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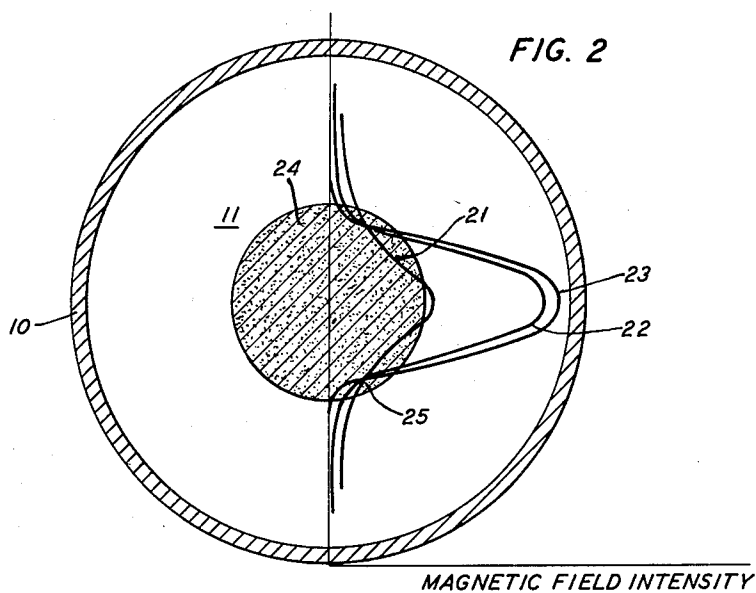
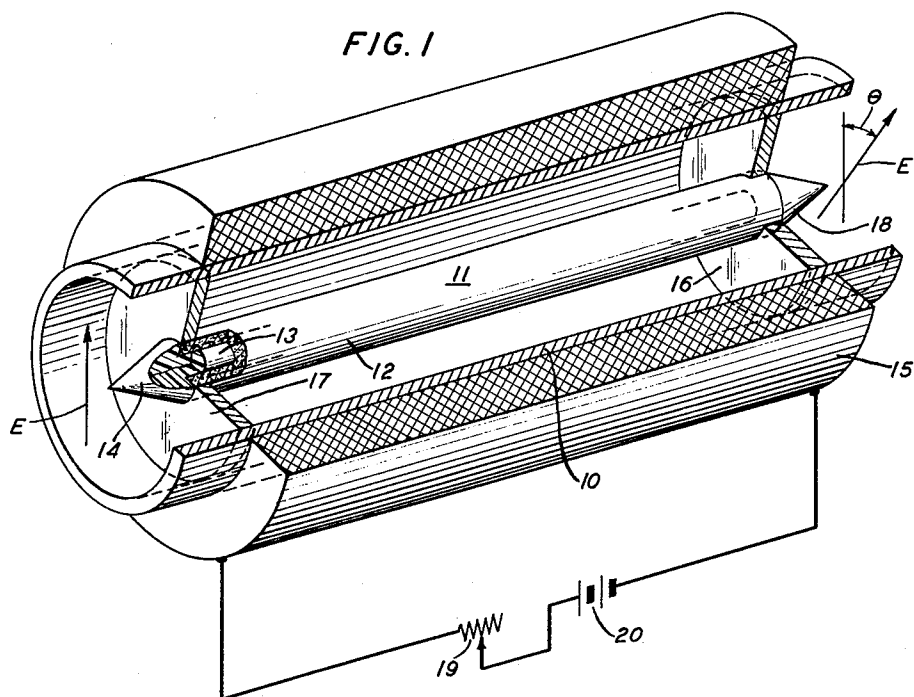
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BROADBAND POLARIZATION ROTATOR

Filed Sept. 29, 1959

2 Sheets-Sheet 1



MAGNETIC FIELD INTENSITY

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FIG. 3

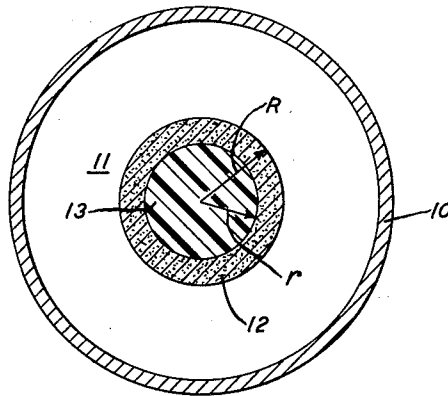
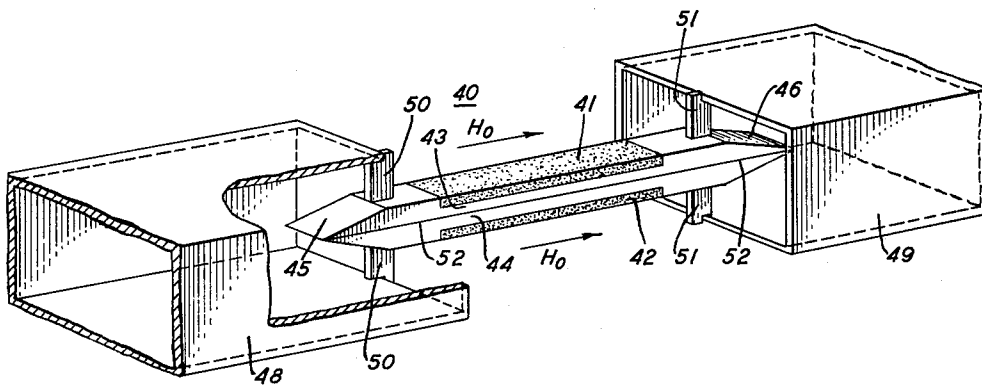


FIG. 4



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BROADBAND POLARIZATION ROTATOR

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This invention relates to electromagnetic waveguide transmission systems, and more particularly to broad-band gyromagnetic components for use in such systems.

Elements of gyromagnetic material have been utilized inside hollow metallic waveguides to produce numerous useful and important effects upon electromagnetic wave energy propagating therethrough. One class of component that has been developed makes use of the so-called "Faraday effect" rotation of the wave energy produced by a longitudinally magnetized element of gyromagnetic material. These Faraday rotators have been applied at microwave frequencies as components of isolators, modulators, attenuators, circulators, phase changers, etc.

Although there is a ready need for many of the above-mentioned devices, their commercial acceptance has been slowed by the fact that the rotation obtained with currently known gyromagnetic materials varies as a function of the operating frequency. As a consequence, they have been commercially unsuitable for use in communication systems which operate over broad bands of frequencies.

It is therefore the general object of this invention to compensate for the frequency dependency of gyromagnetic material in electromagnetic wave devices.

A typical prior art device is characterized by an elongated element of gyromagnetic material, usually ferrite, located in a round metallic waveguide and subjected to an applied direct-current magnetic biasing field. The Faraday rotator, in particular, has its applied magnetic field directed parallel to the longitudinal axis of the ferrite. It has been shown that the angle of rotation of the plane of polarization of electromagnetic wave energy transmitted through such a device increases with increasing frequency. The reason for this frequency dependence of Faraday rotators is well known. In an infinite, uniform, dielectric material, the distribution of the electromagnetic wave energy would be uniform and independent of frequency. However, when a dielectric material is surrounded by another medium having a different dielectric constant, the exciting wave energy is distributed between the high dielectric element and the generally lower dielectric medium surrounding it. As the frequency of the wave energy increases, a redistribution of the energy between the element and the surrounding medium takes place, with a higher concentration of energy appearing in the high dielectric element and a concomitant decrease in concentration of energy occurring in the surrounding medium. Since the rotation effect provided by such a device depends upon the concentration of wave energy in the ferrite, any change in the concentration results in a change in the resulting rotation.

It has been discovered that while the total energy density in the higher dielectric material increases with increasing frequency, there are areas within the material wherein the energy density remains substantially constant as the frequency changes. Consequently, if the active material, i.e., the ferrite, is confined primarily to these areas wherein the energy density remains reasonably constant, the rotation produced would likewise remain reasonably constant.

It is, therefore, a specific object of this invention to couple wave energy to a dielectric structure wherein the gyromagnetic material is confined to that portion of the

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structure wherein the energy density remains substantially constant.

In accordance with the invention, broad-band Faraday rotation is produced by means of a compound structure consisting of a dielectric material surrounded by a sheath of gyromagnetic material. The two materials are in contact along their common extent and are selected to have substantially equal dielectric constants so as to provide a homogeneous dielectric structure to electromagnetic wave energy propagating therethrough. By proportioning the relative dimensions of the gyromagnetic material and the dielectric core material, the change in rotation per unit length for a given change in the operating frequency is substantially reduced.

In a second embodiment of the invention the gyromagnetic material comprises two longitudinally extending rectangular slabs separated by a nongyromagnetic dielectric member. The latter arrangement is used, in the illustrative embodiment shown, in conjunction with a distributed lossy film to produce broad-band attenuation.

These and other objects and advantages, the nature of the present invention, and its various features, will appear more fully upon consideration of the various illustrative embodiments now to be described in detail in connection with the accompanying drawings, in which:

FIG. 1 is a perspective view of an embodiment of the invention showing a cylindrical composite rod in a circular waveguide;

FIG. 2 shows, by way of illustration, the variation of radio frequency magnetic field intensity in a dielectric rod as a function of frequency;

FIG. 3 is a cross-sectional view of the waveguide and composite rod of FIG. 1; and

FIG. 4 is a perspective view of a second embodiment of the invention showing a rectangular composite rod used as a dielectric waveguide.

In more detail, FIG. 1 is an embodiment of a polarization rotator in accordance with the invention, given by way of example, comprising a round waveguide 10 of the metallic shield type proportioned to support linearly polarized electromagnetic waves and preferably dimensioned so that only the various polarizations of the dominant TE_{11} mode can be propagated. Interposed longitudinally within guide 10 along its axis is the composite dielectric member 11, comprising a magnetic polarizable cylindrical element of gyromagnetic material 12 and an inner core of nongyromagnetic dielectric material 13.

The term "gyromagnetic material" is employed here in its accepted sense as designating the class of magnetic polarizable materials having unpaired spin systems involving portions of the atoms thereof that are capable of being aligned by an external magnetic polarizing field and which exhibit a significant precessional motion at a frequency within the range contemplated by the invention under the combined influence of said polarizing field and an orthogonally directed varying magnetic field component. This precessional motion is characterized as having an angular momentum, a gyroscopic moment and a magnetic moment. Typical of such materials are ionized gases, paramagnetic materials and ferromagnetic material, the latter including the spinels such as magnesium aluminum ferrite, aluminum zinc ferrite and the garnet-like materials such as yttrium iron garnet.

Whereas some gyromagnetic materials, such as ferrite, have a dielectric constant substantially greater than air and as such may be properly termed "dielectric material," the inner core 13 is to be distinguished from the gyromagnetic cylinder 12 in that the former exhibits substantially no gyromagnetic properties whereas the latter material exhibits pronounced gyromagnetic properties. Both the inner core 13 and the outer cylinder 12 are

chosen to have substantially equal dielectric constants and as such appear as a homogeneous dielectric rod 11 to electromagnetic wave energy propagating thereby. Each end of the rod 11 may be tapered by means of the conical sections 14 and 18 to decrease reflections of wave energy incident upon rod 11 in a manner well known in the art. The sections are made of the same material as core 13 and provide a relatively smooth transition for the incident wave energy. Low-loss low-dielectric disks 16 and 17 located at the ends of rod 11 support the rod within guide 10.

Suitable means for producing the necessary longitudinal magnetic field in rod 11 surrounds the guide 10. For the purposes of illustration, this may be a single solenoid 15 energized by a source 20. Control means for varying the biasing field is provided by rheostat 19. This field, however, may be supplied by a solenoid of other suitable design, by a permanent magnet structure, or the gyromagnetic cylinder 12 may be permanently magnetized, if desired.

In the ordinary operation of a Faraday rotator, that is, with the composite rod 11 replaced with a solid rod of ferrite, a plane polarized wave of frequency f_0 incident upon a magnetically biased ferrite can be considered as comprising two oppositely rotating circularly polarized wave components. The biased ferrite exhibits respectively different permeabilities to each of the oppositely polarized component waves. As a consequence, one of the components has a smaller phase velocity than the other and the two component waves are propagated through the ferrite medium at unequal velocities. Upon emergence from the medium the component waves combine to reform a resultant plane polarized wave which is, in general, polarized at a different angle, θ_0 , from the original wave due to the phase difference between the components introduced during propagation through the ferrite. A wave of frequency f_1 , greater than f_0 , will have its plane of polarization rotated by an angle, θ_1 , greater than θ_0 . This is a result of the peculiar waveguiding properties of the ferrite. At frequency f_0 a certain portion of the radio frequency wave energy is propagated through the ferrite element whereas the remaining portion of the wave energy propagates in the air space between the ferrite and the waveguide wall. At the higher frequency f_1 , a greater proportion of the radio frequency wave energy is concentrated in the ferrite during its propagation therethrough than was the case at frequency f_0 . As a consequence, the aforementioned anisotropic permeability property of the ferrite is enhanced, and the difference between the permeabilities exhibited respectively to the two circularly polarized wave components is increased. Upon emergence from the ferrite, therefore, the two components have a greater phase difference between them at frequency f_1 than they do at frequency f_0 and a greater angle of rotation is thereby produced.

The effect produced upon the high frequency magnetic field distribution by increasing the signal frequency is graphically portrayed in FIG. 2. Specifically, FIG. 2 is a cross-sectional view of the embodiment of FIG. 1 showing member 11, for the purpose of this discussion, as a uniform dielectric rod supported along the axis of guide 10. The intervening space between rod 11 and the inner surface of guide 10 is filled with air or some other low-loss material having a dielectric constant substantially less than that of rod 11.

The abscissa of the graph in FIG. 2 represents the relative intensity of the transverse component of the radio frequency magnetic field within guide 10, and the ordinate represents the position within the guide along the diameter. As shown by curve 21, at a frequency f_0 , the magnetic field intensity is not uniform but varies across the guide. Specifically, the field has some low value at the guide wall, increases slightly in the interval between the guide wall and rod 11, then increases rapidly

within rod 11, reaching a maximum at the center. The field distribution in the other half of the guide is the mirror image of that described, symmetrically decreasing from the center to the same low value at the guide wall.

As the signal frequency is increased to a higher frequency f_1 , the radio frequency field intensity assumes the shape of curve 22, while a still further increase in signal frequency to f_2 , causes a corresponding further concentration of the magnetic field in the dielectric rod 11, as shown by curve 23.

While it is evident that there is a substantial concentration of the field in the center portion of rod 11, it is equally evident that along the edges of the rod, in regions 24 and 25, the overall change in the total field is relatively small. If the field remains reasonably constant, it naturally follows that the effect of the anisotropic permeability of any ferrite material in these regions will remain substantially constant.

In the above discussion the dielectric rod 11 was considered as an entity for the purposes of examining the effect of increasing the frequency upon the field distribution. If now, however, the rod is designed so that the gyromagnetic material is limited to the regions 24 and 25 only, and the remainder of the rod is composed of nongyromagnetic dielectric material, changes in the intensity of the radio frequency magnetic field in the central portion of rod 11 comprising the nongyromagnetic material, due to changes in operating frequency will not produce corresponding changes in the resulting rotation of the plane of polarization of the incident electromagnetic wave.

In FIG. 3 there is shown a cross-sectional view of the embodiment of FIG. 1 with member 11 constructed in accordance with the teachings of the invention. Specifically, the rod of nongyromagnetic material of radius r is shown surrounded by the cylinder of gyromagnetic material of outer radius R . The ratio of the two radii, R/r , is preferably about two or less. In general, the smaller the ratio the greater the bandwidth. However, whereas the bandwidth increases as the ratio of the radii decreases, the amount of rotation produced for a given length of rod is correspondingly decreased. Thus, the three factors, bandwidth, rotation, and length of rod 11 are adjusted to suit the particular application. For a given bandwidth, and a given angular rotation of the plane of polarization, the length of member 11 will be determined.

In the embodiment of the invention shown in FIG. 1, the gyromagnetic element was located within a conductively bounded sheath in the usual fashion. In many applications, however, it is desirable to vary the strength, or orientation of the magnetic field applied to the gyromagnetic element, and it is often advantageous to vary the field rapidly and/or continuously. However, when the magnetic field is so varied, eddy currents are set up in the metallic waveguide sheath which tend to prevent the magnetic field from penetrating to the gyromagnetic element. Inefficient operation results as a consequence. Furthermore, the magnetic structure 15 must, of necessity, be larger in such an embodiment than would be the case if the biasing field structure could be applied directly over the gyromagnetic material itself. It has been recognized that wave energy may be propagated along a dielectric rod without a conductively bounded sheath and while a portion of the wave energy is propagated outside the dielectric material, the field inside the dielectric rod conforms closely to those modes of propagation expected in a metal tube waveguide. As a consequence, all the usual effects of the gyromagnetic materials upon the propagating wave are substantially the same. In particular, the distribution of the radio frequency magnetic fields within the dielectric member 11, as described above, will be substantially unaffected by the absence of the metallic sheath, with the added advantage that the eddy current problem vanishes and the size of the biasing structure may be correspondingly reduced.

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In a second embodiment of the invention, shown in FIG. 4, a broad-band attenuator is illustrated utilizing the dielectric waveguide effect mentioned above and the broad-banding principles of the invention. The details of the embodiment of FIG. 4 differ slightly from those of FIG. 1 in the geometric arrangement of the gyromagnetic material and the nongyromagnetic dielectric material comprising the composite dielectric waveguide structure 40. In particular, the gyromagnetic material is in the form of two longitudinally extending rectangular slabs 41 and 42 which are separated by the two nongyromagnetic dielectric members 43 and 44. At both ends, beyond the extent of the slabs 41 and 42, the members 43 and 44 widen to the full height of the composite structure 40 to form a homogeneous dielectric member which is then tapered to decrease reflections of the incident wave energy. The tapered ends, 45 and 46, extend into, and couple to, the rectangular waveguides 48 and 49, respectively. Supporting waveguide 40 between the two conductively bounded rectangular waveguides 48 and 49 are a pair of low-loss, low dielectric supports 50 and 51.

The gyromagnetic slabs illustrated are permanently magnetized parallel to the direction of propagation, as shown by the arrows H_0 . Other suitable means for producing the necessary steady magnetic fields in slabs 41 and 42 may, however, be used.

Extending throughout the dielectric waveguide 40 and separating its upper and lower halves, is a film of lossy material 52.

In operation, the direction of polarization of linearly polarized wave energy, applied to the dielectric waveguide 40 from either of the rectangular guides, is rotated in the plane of the lossy film under the influence of the longitudinally polarized gyromagnetic material. Initially, all components of the applied wave are perpendicular to the plane of the lossy material. As the wave progresses along the rod, however, the direction of polarization changes, producing a component parallel to the plane of the lossy material. This rotational effect takes place continuously along the extent of the gyromagnetic slabs and results in a continuous coupling of radio frequency energy to the lossy film 52. The energy so coupled is dissipated within the lossy material. An attenuator so constructed differs fundamentally from the Faraday rotational type attenuator wherein the lossy material is concentrated at discrete intervals at either end. In such devices the loss characteristic has a typical cosine squared power variation which requires, for maximum loss, that the plane of polarization coincide exactly with the plane of the lossy material. Variations which tend to increase or decrease the rotation result in increases in the transmission through the attenuator. In particular, it is possible, for example, for the transmission to be completely unaffected by the presence of the loss material where, for example, the rotation results in a 180 degree reversal in the direction of polarization. However, by distributing the loss film over the length of the gyromagnetic material so as to couple thereto continuously, the power variation as a function of angular rotation, is given by

$$[\cos^2 \rho d] e^{-\frac{d}{2} \left(1 - \frac{\sin 2\rho d}{2\rho d} \right)}$$

in the first approximation, where d is the length of the rotator, and ρ is the rotation per unit length.

It will be noted that as d increases, the exponential term approaches $e^{-d/2}$. Ideally, then, the transmission through an attenuator in accordance with the invention goes from unity at $\rho d = 0$ to 0 at $\rho d = 90^\circ$, and remains below some arbitrary level, determined by d , as the rotation is increased. The attenuator may then be designed to maintain a given minimum attenuation over a substantially greater range of anticipated variations in rotation. This feature is especially valuable when the device is used in a broadband, closed feedback loop because it makes it impossible, in most applications, for the device to go into

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positive feedback operation over the range of operating frequencies.

The amount of attenuation may be varied, and the signal consequently modulated, by superimposing a variable field upon the steady biasing field H_0 . By virtue of the construction of the attenuator shown in FIG. 4, the modulating means (not shown) may be mounted directly over the unsheathed rod 40, thus allowing rapid variations of the attenuation without the deleterious interference of eddy currents, as explained hereinbefore.

Of particular interest in the above-described devices is the amplitude of the steady biasing field required to operate the several embodiments of the invention. The phenomenon of Faraday rotation upon which these rotators depend for their operation occurs for any non-zero magnetizing field. While the actual field required for any particular amount of rotation will depend upon the length, diameter, and the proportions of ferrite and dielectric material used in the rotator, typical designs operate with magnetizing fields of one hundred gauss or less.

This becomes of especial importance in designing attenuators or modulators for the ever-increasing frequencies of today's microwave systems. The higher frequencies tend to rule out, or make difficult, the use of such phenomena as gyromagnetic resonance where the magnetizing field is proportional to the frequency of operation.

For example: An isolator, in accordance with the invention can be built to operate over a 20% band at 50 kilomegacycles per second with an untuned magnetizing field of as little as 50 gauss. Typical magnetizing fields for field displacement and resonance isolators at this frequency are 14,000 and 18,000 gauss, respectively. Neither of these isolators has yet been made to approach the 20% bandwidth without benefit of tuning the magnetizing field.

In all cases it is understood that the above-described arrangements are 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. In combination, a section of transmission line for supporting electromagnetic wave energy, means for applying linearly polarized wave energy to said line, means for rotating the direction of polarization of said wave energy comprising a composite dielectric rod longitudinally disposed along said line, said rod comprising an outer layer of gyromagnetic material having a first dielectric constant and an inner core of nongyromagnetic material having a second dielectric constant substantially equal to said first dielectric constant, said gyromagnetic and said nongyromagnetic material being in contact along their common length and magnetic means for longitudinally biasing said rod.

2. The combination according to claim 1 wherein said line is a conductively bounded waveguide and wherein said rod is disposed within said waveguide.

3. In combination, a section of transmission line for supporting electromagnetic wave energy, means for applying linearly polarized wave energy to said line, means for rotating the direction of polarization of said wave energy comprising a composite dielectric rod longitudinally disposed along said line comprising a nongyromagnetic inner circular cylindrical core having a first dielectric constant surrounded by a hollow circular cylindrical outer layer of gyromagnetic material having a second dielectric constant substantially equal to said first dielectric constant, said core and said outer layer being in contact along their common length, and magnetic means for longitudinally biasing said gyromagnetic material.

4. The combination according to claim 3 wherein said inner core has a radius r and said hollow cylinder has an outer radius R and wherein the ratio of R to r is less than 2.

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5. An attenuator for electromagnetic wave energy comprising an inner pair of nongyromagnetic dielectric members having a first dielectric constant separated by a planar layer of electrically lossy material, an outer pair of members having a second dielectric constant and capable of exhibiting gyromagnetic properties at the operating frequency of said attenuator in contact with said dielectric members, and means for magnetically biasing said second pair of members in a direction parallel to the plane of said layer.

6. The combination according to claim 5 wherein said first dielectric constant and said second dielectric constant are substantially equal.

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