July 26, 1960 W. J. CROWE 2,946,966

NONRECIPROCAL WAVE TRANSMISSION

Filed Dec. 30, 1957

FIG. 1

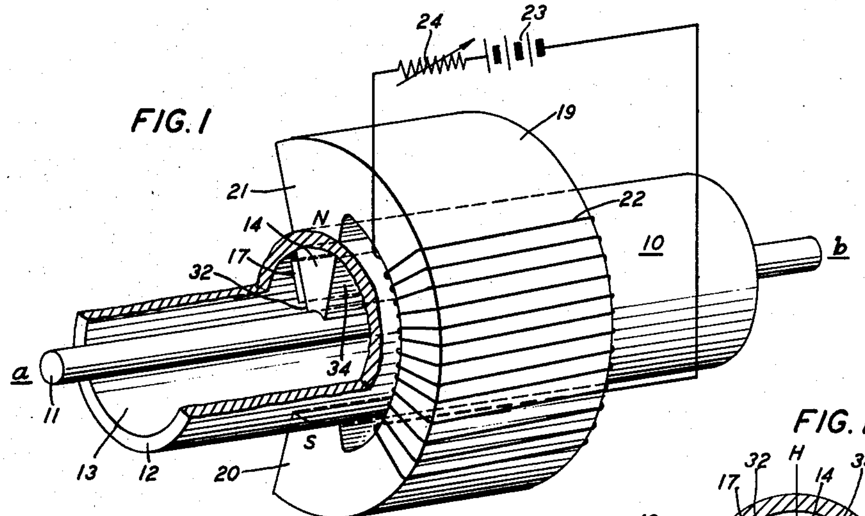


FIG. 1A

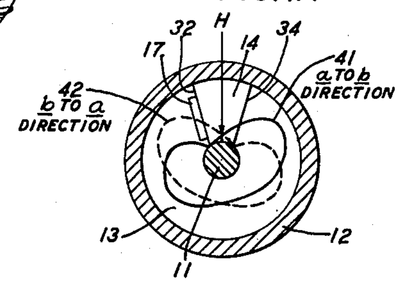


FIG. 2

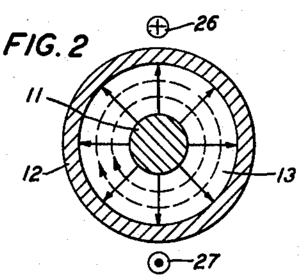


FIG. 3

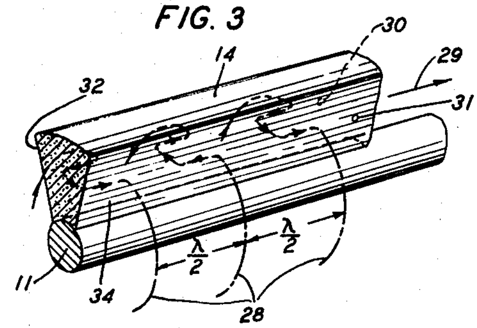
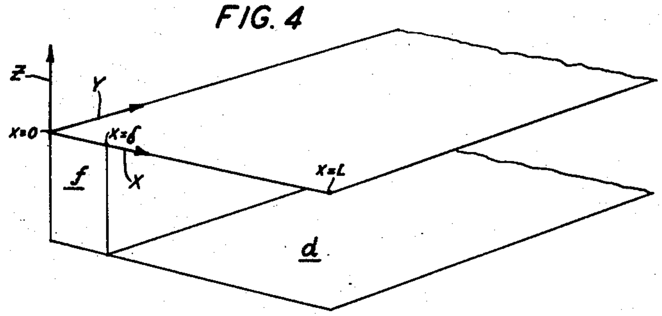


FIG. 4



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United States Patent Office

2,946,966

Patented July 26, 1960

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2,946,966
NONRECIPROCAL WAVE TRANSMISSION

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Filed Dec. 30, 1957, Ser. No. 705,981

3 Claims. (Cl. 333—24)

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

The use of ferrite materials having gyromagnetic properties to obtain nonreciprocal effects in microwave transmission circuits is widely known and has found numerous applications in the wave guide transmission art. These effects have generally been explained by the "electron spin coupling" concept whereby the electron spins in the ferrite material couple with circularly polarized magnetic field components of a wave propagated through the ferrite medium. According to this theory, a region of circular polarization must exist in the propagated wave and therefore longitudinal magnetic field components must exist in the field pattern of the wave. The greater proportion of the modes capable of being supported in conventional hollow pipe wave guides have such longitudinal components and accordingly such guides have been used extensively for nonreciprocal microwave circuit components. Hollow pipe wave guides, however, have a limited frequency range, the lowest frequency capable of transmission being determined by the dimensions of the guide.

The mode best suited and most widely used for lower frequency transmission is the dominant mode of the two-conductor coaxial line. This mode is a TEM mode having transverse field components exclusively, and theoretically having no cutoff frequency. Since the TEM mode has no longitudinal magnetic field components, the region of circular polarization necessary for nonreciprocal effects does not exist in the unperturbed coaxial line. Due to this fact, no direct nonreciprocal structures have been available for frequencies below the microwave range, until recently.

However, in two copending applications by H. Seidel, Serial Nos. 554,237 and 554,271, both of which were filed on December 20, 1955, it has been disclosed that an abrupt discontinuity of dielectric constants in the transmission medium supporting a purely transverse magnetic mode of electromagnetic wave energy perturbs the wave so as to tend to form longitudinal components of magnetic flux in the region near the discontinuity. Such a discontinuity exists at the faces of a ferrite slab located within a medium of relatively low dielectric constant. The time relation between these longitudinal components of magnetic flux and the original transverse components of the propagated wave produces a circular of elliptical polarization of flux in the region near the longitudinal ferrite faces. These regions of circular polarization have rotating components of magnetic flux which have opposite senses of rotation on the opposite faces of the ferrite element. It was heretofore believed that even though these circularly polarized components may interact with the ferrite material, if the flux intensities on the opposite faces are of the same magnitude, these effects cancel each other out and no net result can be observed.

In the above-mentioned copending applications special types of asymmetric dielectric and ferrite loading are utilized to establish a difference between the flux intensities at opposite faces of the ferrite slab. As a consequence, the effective permeabilities and/or phase constants are different for opposite directions of propagation, respectively, through the line. In this way nonreciprocal phase shifters, gyromagnetic resonance isolators, and resistance sheet field-displacement isolators may be provided for coaxial lines.

Further analysis in accordance with the present invention, however, has dtmonstrated that the nonreciprocal phase constants considered essential in the above-mentioned copending applications for all nonreciprocal effects including a non reciprocal attenuation in a resitance sheet field displacement isolator, is not in fact a necessary condition. This recognition is based upon the fact that nonreciprocal field displacement may exist even in the presence of a completely reciprocal phase constant in a properly designed structure.

It is the principal object of this invention to provide isolator action in a transmission line supporting the TEM mode with a structurally simplified field displacement device.

In accordance with the invention, it has been found that field displacement by an element exhibiting the gyromagnetic effect at wave energy frequencies within a given range of operating frequencies is a nonreciprocal effect that can be produced even though phase shift produced by the element is reciprocal and the resonance attenuation that would be produced under like conditions (but with a magnetic biasing field of proper intensity) would also be reciprocal in operation. Hereinafter, when the term gyromagnetic material, or medium, is used the more completely descriptive definition above will be implied. This nonreciprocal operation occurs because of a push-pull effect characteristic of gyromagnetic material relative to field displacement that does not otherwise exist relative to other effects. Consider a slab of ferrite extending longitudinally in a coaxial line such that the TEM mode therein is perturbed to provide rotating magnetic field components (relative to the transverse magnetic field biasing the ferrite), which rotation is of opposite sense at the two opposite faces of the slab as discussed above. Accordingly, the permeability at one face is greater than unity while at the other face it is less than unity. This results, at one face, in the ferrite tending to concentrate the electric field components at that face, i.e., to "displace" or "pull" the electric field pattern of the radio-frequency wave toward that face. But the other face of the slab, because of the different permeability caused by the opposite sense of circular polarization, will "displace" or "push" the electric radio-frequency field pattern away from itself. But this means, in a coaxial line, that the field will concomitantly, of necessity, be displaced toward the first face of the slab. The actions of the opposite faces of the slabs cooperate to produce the same effect. For one direction of propagation the first face "pulls" the electric field to itself while the second face "pushes" the electric field from itself toward the first face. For the opposite direction of propagation everything is reversed. Accordingly, at either face the field displacement is nonreciprocal, i.e., there is an electric field intensity differential between waves traveling in opposite directions through the coaxial line. Lossy material at one face of the ferrite slab will produce a loss proportional to the electric field intensity thereat. Since this intensity is different for opposite directions of propagation through the line, the attenuation produced by the lossy material is nonreciprocal.

In the preferred embodiment of the invention, solely a single sectoral slab of gyromagnetic material magnetically biased in a transverse direction, with a coating of lossy material disposed solely on one face, is located in the coaxial line. The coaxial line is otherwise filled with a homogeneous dielectric material of low dielectric constant. In this way, nonreciprocal attenuation is provided. However, the most efficient nonreciprocal attenuator or isolator requires substantially zero loss in the forward direction of propagation which in turn requires more than a mere diminution of the intensity of the electric field pattern at the lossy material for the forward direction; it requires zero electric field intensity, a complete null. In accordance with the invention, a relationship between the thickness of the ferrite slab and other parameters of the coaxial line isolator is established to provide such an electric field null.

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 accompanying drawings and the following detailed description of these drawings.

In the drawings:

Fig. 1 is a perspective view of the principal embodiment of the invention showing a ferrite slab with a resistive element on one face loading a coaxial line and capable of exhibiting nonreciprocal attenuation;

Fig. 1A is a cross sectional view of the coaxial line isolator of Fig. 1;

Fig. 2, given for the purpose of illustration, is a cross sectional view of an unloaded coaxial line showing the field configuration of the dominant mode wave in such a line at a particular instant;

Fig. 3, given for the purpose of illustration, is a partial view of the ferrite element in the structure of Fig. 1 showing typical magnetic flux lines in the ferrite element at a particular instant; and

Fig. 4, given for purposes of explanation, is a perspective view of parallel plate wave guiding structure, loaded with a ferrite slab, which is an electrical analog of a coaxial line such as that of Fig. 2.

Referring more particularly to Figs. 1 and 1A, a nonreciprocal attenuator, or isolator, is shown as one illustrative embodiment of the present invention. The nonreciprocal attenuator of Fig. 1 includes a section of coaxial line **10** having two branches represented by *a* and *b* and comprising an inner cylindrical conductor **11** and a concentric outer cylindrical conductor **12**, separated by a region **13**. Region **13** is filled with a homogeneous dielectric material which may include air, polyethylene, or other of the many materials normally used for this purpose. Extending between inner conductor **11** and outer conductor **12**, and partially filling region **13** between branches *a* and *b*, is a sector-shaped element **14**. Element **14** extends longitudinally along line **10** for a distance of at least several wavelengths of the wave energy being transmitted in line **10**.

Element **14** has two oppositely disposed longitudinal faces **32** and **34** and is composed of ferrite materials combined in a manner hereafter described. It may, for example, be a combination of iron oxide and a small amount of one or more metals such as nickels, magnesium, zinc, manganese or aluminum. These materials are characterized by the fact that they exhibit gyromagnetic properties at microwave frequencies and can, therefore, be spoken of as gyromagnetic materials. As a specific example, elements **14** and **15** may be made of magnesium-manganese-aluminum ferrite prepared in the manner described by C. L. Hogan in his United States Patent No. 2,748,353, which issued May 29, 1956. Element **14** may be provided with wedge-like tapers at both ends, to prevent undue reflections of wave energy therefrom.

Element **14** is biased by a steady magnetic field so as to be polarized at right angles to the axis of guide **10**. As shown in Fig. 1, this polarizing field may be supplied by a solenoid structure comprising magnetic core **19** having two pole-pieces **20** and **21** displaced around the periphery of and extending longitudinally along guide **10** in the region of element **14**. Turns of wire **22** are so wound on core **19** and connected to source of potential **23** that they produce a north magnetic pole N at pole-piece **21** and a south magnetic pole S at pole-piece **20**. The magnetic field produced by this solenoid therefore extends from pole-piece **21** through element **14** in a direction from outer conductor **12** to inner conductor **11** and back to pole-piece **20**, thus radially polarizing element **14**. This field may be supplied by any other means which will produce the desired direction of polarization in element **14**. The field may, for example, be supplied by other configurations of magnetic cores in an electrical solenoid, by an electrical solenoid without a magnetic core, by a permanently magnetized core, or by permanently magnetizing element **14** itself.

In Fig. 1, the strength of the magnetic field in element **14** can be varied by means of variable resistor **24** connected in series with source of potential **23**. The strength of this field is adjusted to a value outside the region of gyromagnetic resonance for element **14** in the operating frequency band.

Resistive sheet **17** is attached to element **14** on face **32** and extends longitudinally along element **14**. Sheet **17** is composed of any material which has a high rate of dissipation of electrical energy. For example, sheet **17** may be composed of polyethylene loaded with carbon particles, or it may be a resistive film sprayed on element **14**. It will be shown that for the direction of propagation into the plane of the paper a field distribution will result such as that of curve **41** in Fig. 1A. As a consequence, there will be substantially no electric field vectors parallel to sheet **17** and the wave will be substantially unattenuated. However, for the direction of propagation out of the plane of the paper corresponding to the field distribution represented by curve **42**, substantial electric field intensity vectors will exist parallel to sheet **17**. These electrical field vectors will induce radial currents in sheet **17** which will be dissipated by its resistive properties. How this non-reciprocal field distribution occurs will now be explained.

An understanding of the present invention can be more readily obtained by an understanding of the gyromagnetic properties of ferrite materials at microwave frequencies. One physical explanation which has been advanced to explain these properties is the so-called "spin coupling" theory. According to this theory, unpaired electron spins in ferrite materials tend to align their axes of spin with an externally applied magnetic field. The individual spinning electrons have an angular momentum associated with their mass and a magnetic moment associated with their charge. The alignment of these magnetic moments is the phenomenon which gives rise to the classical magnetic properties of ferrous materials. If the spin axes of the electrons are momentarily deflected from alignment with the externally applied field, they will not immediately realign themselves, but will precess about the line of the externally applied field much like a gyroscope. This precession of the unpaired electron spins tends to be in a clockwise sense when looking along the line of the applied field in the direction of this field.

When the deflection from alignment with the applied field is caused by a periodically varying magnetic field transverse to the line of the applied field, the resulting precession of the magnetic moment of the electron spins will be circular or elliptical and will produce components of magnetic flux which are circularly or elliptically polarized. Such a periodically varying magnetic field exists as part of a transversely propagated electromagnetic wave. If the transversely propagated wave also has components of circularly polarized magnetic flux, the two circularly polarized components become coupled to each other. Furthermore, since the circularly polarized components of flux produced by the electron spins are always in the same angular sense, the coupling effect can be made nonreciprocal merely by choosing a wave having circularly polarized components of magnetic flux which have opposite angular senses for opposite directions of propagation. According to this theory, therefore, the conditions of nonreciprocity for a transmitted electromagnetic wave are components of circularly polarized magnetic flux, and a reversal in the angular sense of this circular polarization with a reversal in the direction of propagation. That the applicant's structure satisfies these requirements can be readily seen by considering Figs. 2 and 3, given for the purposes of illustration.

In Fig. 2 is shown a cross sectional view of a coaxial line, much like line **10** of Figs. 1 and 1A comprising an inner cylindrical conductor **11** and a concentric outer cylindrical conductor **12** separated by a region **13** filled with a suitable dielectric material. Within region **13** of Fig. 2 is shown the field configuration of the dominant TEM mode wave in such a coaxial line at a particular instant of time. It should be noted that both the electric field lines and the magnetic field lines are entirely transverse to the directions of propagation of electromganetic waves in the coaxial line, these directions of propagation being represented by conventional notation at circles **26** and **27** as into or out of the plane of the paper. Furthermore, the electric field lines, represented by the solid lines in Fig. 2, are radial lines extending between conductors **11** and **12**, and the magnetic field lines, represented by the dashed lines of Fig. 2, form concentric circular loops around inner conductor **11**. The arrows on the individual electric and magnetic field lines represent their direction at the particular instant. It should be further noted that the electromagnetic field of the coaxial line is uniformly distributed throughout region **13**. With these facts in mind, Fig. 3 may now be considered.

In Fig. 3 is shown, for the purpose of illustration, part of element **14** of Figs. 1 and 1A, and the corresponding portion of inner conductor **11**. Also shown are magnetic flux lines **28**, representing portions of certain of the magnetic field loops of the dominant mode wave in line **10** of Fig. 1 at a particular instant. Flux lines **28** represent distorted portions of magnetic flux in each successive half-wavelength of wave energy, and the arrows on lines **28** represent the direction of polarization of the flux at the particular instant in question. Arrow **29** represents the direction of propagation of the wave. It should be noted that the direction of polarization of the magnetic flux reverses each half-wavelength.

Assuming that the dielectric constant of element **14** in Fig. 3 is substantially greater than the dielectric constants of the surrounding medium, the electromagnetic wave is perturbed in that the wave will travel more slowly in element **14** than in the surrounding media. Ferrite materials of the type contemplated have a dielectric constant on the order of ten to fifteen while the surrounding medium may, for example, be air with a dielectric constant of substantially unity, or polyethylene with a dielectric constant of about 2.25. Thus, from a simplified viewpoint, the portions of flux lines **28** in element **14** appear to "lag" behind the portions in the surrounding medium. Since these flux lines must be continuous fully closed loops, longitudinal flux components are set up in the regions near the walls of element **14**. Now consider points **30** and **31** on opposite faces **32** and **34**, respectively, of element **14**. As the wave propagates to the right in the direction of arrow **29**, point **30** is confronted with vector components of magnetic flux which assume successively different directions of polarization over a time interval corresponding to one wavelength. Thus point **30** "sees" a component of magnetic flux which is circularly or elliptically polarized in a clockwise sense when looking from above. Similarly, point **31** "sees" a counterclockwise rotating component of magnetic flux. If the direction of propagation of the wave is reversed, that is, if the wave travels in a direction opposite to the direction of arrow **29**, it is apparent that the flux components in element **14** would lag in the opposite direction and the sense of circular polarization at points **30** and **31** would be reversed, namely, the polarization would be counterclockwise at point **30** and clockwise at **31**.

Returning again to Figs. 1 and 1A, from the above it is apparent that a wave traveling from branch *a* to branch *b* of line **10** would present a clockwise circularly polarized component of magnetic flux near face **32** of element **14**. Furthermore, such a wave would present a counterclockwise circularly polarized component of magnetic flux at face **34** of element **14**. With element **14** polarized by a steady magnetic field as before indicated, i.e., in a direction from outer conductor **12** to inner conductor **11**, the angular sense of the precessing electron spin within the ferrite material will be clockwise when looking from above. It can be seen that for such a wave propagating from branch *a* to branch *b*, the angular sense of the electron spin precession and the angular sense of the polarized flux will be the same at face **32** and opposite at face **34**. The wave will encounter, therefore, in the ferrite region at face **32** a magnetic permeability of less than unity, due to this agreement in directions of polarizations. On the other hand, a permeability greater than unity will be encountered at the region of face **34** due to the opposing polarizations. As a consequence, face **32** will tend to displace electric intensity lines of the wave away from itself so as to concentrate in the surrounding regions with only a small amount in the region near face **32**. Effectively, then, the field will be "displaced" away from face **32**. Face **34** of the ferrite acts cooperatively to further enhance this effect since the permeability that the wave will encounter at face **34** is greater than unity, the electric intensity lines affected thereby will tend to concentrate in the region of face **34** with only a small amount in the surrounding regions. Thus, the effect of the two faces providing permeabilities respectively lower and greater than unity is to cooperatively displace the electric lines of force in the same absolute direction. As a consequence the electric field intensity of the radio-frequency wave is much greater at one face **34** than at the other face **32** of element **14** in the direction from *a* to *b* as indicated by solid line **41** of Fig. 1A (curves **41** and **42** represent absolute values of electric field intensity within the coaxial line, using the periphery of inner conductor **11** as abscissa, and radial lines as ordinates).

Considering now a wave propagating from branch *b* to branch *a*, the whole situation is reversed. Thus the angular sense of the circular polarization and the electron spin precession will be opposite at face **32** and in agreement at face **34**. The wave, therefore, traveling in this direction will encounter permeabilities relative to unity which are opposite to those for the *a* to *b* direction. The field displacement in line **10**, being a function of permeability, will be different, therefore, for opposite directions of propagation, and hence nonreciprocal. This means that faces **32** and **34** will cooperate now to displace the electric field components of the radio-frequency wave in the opposite sense from which it displaced them in a wave traveling in the *a* to *b* direction. The electric field intensity distribution for the *b* to *a* direction is, therefore, represented by broken line curve **42**. In the plane of resistive element **17**, it may therefore be noted that the electric field intensity for the direction of propagation from *a* to *b* is zero while in the derection from *b* to *a* it is a substantial amount. Accordingly, wave energy propagating from *a* to *b* will supply no attenuation while for the reverse direction of propagation the wave energy will be substantially completely attenuated.

It has above been demonstrated that the structure of the invention will provide a differential in the electric field intensity distribution at the lossy element. To ensure that an electric field null appears at the lossy element for one direction of propagation, it is necessary to proportion certain parameters of the embodiment of the Fig. 1 according to a special relationship. If this is done, substantially zero loss is obtained in one direction of propagation (while a large loss occurs for the opposite direction of progagation); and efficient isolator action is achieved.

To develop this parametric relationship, the ferrite slab loaded coaxial line may be viewed as a parallel plate transmission line, as in Fig. 4, to render the mathematical synthesis reasonably manageable. The compatibility and similarity of these two structures for these purposes is well known in the art, and is discussed in detail in such standard works in the microwave art as "Principles and Applications of Waveguide Transmission," by G. C. Southworth, D. Van Nostrand Co., Inc., 1950, at pages 93 and 96. Thus, if the two parallel plates of Fig. 4 were bent into concentric cylinders, they would be coaxial in the same way as conductors **11** and **12** of Fig. 2, and separated by a space (as **13** in Fig. 2) if the plates are of different transverse widths in the x direction. However, as Southworth indicates, the error introduced into various calculations of interest by treating the parallel plates as if of equal width is ordinarily small. In this arrangement the transverse electric field components, which extended radially in the coaxial line, will now extend vertically, while the transverse magnetic components, which extended circularly and concentrically in the coaxial line, will now extend horizontally. In Fig. 4, the ferrite slab at the left-hand of the parallel plate guide is the analog of the sectoral ferrite slab of the coaxial line. As indicated, the left-hand face of the slab corresponds to a position $x=0$, the right-hand face, or thickness of the slab, to $x=\delta$, and the right-hand end, or width, of the parallel plates to $x=L$. In a coaxial line, δ is the thickness of the sectoral ferrite slab measured along the arc of a circle concentric to and midway between, the outer surface of the inner conductor and the inner surface of the outer conductor, while L is the circumference of that same circle.

It may be noted that when the plates are bent to form a coaxial line, $x=0$ and $x=L$ describe the same point. In the discussion to follow, all field component parameters within the ferrite slab are so indicated by a superscript f, while those in the air or dielectric medium are indicated by a superscript d.

A relationship which provides an electric field null at $x=0$, must not only be one such that the vertical electric field component, E_z, is zero thereat, but must also be compatible with the required boundary conditions for a wave transmission line. Thus E_z^f must equal E_z^d at $x=\delta$; similarly the longitudinal magnetic intensity field component in the ferrite in the y direction, h_y^f, at $x=0$ must equal h_y^d, at $x=L$; in addition at $x=\delta$ it must also be the case that $h_y^f=h_y^d$. If it is possible to develop a relationship satisfying all these conditions, then it is possible to establish an electric field null at the face of the ferrite slab.

The first condition is that there be an electric field null at $x=0$, and $x=L$ and thus

$$E_z^f=A \sin k_m\chi \quad (1)$$

$$E_z^d=B \sin k_d(L-x) \quad (2)$$

would provide such a null, where A and B are the amplitudes of the electric field intensity distributions in the ferrite and air regions, respectively, while transverse phase constants k_d and k_m are the rate of change of the electric field intensities respectively. Performing the operations rite, respectively.

From Maxwell's equations

$$\text{Curl } \bar{E}=-\mu_0(1+\chi)\frac{\partial H}{\partial t} \quad (3)$$

it may be demonstrated that

$$\text{Curl } \bar{E}=-j\omega\mu_0(1+[\chi])\bar{H} \quad (4)$$

where $[\chi]$ is the magnetic susceptibility in tensor form as is appropriate in the analysis of field distributions in ferrite material, μ_0 is the permeability of free space, ω is 2π times frequency and $j=\sqrt{-1}$; the vectors $\bar{E}$ and $\bar{H}$ represent in standard notation, the electric and magnetic field intensities respectively. Performing the operations indicated in Equation 4, substituting Equations 1 and 2 In into the expanded form of (4), and collecting terms for the significant components, provides the expressions:

$$h_y^f=\frac{A\beta\rho}{\omega\mu_0\theta}\sin k_m\chi+\frac{Ak_m\rho}{j\omega\mu_0}\cos k_m\chi \quad (5)$$

$$h_y^d=-\frac{Bk_d}{j\omega\mu_0}\cos k_d(L-x) \quad (6)$$

In (5) and (6), β is the phase constant of the transmission path, while ρ and θ are merely shorthand notations for

$$\frac{1+\chi_{xx}}{(1+\chi_{xx})^2+\chi^2_{xy}} \text{ and } \frac{1+\chi_{xx}}{\chi_{xy}}$$

respectively; χ_{xx} and χ_{xy} are the diagonal and off diagonal components of the magnetic susceptibility tensor, $[\chi]$. From the prior discussion, the following necessary conditions were established:

$$h_y^f|_{x=0}=h_y^d|_{x=L} \quad (7)$$

$$h_y^f|_{x=\delta}=h_y^d|_{x=\delta} \quad (8)$$

and

$$E_z^f|_{x=\delta}=E_z^d|_{x=\delta} \quad (9)$$

By operating on (5) and (6) as indicated by (7) and (8), we obtain respectively,

$$Ak_m\rho=-Bk_d \quad (10)$$

$$A \sin k_m\delta=B \sin k_d(L-\delta) \quad (11)$$

By operating on Equations 1 and 2 as indicated in 9 we obtain.

$$\frac{Aj\beta\rho}{\theta}\sin k_m\delta+Ak_m\rho\cos k_m\delta=-Bk_d\cos k_d(L-\delta) \quad (12)$$

Thus Equations 10, 11, and 12 incorporate all the necessary conditions for an operative structure with an electric field null at one fact of the ferrite slab, i.e., they incorporate Equations 1, 2, 7, 8, and 9.

Substituting Equations 10 into 11 and 12 and then performing various simplifying algebraic and trigonometric operations provides:

$$\cot k_m\delta=\frac{k_m^2\rho^2-k_d^2-\beta^2\left(j\frac{\rho}{\theta}\right)^2}{2\beta\rho k_m\left(j\frac{\rho}{\theta}\right)} \quad (13)$$

Thus Equation 13 provides a simplified expression which insures an electric field null at a given face of the ferrite slab for one direction of propagation. It should be noted that the phase constant β in the denominator of 13 is linear. Accordingly, for the opposite direction of propagation the sign of β will be reversed and an electric field null will appear elsewhere in the transmission line than at $x=0$ (and in particular at $x=\delta$). Since the resistive material is located solely at $x=0$ in the coaxial line, it is clear that an efficient isolator is provided by this parametric relationship.

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 coaxial transmission line for electromagnetic wave energy adapted to propagate said waves within a given frequency range of interest and having a longitudinal axis,

means for exciting said line in a wave mode having magnetic field components extending solely circumferentially around the inner conductor of said coaxial line, means disposed within said line for producing an electric field intensity differential in at least one portion of said coaxial line for wave energy being transmitted in opposite directions of propagation therealong, said means consisting solely of a single element of magnetic material exhibiting the gyromagnetic effect at frequencies within said given range, said element being magnetically polarized in a direction transverse to said direction of propagation and occupying a part only of the transverse cross section of said line, means including a loss producing coating of material of electrical characteristic different from that of said magnetically polarized material located in said one portion for converting said field intensity differential into a nonreciprocal attenuation, and a homogeneous nonmagnetic dielectric material filling the remainder of said cross section.

2. A transmission line as recited in claim 1 in which said element of magnetic material is in the form of a sector-shaped slab extending longitudinally parallel to said axis and having two planar surfaces which extend radially in transverse cross section, one of said surfaces extending within said one portion, said loss producing coating being contiguous to said one surface.

3. A transmission line as recited in claim 2 having proportions and characteristics satisfying the expression

$$\text{cotangent } k_m\delta = \frac{k_m^2\rho^2 - k_d^2 - \beta^2\left(j\frac{\rho}{\theta}\right)^2}{2\beta\rho k_m\left(j\frac{\rho}{\theta}\right)}$$

to provide an electric field null at said one surface for one direction of propagation therealong, wherein δ is the thickness of said sectoral slab measured along the arc of a circle concentric to and midway between the inner and outer conductors of said coaxial line, β is the phase constant of said line, k_m and k_d are the transverse constants in the magnetic and dielectric materials, respectively, and ρ and θ are functions of the diagonal and off-diagonal components of the magnetic susceptibility tensor.

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