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E. H. TURNER

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NONRECIPROCAL WAVE TRANSMISSION

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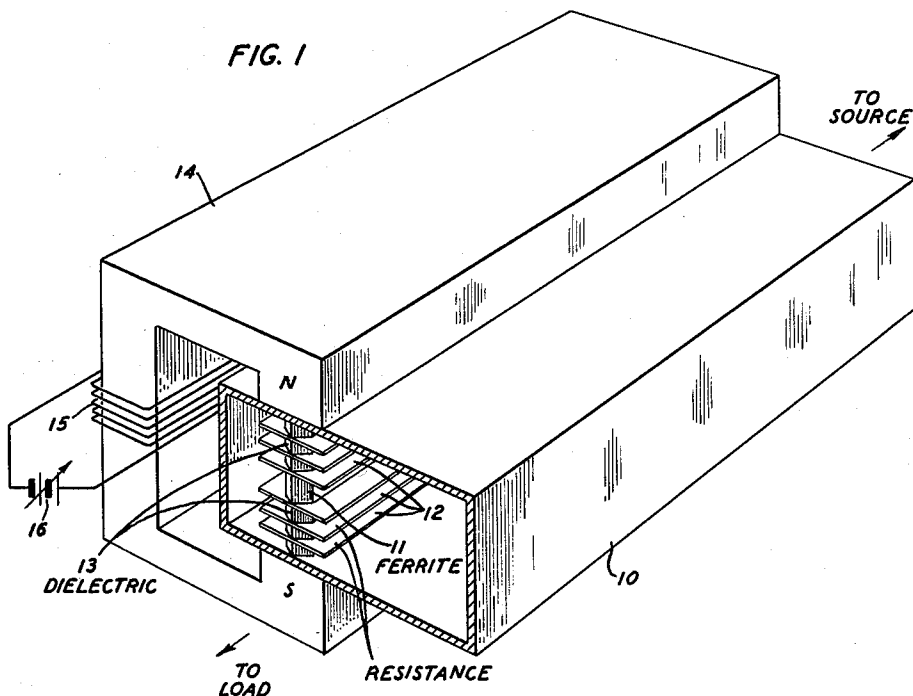


FIG. 2



FIG. 2A

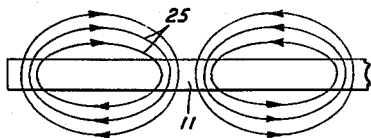


FIG. 3

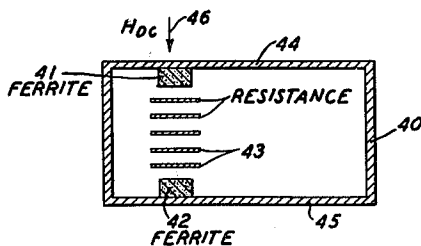
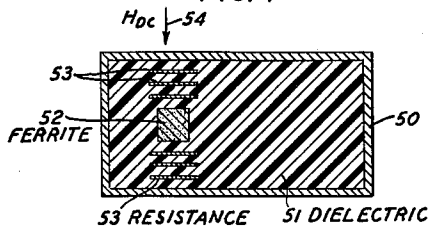


FIG. 4



INVENTOR
E. H. TURNER
BY *Ray M. Porter Jr.*

ATTORNEY

1

2,922,964

NONRECIPROCAL WAVE TRANSMISSION

Edward H. Turner, Red Bank, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

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This invention relates to nonreciprocal microwave electromagnetic wave transmission devices and, more particularly, to improved one-way transmission devices employing the properties of gyromagnetic materials to directionally isolate one electromagnetic device from another.

The desirability of directional isolation in electromagnetic wave systems has been apparent for some time. For example, a very simple but particularly useful application of an isolator is found in a system in which the source or wave generation equipment, for example, a frequency modulated oscillator, is to be worked directly into a load or a transmitting antenna. As is well known, serious matching problems are encountered in such a system since any reflection or other return of energy from the antenna load has an undesirable effect upon the oscillator source. An isolator, therefore, having low loss or attenuation for waves passing from the oscillator to the antenna and high return loss or attenuation for waves passing from the antenna to the oscillator, will greatly simplify the problem.

It is an object of the present invention to introduce a substantially higher degree of attenuation to wave energy propagating in one direction along a transmission path than to wave energy propagating in the opposite direction by new and improved apparatus.

Recently the nonreciprocal properties of polarized elements of gyromagnetic material, often designated ferrites, have been utilized to provide isolators by locating thin resistive elements in particular locations relative to the gyromagnetic material so that currents are induced and dissipated in the resistance for one direction of propagation to a substantially greater extent than for the other direction of propagation. It is recognized that the present invention provides another of several alternative structures each of which has its own outstanding features and advantages that make it primarily suitable for one application and perhaps only secondarily suitable for another application. The principal advantage of the isolator provided by the present invention stems from the fact that it is difficult to obtain a sufficient concentration of energy in a thin vane to dissipate any substantial amount of power without unduly increasing the length of the isolator structure. The isolator in accordance with the present invention provides a substantially increased concentration of resistive material in a given longitudinal length thereby substantially increasing the amount of power that may be dissipated in that length.

Thus, in accordance with the present invention, a plurality of spaced, parallel, resistive vanes are located in the cross section of a conductively bounded rectangular wave guide which is to be interposed in the path requiring isolation. The orientation of the vanes is such that they are normal to the ordinarily transverse electrical polarization of wave energy in the guide and so have no effect upon it. At least one elongated element of gyromagnetic material is located in the vicinity of the vanes and so arranged and biased that for the direction of propagation from the source to the load it has a permeability and di-

2

electric constant product that substantially equals the corresponding product of the material filling the remainder of the guide. For this direction of propagation the element has little effect upon the field patterns of the energy within the guide. For the opposite direction of propagation, however, the element has a substantially different product of permeability constant and dielectric constant from that of the material in the remainder of the guide and acts to support a surrounding electric field having substantial longitudinal electric field components that are intercepted and dissipated by the resistive vanes.

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

In the drawings:

Fig. 1 is a perspective view of a preferred embodiment of the invention showing the relative locations of the gyromagnetic element and the resistive vanes;

Figs. 2 and 2A, given by way of explanation, represent the electric field pattern as supported by the gyromagnetic element of Fig. 1 for one direction of propagation; and

Figs. 3 and 4 show cross-sectional views representing modifications of the embodiment of Fig. 1.

Referring more specifically to Fig. 1, a nonreciprocal attenuator or isolator is shown as an illustrative embodiment of the present invention. The isolator comprises a section 10 of conductive rectangular wave guide which is to be interposed in the path of linearly polarized wave energy requiring isolation, such as between a source and a load. Guide 10 has conductive wide walls of internal transverse dimension of at least one half wavelength of the energy to be conducted thereby and narrow walls of internal transverse dimension substantially one half the wide dimension. Located in guide 10 and centered therein at an asymmetrical position displaced somewhat more than one quarter of the width of guide 10 to the left-hand side of the center line thereof is a stack of elements comprising a center element 11 of gyromagnetic material followed on top and bottom by a plurality of thin vanes 12 of highly resistive material supported and spaced from each other by dielectric spacers 13. The remainder of guide 10 is filled by a nonconductive dielectric medium, which in this embodiment has a low dielectric constant, preferably substantially equal to unity. In the usual case this medium is simply air.

Gyromagnetic element 11 has a transverse cross section of rectangular shape and extends across substantially the center half of the height of guide 10, over about one-fifth of its width, and extends longitudinally along an interval of several wavelengths. The material of element 11 is of the type having electrical and magnetic properties of the type described by the mathematical analysis of D. Polder in Philosophical Magazine, January 1949, volume 40, pages 99 through 115. More specifically, element 11 may be made of any nonconducting ferromagnetic material. For example, it may comprise iron oxide with some of the oxides of one or more bivalent metals such as nickel, magnesium, zinc, manganese, and aluminum, combined in a spinel crystal structure. This material is known as a ferromagnetic spinel or as ferrite. Frequently these materials are first powdered and then molded with a small percentage of binder according to the process described in the publication of C. L. Hogan, "The Microwave Gyrotor" in the Bell System Technical Journal, January 1952.

Resistive vanes 12 may be made of any highly resistive material such as the high resistance metallic alloys of nickel, zinc and/or iron with copper, or they may be

made of a nonmetallic material such as plastic material impregnated with carbon black, or they may be thin films of dielectric material coated by carbon black in a binder. As illustrated, vanes 12 are spaced and supported by spacers 13 of material having a dielectric constant substantially equal to unity with the ends of element 11 and of spacers 13 provided with tapers to prevent undue reflections therefrom. However the vanes may be supported in any other suitable manner such as by being suspended from the top or side walls of guide 10. Vanes 12 can have a transverse dimension which, as illustrated, is comparable or slightly larger than element 11, but this dimension is subject to considerable variation, and vanes 12 may suitably extend across the entire width of guide 10. The number of vanes employed depends upon the power to be dissipated. A single vane would operate in accordance with the invention, but an increased plurality substantially increases the amount of dissipation. The maximum number appears to be limited only by physical considerations.

Element 11 is biased or magnetized by an externally applied polarizing magnetic field at right angles to the direction of propagation of the wave energy in guide 10. As illustrated, this field is supplied by a C-shaped solenoid structure comprising a magnetic core 14 having pole-pieces N and S bearing against the top and bottom walls of guide 10. Turns of wire 15 on core 14 are so wound and connected to a source 16 of variable potential to produce a magnetizing field of this polarity. The field may be provided by a solenoid of other suitable physical design, by a permanent magnet structure, or the gyromagnetic material of element 11 may be permanently magnetized, if desired.

The strength of the magnetizing field is adjusted to the region in which the product of the effective permeability μ of element 11 for waves propagating from the source to the load and the dielectric constant ϵ thereof is equal to the corresponding $\mu\epsilon$ product of the medium surrounding it and filling substantially the remainder of guide 10. It is a characteristic of the gyromagnetic material that for the opposite direction of propagation under this condition of bias the $\mu\epsilon$ product of element 11 will be substantially different from the $\mu\epsilon$ product of the medium surrounding it. When this medium is air, the $\mu\epsilon$ product of it is equal to unity. The possibility of the defined adjustment will be understood when it is recalled that the high frequency magnetic field pattern of the linearly polarized dominant mode wave in a rectangular wave guide forms loops which lie in planes parallel to the wide dimensions of the guide. At points displaced on either side of the center line of the guide this field as a substantial circularly polarized component as the wave propagates along the guide. For a wave propagating in the direction from the load to the source as shown on Fig. 1, a counterclockwise rotating component of the magnetic intensity is presented at a point on the left-hand side of the center line and a clockwise rotating component at a point on the right-hand side of the center line. When the direction of propagation is reversed, the circularly polarized components as seen at these points rotate in respectively opposite directions.

Now, if a strip of ferromagnetic material is placed in the guide to extend through one of these regions of circular polarization and magnetized by a transverse biasing field, a wave which has its radio frequency magnetic field at right angles to the biasing field and which rotates counterclockwise as viewed in the direction N to the S pole of the biasing field will encounter a permeability which increases and becomes greater than unity as the intensity of the biasing field is increased. Conversely, a similar wave which has a clockwise rotating magnetic field will encounter a permeability which decreases and becomes less than unity as the intensity of the biasing field is increased. This result is observed for low values of polarizing magnetic field below that field intensity which

produces ferromagnetic resonance in the material. Presently known ferrites have dielectric constants that are several times greater than unity being, in a typical case, in the order of ten. Therefore, when biased to the region in which the counterclockwise rotating field encounters a permeability of a fraction less than unity, for example, of one-tenth for the typical case assumed above, the $\mu\epsilon$ product will be unity. At the same time the clockwise rotating field encounters a $\mu\epsilon$ product that is greater than the value of the dielectric constant alone.

With these principles in mind the operation of the embodiment of Fig. 1 may be outlined. Since for propagation from the source to the load the $\mu\epsilon$ product of element 11 matches the $\mu\epsilon$ product of the medium surrounding it, the electric field pattern within guide 10 is essentially undisturbed and remains normal to the planes of resistive vane 12. Substantially no attenuation is introduced to the wave for this direction of propagation. For propagation from the load to the source, the $\mu\epsilon$ product of element 11 is substantially different from the $\mu\epsilon$ product of guide 10. Because of the resulting sharp discontinuity of the $\mu\epsilon$ product, element 11 acts as a dielectric wave guide, i.e., a rod or column of material having a different and generally greater $\mu\epsilon$ product than its immediate surroundings and which is not closely contained by a conductive boundary. Predominantly the energy that forms around element 11 will be in the "dominant hybrid mode" which has a major portion of the wave power in a field surrounding the guiding dielectric.

Referring to Figs. 2 and 2A, the electric field pattern of this mode as guided by element 11 is illustrated. It will be seen that the electric field of the dominant hybrid mode forms closed loops 25 that lie substantially in curved surfaces that pass through element 11. These surfaces are normal to the center horizontal plane through element 11 and tend to fan out in the space farthest away from this plane. Therefore at various distances away from element 11 there are substantial longitudinal components. These are the components that are intercepted by vanes 12 of Fig. 1 and generate currents therein which are dissipated by the resistive material of the vanes.

The relative positions of the ferrite and the resistive materials may be reversed as shown in Fig. 3. Referring therefore to Fig. 3, two elongated elements of ferrite 41 and 42 are located adjacent to the top and bottom walls 44 and 45 of guide 40. Between elements 41 and 42 are located the resistive vanes 43. The transverse location of elements 41, 42 and vanes 43 is in general the same as shown for the corresponding elements of Fig. 1 and the basic principles of operation are the same. The polarizing external magnetic field is represented schematically by the vector 46. The advantage of such an arrangement stems from the fact that more space is provided for the field guided by elements 41 and 42 between the surface of the elements and an opposite conductive wall. This provides an opportunity for more longitudinal electric field components to be developed in the vicinity of resistive vanes 43.

Referring to Fig. 4, another embodiment of the invention is shown which constitutes a modification of the structure shown in Fig. 1. Modification will be seen to reside in the fact that the entire guide 50 is filled with a dielectric material 51 in which ferrite element 52 and resistive vanes 53 are embedded. Dielectric 51 comprises a material having a dielectric constant that is substantially greater than that of air but slightly different from the dielectric constant of the material of element 52. The presence of dielectric material 51 substantially reduces the strength of the required external magnetic field, represented schematically by vector 54, since a field which produces a permeability in ferrite 52 of only slightly less than unity for the direction of low loss transmission when the dielectric constant of material 51 is less than that of element 52, or slightly greater than unity when the dielectric constant of material 51 is greater than that of

element 52, will produce a $\mu\epsilon$ product in element 52 that equals the $\mu\epsilon$ product of dielectric 51. This is a substantial advantage since it is the magnetizing field structure which adds a substantial part of the bulk and expense of any ferromagnetic device.

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

What is claimed is:

1. A nonreciprocal attenuator for electromagnetic wave energy comprising a conductively bounded wave guide of rectangular transverse cross section, means for applying wave energy to said guide having transverse electric field components extending parallel to the narrow walls of said guide, an elongated element of magnetically polarizable material exhibiting gyromagnetic properties at the frequency of said wave energy having a dielectric constant ϵ located asymmetrically in the transverse cross section of said guide in a position where said wave has circularly polarized magnetic field components as said wave propagates, said element presenting to said components an effective permeability of μ , the remainder of said guide exclusive of resistive material situated therein being filled by a medium having a dielectric constant ϵ_1 and a permeability constant μ_1 , means for transversely magnetizing said element within said guide to the region in which the product $\mu\epsilon$ equals the product $\mu_1\epsilon_1$ for one direction of propagation and the product $\mu\epsilon$ is different from the product $\mu_1\epsilon_1$ for the opposite direction whereby said transverse electric field is modified to include substantial longitudinal electric field components for said opposite direction of propagation, and a plurality of vanes of resistive material located in the vicinity of said element in planes that are parallel to the wider walls of said guide to attenuate said longitudinal electric field components without attenuating said transverse electric field components.

2. A nonreciprocal component for electromagnetic wave energy comprising a conductively bounded wave guide of rectangular transverse cross section, an elongated element of magnetically polarizable material exhibiting gyromagnetic properties at the frequency of wave energy supportable by said guide located transversely to one side of the center of said cross section and extending longitudinally therein for several wavelengths of said wave energy, means for transversely magnetizing said element, and at least one thin element of resistive material extending longitudinally in a plane parallel to and spaced from the wider walls of said guide on the same side of said center as said element.

3. An electromagnetic wave component comprising an electromagnetic wave guiding path, means for applying linearly polarized wave energy to said path for propagation therealong, an elongated element of magnetically polarizable material exhibiting gyromagnetic properties at the frequency of said wave energy located asymmetrically in the transverse field pattern of said energy, means for transversely magnetizing said element, and a plurality of vanes of resistive material located in the vicinity of said element exclusively in planes that are normal to the electric polarization of said linearly polarized energy.

4. An electromagnetic wave energy component comprising a guiding path for said wave energy, means for applying wave energy having transverse electric field components polarized in a given direction to said path for propagation therealong, an elongated element of magnetically polarizable material exhibiting gyromagnetic properties at the frequency of said wave energy located in said path at a location having substantial circularly

polarized magnetic field components as said wave energy propagates, means for magnetizing said element in a direction perpendicular to said path, and attenuating means having an extent parallel to said given direction substantially less than the extent both longitudinally along said path and normal to said given direction for attenuating electric field components extending longitudinally along said path in the vicinity of said element without attenuating said transverse electric field components extending in said given direction.

5. A component according to claim 4 wherein said attenuating means comprises a plurality of thin surfaces of resistive material extending on opposite sides of said element and being normal to said transverse electric field components.

6. A component according to claim 4 including two elements of said magnetically polarizable material wherein said attenuating means comprises a plurality of thin surfaces of resistive material extending between said elements and being normal to said transverse electric field components.

7. A component according to claim 4 including a material immediately surrounding said element, which material has a dielectric constant greater than unity and different from that of said element.

8. An electromagnetic wave component comprising a section of conductively bounded wave guide, at least one elongated element of magnetically polarizable material exhibiting gyromagnetic properties at the frequency of wave energy supportable by said guide located asymmetrically in the transverse cross section of said guide, at least one thin vane of resistive material spaced from the conductive boundary of said guide and located in a plane that is normal to the electric vector of wave energy propagating therealong, the remainder of said guide being filled with a non-conducting medium, and means for transversely magnetizing said element in said guide to the region in which the product of the effective permeability thereof and the dielectric constant thereof for wave energy propagating in one direction therealong is substantially equal to the corresponding product of said non-conducting medium.

9. A nonreciprocal component for electromagnetic wave energy comprising a conductively bounded wave guide of rectangular transverse cross section, at least one elongated element of magnetically polarizable material exhibiting gyromagnetic properties at the frequency of wave energy supportable by said guide located transversely to one side of the center of said cross section, at least one thin vane of resistive material located transversely symmetrically with respect to said elongated element in a plane parallel to and spaced from the wider walls of said guide, the remainder of said guide being filled with a non-conducting medium, and means for transversely magnetizing said element in said guide to the region in which the product of the effective permeability thereof and the dielectric constant thereof for wave energy propagating in one direction therealong is substantially equal to the corresponding product of said non-conducting medium.

10. An electromagnetic wave component comprising a section of conductively bounded wave guide, at least one elongated element of magnetically polarizable material exhibiting gyromagnetic properties at the frequency of wave energy supportable by said guide located asymmetrically in the transverse cross section of said guide, at least one thin vane of resistive material spaced from the conductive boundary of said guide and located in a plane that is normal to the electric vector of wave energy propagating therealong, the remainder of said guide being filled with a non-conducting medium, and means for transversely magnetizing said element to the region in which for one direction of propagation therealong the product of the effective permeability and the dielectric constant of said element and the correspond-

ing product of said non-conducting medium are substantially equal and constant throughout the cross section of said guide.

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10