnetically polarizable element for one direction of propagation of said waves through said attenuator, said resistive part of said remaining wall forming a central portion thereof and being exposed to the wave propagation path of said wave guide.

3. An isolator for electromagnetic waves within a given frequency range of interest comprising at least three conductively connected conductive plates extending longitudinally parallel to each other, an intermediate one of said plates being narrower in width than the other of said plates, a sheet of resistive material positioned normal to said conductive plates and spaced away from said intermediate plate in symmetrical relationship therewith, at least one magnetically polarized element of material which exhibits the gyromagnetic effect at frequencies within said given range mounted between two of said conductive plates, and reciprocal loading means included between two of said plates for producing an electrical balance for one direction of energy propagation through said isolator.

4. An isolator for electromagnetic waves according to claim 3 wherein said reciprocal loading means comprises a member of dielectric material which is oppositely disposed to said element of magnetically polarized material.

5. A nonreciprocal electromagnetic wave guiding structure for waves within a given frequency range of interest comprising a wave guide of rectangular transverse cross section with pairs of opposed broad and narrow walls, said broad walls and one wall of said narrow walls being conductive, a partial width conductive plate extending from and conductively connected to said one conductive narrow wall in a direction parallel to said broad walls thereby forming a pair of simply interconnected inner compartments, a magnetically polarized element of material which exhibits the gyromagnetic effect at frequencies within said given range mounted within one of said inner compartments, an element of dielectric material mounted within the other of said compartments for balancing said structure electrically for one direction of energy propagation therethrough, and at least the central portion of the other wall of said pair of narrow walls being composed of an energy dissipating material which is exposed to said inner compartments.

6. In combination, a longitudinally extending E-shaped conductive wave guiding member for electromagnetic wave energy within a given frequency range of interest comprising three parallel planes and one mutually perpendicular end plane, the center plane of said three parallel planes being of less width than the remaining pair

of parallel planes, a bounding member of resistive material spaced away from said center plane and extending perpendicularly between the extreme edges of said remaining pair of parallel planes, a magnetically polarized element of material which exhibits the gyromagnetic effect at frequencies within said given range located between said center plane and one of the planes of said remaining pair, and an element of dielectric material located between said center plane and the other of the planes of said remaining pair, said dielectric material having a dielectric constant-permeability product for one direction of propagation which causes said guiding member to be balanced electrically for said one direction of propagation.

7. A nonreciprocal electromagnetic wave energy guiding structure for waves within a given frequency range of interest and having a rectangular transverse cross section, said structure comprising an odd numbered plurality of parallel conducting plates extending in the path of said energy, a conductive wall extending in a direction perpendicular to said plates and conductively connected at least to the outer ones and the central one of said plates, a sheet of resistive material forming a central portion of the remaining boundary wall of said structure positioned parallel to said perpendicular wall and extending between two alternate ones of said plates, an element of magnetically polarized material which exhibits the gyromagnetic effect at frequencies within said given range interposed between two of said plates, and an element of dielectric material interposed within said structure electrically opposite to said magnetically polarized element, said dielectric element having a dielectric constant-permeability product for one direction of propagation which causes said guiding structure to be balanced electrically for said one direction of propagation.

References Cited in the file of this patent

UNITED STATES PATENTS

2,231,602	Southworth	Feb. 11, 1941
2,281,552	Barrow	May 2, 1942
2,511,610	Wheeler	June 13, 1950
2,644,930	Luhrs	July 7, 1953
2,721,312	Grieg	Oct. 18, 1955
2,745,069	Hewitt	May 8, 1956
2,755,447	Englemann	July 17, 1956
2,802,991	Coale	Aug. 13, 1957
2,824,280	Beers	Feb. 18, 1958

OTHER REFERENCES

"N.B.S. Magnetic Attenuator," Technical News Bulletin of the Bureau of Standards, vol. 35, No. 8, August 1951, pages 110-11.

Fox et al.: "Behavior and Applications of Ferrite," Bell Technical Journal, vol. 34, No. 1, pages 5-104.

Darrow: Bell System Technical Journal, vol. 32, Nos. 1 and 2, January and March 1953, pages 74-99 and 384-405. (Copy in Scientific Library.)

Spectroscopy at Radio and Microwave Frequencies, (D. J. E. Ingram), published by Butterworths Scientific Publications (London), 1955, pages 205 and 215 relied on. (Copy in Scientific Library.)