

Dec. 12, 1961

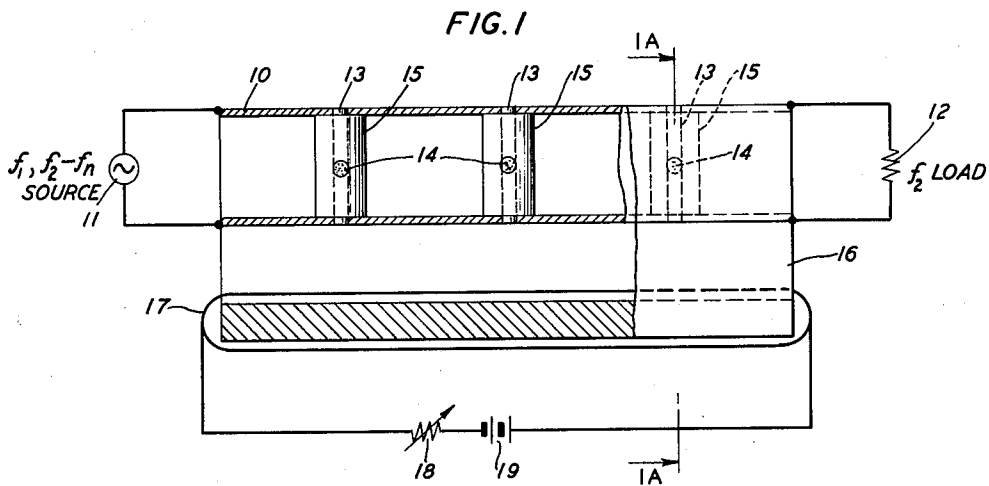
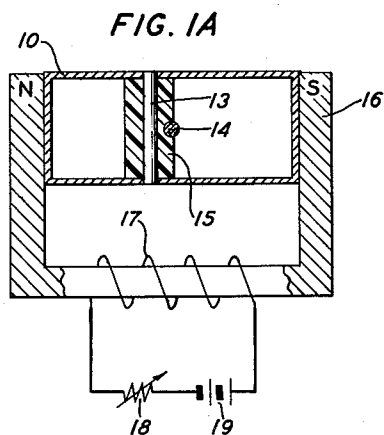
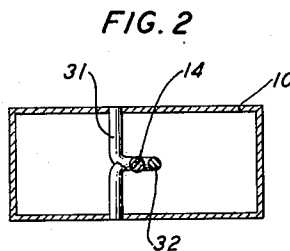
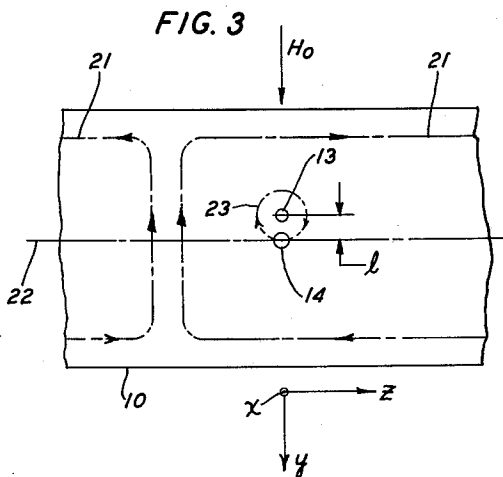
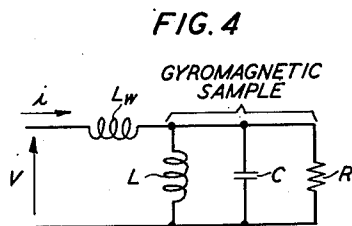
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3,013,229

GYROMAGNETIC MICROWAVE FILTER DEVICES

Filed Nov. 17, 1958

2 Sheets-Sheet 1



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GYROMAGNETIC MICROWAVE FILTER DEVICES

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2 Sheets-Sheet 2

FIG. 5

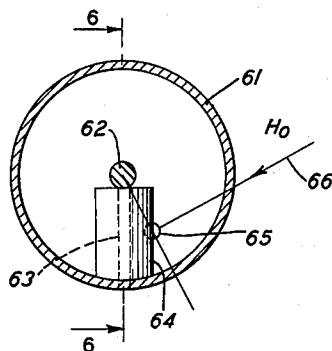


FIG. 6

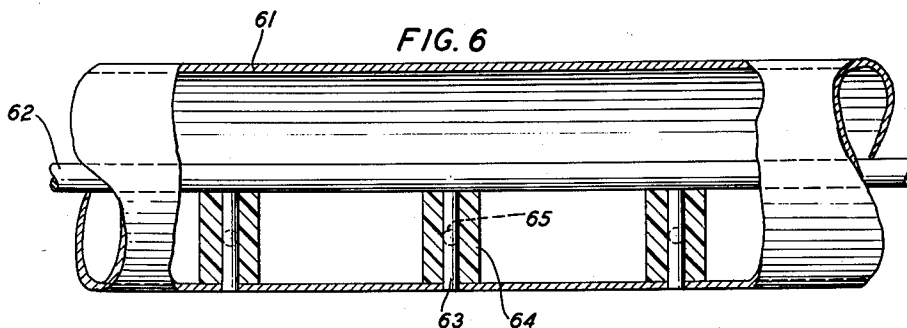


FIG. 8

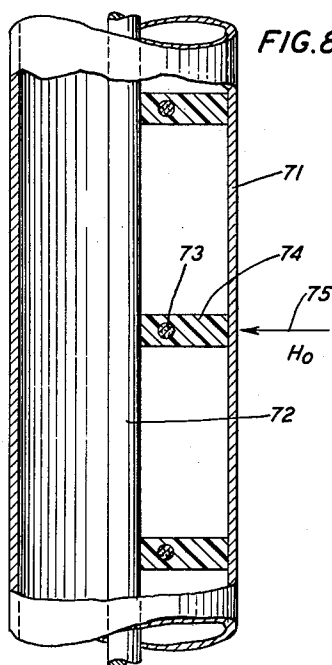
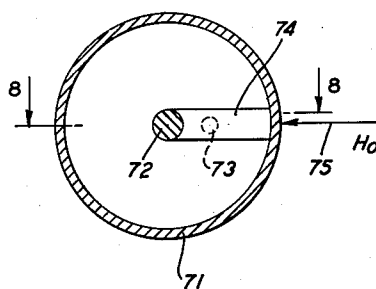


FIG. 7



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GYROMAGNETIC MICROWAVE FILTER
DEVICES

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Filed Nov. 17, 1958, Ser. No. 774,172
11 Claims. (Cl. 333-73)

This invention relates to electromagnetic wave transmission systems and more particularly to transmission systems utilizing the properties of polarized magnetic materials exhibiting gyromagnetic effects at the frequency of the wave energy.

The phenomena of gyromagnetic resonance is one that is now well known to this art and countless papers, publications and patents have appeared in the past decade describing the theoretical and experimental aspects thereof. Most of this attention has been directed to the phenomena in materials known as polycrystalline ferrite. In general, if the material is biased by a steady polarizing magnetic field certain electron combinations within the material are aligned with the field. If a high frequency electromagnetic field is then applied to the material at right angles to the polarizing field, the electrons begin to precess at a frequency determined by the strength of the polarizing field. When the frequency of the high frequency energy equals the frequency of precession, the condition of resonance is produced. Heretofore the most pronounced manifestation of this resonance was its loss characteristics (the imaginary part of the radio frequency permeability presented by the material to wave energy) and its ability to absorb and dissipate energy from the high frequency field. This phenomena has been utilized to make loss-introducing devices such as attenuators, isolators, modulators and the like.

There is also a reactive effect (the real part of the radio frequency permeability) associated with the condition of resonance, like the reactive characteristic of a lumped constant resonant circuit or a resonant cavity, but this reactive "circuit" is so loosely coupled to the wave energy in the prior devices, i.e., its impedance was so small compared to the characteristic impedance of the wave guide, transmission line or energy source that the reactive effect is completely masked at resonance by the loss. Devices which depended for their operation upon the real part of the permeability had to be operated either substantially above or substantially below resonance to avoid excessive loss. It was not possible to utilize the "tuned circuit" characteristic at resonance.

It is, therefore, a broad object of the present invention to minimize loss and emphasize reactance in gyromagnetic samples biased to gyromagnetic resonance.

It has been recognized that if very tiny samples of material could be used and if the material is one that has a very narrow line width at resonance, the loss could be reduced. However, the coupling between the material and the high frequency field would be similarly reduced and the reactive effect would still be of no value. However, it has been further recognized that if the small sample could be more tightly coupled to the wave energy, i.e., if its impedance as seen by the incident wave could be increased so that this impedance is large compared to the wave guide impedance, the reactive characteristics of the circuit could be made to predominate.

It is, therefore, a more specific object of the present invention to increase the coupling between very small samples of gyromagnetic material and the magnetic field of high frequency electromagnetic wave energy.

In accordance with the present invention, tight coupling between such a sample and a radio frequency field is produced by causing the field to induce a high current

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in a short, low resistance conductor and by disposing the sample in the induced magnetic field produced by this current. The location of the sample and the direction of the polarizing field are particularly selected so that the conditions for gyromagnetic precession in the sample exist only with respect to the induced field and not to the original radio frequency field. Since the induced field is highly concentrated in the limited region immediately surrounding the conductor and therefore has many times the intensity of the wave field in the regions preceding and following the conductors, much tighter coupling is obtained between the wave and the gyromagnetic sample than if the sample were merely disposed in the wave field. Viewed in another way, the conductor serves as a transformer to match the impedance of the guide or wave energy to the impedance of the resonant "circuit" within the gyromagnetic sample thereby increasing the coupling between them. It will be shown that the combination of such a current-carrying conductor and a resonant sample of gyromagnetic material is equivalent to a parallel resonant tuned circuit with high Q and very low loss. In one embodiment of the invention to be described such a combination is placed in a conductively bounded wave guide to produce a magnetically controllable low loss bandpass resonance type filter. In other embodiments the principles of the invention are applied to TEM transmission systems such as coaxial conductors.

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

In the drawings:

FIG. 1 is a partially cutaway view showing a rectangular wave guide bandpass filter in accordance with the present invention;

FIG. 1A is a transverse cross-sectional view of FIG. 1 taken as indicated;

FIG. 2 represents a modification of the structure of FIGS. 1 and 1A;

FIG. 3 is a diagrammatic representation of wave field patterns associated with the embodiment of FIGS. 1 and 1A;

FIG. 4 illustrates the equivalent circuit of a portion of the structure of FIGS. 1 and 1A;

FIGS. 5 and 6 illustrate a coaxial transmission line bandpass filter in accordance with the invention; and

FIGS. 7 and 8 represent a coaxial transmission line band rejection filter in accordance with the invention.

Referring more particularly to FIG. 1 and the transverse cross section thereof shown in FIG. 1A, an illustrative embodiment of the invention having low loss bandpass filter characteristics is shown which comprises a section 10 of conductively bounded rectangular wave guide which is interposed in the path of linearly polarized dominant mode wave energy to be filtered. Disposed in guide 10 are at least one and preferably a plurality of low resistance posts, rods or conductors 13 extending between and conductively fastened to the top and bottom wide walls of guide 10 along a longitudinal plane that is preferably slightly displaced to one side of the longitudinal center line thereof. When a plurality are employed, the several conductors 13 are spaced from each other by approximately a half wavelength of a frequency just above the highest frequency in the band of interest. Suitably supported between each conductor 13 and the furthest narrow wall of guide 10 is a small, highly polished sample 14 of gyromagnetic material. This position preferably places samples 14 upon the longitudinal axis of guide 10. In the description which follows it will be

assumed that samples 14 are spherical in shape for convenience in handling the mathematical analysis but this shape is by no means essential to the principles of the invention. Regardless of shape, the maximum dimension of sample 14, the diameter of posts 13 and the spacing between each post 13 and its contiguous sample 14 are generally of the same order of magnitude being each equal to a small fraction of the wavelength of the energy in the passband. In particular, the maximum dimension of the samples 14 should be small enough so that only the resonance mode of uniform precession can be sustained therein. Higher order modes are undesirable because of the losses associated therewith. As illustrated, spheres 14 may be supported in position by being embedded in the circumference of cylinders 15 of any low dielectric constant material, such as polyfoam, surrounding each of the posts 13 although any other support means will be satisfactory.

The term gyromagnetic material is employed here to describe the composition of spheres 14 according to its accepted sense. As such it designates a broad class of magnetically polarizable materials having unpaired spin systems involving portions of 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 the 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 materials, the latter including the spinels such as magnesium aluminum ferrite, aluminum zinc ferrite and the rare earth iron oxides having a garnet-like structure of the formula $A_3B_5O_{12}$ where O is oxygen, A is at least one element selected from the group consisting of yttrium and the rare earths having an atomic number between 62 and 71 inclusive, and B is iron optionally containing at least one element selected from the group consisting of gallium, aluminum, scandium, indium and chromium. While the present invention may be practical with any of these materials, it is most useful when used in conjunction with those gyromagnetic materials that have narrow resonance line widths and low losses. For this reason it appears preferable to employ as a specific material for spheres 14 one of the garnet-like materials, for example, aluminum-substituted yttrium iron oxide. It further appears that in order to further reduce losses, the sample should be highly polished on its external surfaces.

Spheres 14 are polarized by a magnetic field extending through the spheres perpendicular to the direction of propagation of wave energy through guide 10 and perpendicular to the narrow walls of guide 10. This field may be supplied as illustrated by a magnetic structure 16 comprising a C-shaped magnetic core which has pole-pieces spaced apart to form an air gap in which the magnetic field is concentrated and between which guide 10 and spheres 14 are received. Turns of wire 17 on core 16 are so wound and connected through rheostat 18 to a source of potential 19 that north and south poles are produced in the pole pieces on either side of guide 10. The field may, however, be supplied by a magnetic structure of other design or the spheres may themselves be permanently magnetized.

The above-defined physical relationships have been specified in order to establish certain essential relationships in accordance with the invention between the radio frequency magnetic field components of energy supported by guide 10, the magnetic field produced by and surrounding the conductive posts 13 and the steady polarizing magnetic field supplied by magnetic structure 16. These relationships are shown in FIG. 3 and should be understood before proceeding to the detailed analysis of

the principles of the invention. Thus, FIG. 3 shows a schematic view of the wider transverse dimension of guide 10 and is shown in an x, y, z coordinate system for reference purposes. The radio frequency magnetic field of the dominant mode in guide 10 comprises loops 21 that lie in planes parallel to the wider walls of guide 10. Along the longitudinal center line 22 thereof this field is substantially purely transverse in the y direction. A substantial induction current i in the x direction is induced by the wave fields in post 13 that in turn has a magnetic field 23 concentric with post 13. Sphere 14 is located upon the center line 22 of the guide between the post and the narrow wall which places it at a point where the y directed transverse radio frequency field is normal to the z directed component of the concentric induced field. The polarizing field H_0 is then applied parallel to the transverse field and normal to the z directed induced components within sphere 14.

Following the conventional analysis now well established in this art, sphere 14 may be considered as an assembly of small magnets, or electron spins, which are aligned by the steady polarizing magnetic field H_0 in a direction parallel to that field. Under the influence of the z directed component of the high frequency induced field surrounding posts 13, the spins are caused to precess about the direction of the polarizing field in the manner now very familiar to the art. The y directed transverse radio frequency magnetic field, being parallel to the polarizing field, has no effect upon the spins.

Assuming that the ends of conductor 13 are located at such a distance from the sphere that the fields from the sphere are negligible, the magnetic field H_y due to the current i_x in the conductor is then given by:

$$H_y = -\frac{i_x}{2\pi l} \quad (1)$$

This magnetic field will induce motion of the electron spins in the material of sphere 14 in accordance with the usual small signal equations of motion for the magnetization. We then obtain for $\dot{m}_x$ and $\dot{m}_y$,

$$\dot{m}_x = \gamma M_s H_0 - \gamma M_s H_y - \alpha m_x \quad (2)$$

$$\dot{m}_y = -\gamma m_x H_0 + \gamma M_s H_x - \alpha m_y$$

where

γ is the gyromagnetic ratio, .0351 mc./amp./meter
 M_s is the magnetic moment of the sphere per unit volume
 α is a damping factor which leads to a constant, line width at any frequency (see Equation 15), and
 H_0 is the D.-C. magnetic field in amps./meter

Assuming steady state A.-C. quantities, we obtain for m_x and m_y ,

$$m_x = \gamma M_s \frac{\gamma H_0 H_x - (j\omega + \alpha) H_y}{(\gamma H_0)^2 - \omega^2 + j2\omega\alpha + \alpha^2} \quad (3)$$

and

$$m_y = \gamma M_s \frac{(j\omega + \alpha) H_x + \gamma H_0 H_y}{(\gamma H_0)^2 - \omega^2 + j2\omega\alpha + \alpha^2} \quad (4)$$

The A.-C. magnetization then gives rise to a dipolar magnetic field in accordance with the relation

$$H_y = -\frac{\dot{m}_y v}{(x'^2 + z'^2)^{3/2}} \quad (5)$$

where x' and z' are measured from the center of sphere 14, and y' , also measured from the center of sphere 14, is zero, and v is the volume of the sphere.

The voltage induced in the wire 13 by the magnetic field of 5 is then given by

$$V = \frac{\mu_0}{2\pi l} \dot{m}_y \quad (6)$$

We can now relate the circuit voltage at the ends of wire

13 to the current in the wire using (1), (4) and (6), and assuming a self-inductance in the wire due to its own magnetic field of L_w

$$\frac{V}{i} = \frac{\mu_o v}{(2\pi l)^2} \gamma^2 M_z H_o \frac{j\omega}{(\gamma H_o)^2 - \omega^2 + j2\omega\alpha + \alpha^2} + j\omega L_w \quad (7)$$

Equation 7 may be represented by the equivalent circuit of FIG. 4 comprising the parallel combination of inductance L , capacitance C and resistance R in series with the self-inductance L_w for which

$$\frac{V}{i} = \frac{j\omega}{\frac{1}{L} - \omega^2 C + j\omega \frac{1}{R}} + j\omega L_w \quad (8)$$

by allowing

$$L = \frac{\mu_o}{(2\pi l)^2} \frac{M_z}{H_o} \frac{1}{1 + \left(\frac{\alpha}{\gamma H_o}\right)^2} \approx \frac{k}{\gamma H_o} \quad (9)$$

$$C = \frac{(2\pi l)^2}{\mu_o \gamma^2 M_z H_o} = \frac{1}{k \gamma H_o} \quad (10)$$

$$R = \frac{\mu_o \gamma^2 M_z H_o}{(2\pi l)^2 2\alpha} = k \frac{\gamma H_o}{2\alpha} \quad (11)$$

where k is a coupling resistance defined by

$$k = \frac{\mu_o \gamma M_z}{(2\pi l)^2} \quad (12)$$

The damping factor α is related to the magnetic field line width of the material, H_L , by

$$\alpha = \frac{\gamma H_L}{2} \quad (13)$$

and the magnetic moment M_z is given by

$$M_z = \frac{4\pi}{3} r_o^3 M_s \quad (14)$$

where M_s is the magnetic moment per M^3 .

This analysis shows that the gyromagnetic sample 14 together with its proximate and coupled conductor 13 constitute a parallel resonant circuit accurately represented by an equivalent R, L, C circuit. As is well known the resonant frequency f_0 of such a parallel resonant circuit is given by

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (15)$$

Substituting the equivalent values from Equations 9 and 10,

$$f_0 = \frac{\gamma H_o}{2\pi} \quad (16)$$

which is well known to be the gyromagnetic resonant frequency of the sample itself when biased by a polarizing field H_o .

Similarly the Q of the circuit is

$$Q = \frac{R}{2\pi f_0 L} = \frac{f_0}{\Delta f} \quad (17)$$

where Δf is given by

$$\frac{\gamma H_L}{2\pi}$$

or the intrinsic line width of the material.

When this circuit is placed in a wave guide or other nonreactive loaded transmission line, the losses in the combination will be low if the loaded Q_L , including the effective impedance of the guide load, is low compared to the unloaded Q of Equation 17. In other words if the R of Equation 11 is large compared to the wave guide impedance that it shunts, the losses will be low in the gyromagnetic sample.

In a typical embodiment employing yttrium iron garnet samples of .03 inch diameter to operate at a frequency 9 kmc., the material has a Δf of 1.4 mc. and a Q of 6000. However, the value of R according to Equation 11 can be made equal to 40 ohms. This is sufficiently high that the impedance of the circuit to which it is connected or which it shunts can in practice be made much lower.

When one or more of these resonant circuits are connected between the top and bottom walls of a wave guide as in FIG. 1, they each constitute a wave-reflecting short circuit for all frequencies except those within the band for which the sample itself is at gyromagnetic resonance. Any possible additional resonance arising from the reactance of the conductors themselves when a plurality are employed may be easily caused to fall outside the range of interest by properly selecting the half wavelength spacing between them as noted above. Since the parallel combination at resonance has a high impedance, the short circuits of conductors 13 are opened for the band of frequencies centered upon the gyromagnetic resonant frequency of samples 14. This band is readily selected, adjusted or varied by means of controlling the strength of the polarizing magnetic field. Thus, if wave energy is supplied from a source 11 including a large range of frequencies $f_1, f_2 \dots f_n$ each representing a successively higher center frequency of several bands of frequencies and if the strength of the polarizing field is adjusted by means of rheostat 18 to produce gyromagnetic resonance in the samples 14 at the frequency f_2 , components of the frequency band f_2 will pass with little attenuation along guide 10 to be delivered to load 12 for utilization. The remaining frequencies f_1 and f_n outside the band of gyromagnetic resonance will, however, encounter a plurality of substantially short circuits along the length of guide 10 and will be reflected toward the source.

FIG. 2 represents a modification of the structure of FIGS. 1 and 1A in which a loop 32 in a conductor 31 may replace the straight conductor 13 of FIGS. 1 and 1A. Loop 32 is designed to encircle sample 14 and lies as nearly as possible in a plane parallel to the wide walls of guide 10. It may be shown that the addition of such a loop increases the coupling to the sample by a factor π^2 as compared with the coupling to a straight conductor. In the embodiment noted above this means that the value of R according to Equation 13 now exceeds 400 ohms. The induced magnetic field at the center of such a loop is perpendicular to the wide walls of the guide and, therefore, bears the proper relationship to the polarizing magnetic field set forth above.

In the embodiments described employing a plurality of conductors and associated gyromagnetic samples, it was assumed that any natural resonance due merely to the spaced conductors acting as reactive elements and not to the gyromagnetic properties thereof should be avoided in the band of interest by proper selection of the spacing therebetween. It should be noted, however, that in a filter that does not need to be magnetically tuned, i.e., one of fixed adjustment, the conductive elements may be spaced a half wavelength apart in the passband frequency. This will produce a cumulative effect between the gyromagnetic resonance of each sample along with the resonance due to the physical spacing.

A further special mode of operation of the invention should be noted. The operation described above assumes electromagnetic wave power levels of moderate values. It is well known that above a certain power level, the uniform precession of gyromagnetic resonance is strongly damped by spin wave coupling. Breakdown of the uniform precession destroys the coupling mechanism so that at high power levels the gyromagnetic sample and its associated conductor appear as a short circuit at the resonant frequency just as it does at frequencies removed from resonance. Thus, power limiting or TR switch operation is inherent in the structures of the present invention.

The principles of the invention may be applied to co-

axial transmission lines and an illustrative embodiment is shown in FIG. 5 and the longitudinal view thereof shown in FIG. 6. The coaxial line illustrated is conventional and comprises an outer conductive shield 61 and an inner axial conductor 62. A plurality of shorting conductors 63 in accordance with the invention are disposed longitudinally at intervals perpendicular to and electrically connected between conductors 61 and 62. Supported to one side of and in the same transverse plane as conductors 63 by dielectric supports 64 are samples 65 of gyromagnetic material. The polarizing field represented schematically by vector 66 is preferably applied perpendicular to the axis of conductor 62 at such an angle that it is also perpendicular to a line passing through the axis of conductor 62 and sample 65. This field is, therefore, tangent to the concentric magnetic field of the TEM mode normally excited in a coaxial conductor and perpendicular to the induced magnetic field concentric with conductor 63 within sample 65.

As in the embodiment of FIG. 1, conductors 63 constitute short circuits, effectively reflecting wave energy except in the band of frequencies for which the gyromagnetic resonance of sample 65 causes the parallel resonant combination to appear as a very high impedance thereby removing the short and allowing these frequencies to pass along the line. The same considerations bearing upon the spacing of conductors 63, the size and composition of samples 65 and the strength of the polarizing field set forth in connection with the wave guide embodiment of FIGS. 1 and 1A apply also to this embodiment.

The principles of the invention may be utilized to produce a filter having band rejection characteristics. Such an embodiment is illustrated in terms of a coaxial transmission line in FIG. 7 and the longitudinal view thereof in FIG. 8 wherein 71 represents the outer cylindrical conductor of the line and 72 represents the inner axial conductor thereof. No shorting conductors are involved in this embodiment, but instead, portions of the inner conductor 72 itself are associated with a plurality of spaced samples 73 of gyromagnetic material suitably supported by dielectric supports 74. The transverse polarizing field represented schematically by vector 75 is applied in this embodiment perpendicular to the axis of conductor 72 and in a plane that passes through samples 73 and conductor 72. This field is, therefore, normal within samples 73 to the concentric magnetic field of the TEM mode supported by the line.

Samples 73 together with the "proximate" portions of conductor 72 constitute parallel resonant circuits in accordance with the principles discussed in detail hereinbefore. However, these parallel resonant circuits now appear in series with the center conductor of the coaxial transmission line. At all frequencies removed from the gyromagnetic resonant frequency of samples 73, the parallel resonant combination has a low impedance and wave energy at these frequencies is freely transmitted along the line. At the resonant frequency the parallel resonant combination appears as a very high impedance thereby in effect opening the center conductor 72 and producing a wave energy reflecting discontinuity at the frequency of gyromagnetic resonance in the samples 73.

While the principles of the invention have been illustrated with respect to rectangular wave guides and coaxial transmission lines, it is obvious that they may be likewise applied to wave guides of other cross-sectional shapes and to other forms of TEM transmission lines, such as strip lines. These principles may also be applied to balanced two-conductor transmission lines such as Letcher wires.

In all events, it is to be understood that the above-described arrangements are merely illustrative of a small number of the many possible applications of the principles of the invention. Numerous and varied other arrangements in accordance with these principles may read-

ily be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, a guiding path for electromagnetic wave energy having a field pattern including loops of magnetic field, a gyromagnetic element having over-all dimensions that are small compared to the wavelength of said energy and that comprises homogeneous polarized material exhibiting gyromagnetic effects at the frequency of said wave energy, means for coupling said gyromagnetic element to said wave energy comprising an elongated low loss highly conductive element having transverse dimensions that are all comparable to the dimensions of said gyromagnetic element disposed with a central portion of the elongated extent thereof adjacent to said gyromagnetic element and disposed in said field pattern with the elongated longitudinal axis thereof substantially normal to the plane of said loops so that substantial longitudinal currents flow in said conductive element and means for applying a polarizing magnetic field to said element in a direction that is substantially parallel to the portion of said magnetic field loops within said element.

2. The combination according to claim 1 wherein said gyromagnetic element is polarized in a direction normal to a magnetic field component within said gyromagnetic element that is induced by said current.

3. The combination according to claim 1 wherein said guiding path is a rectangular wave guide wherein said conductive element extends between the wider walls thereof and wherein said gyromagnetic element is disposed upon the longitudinal center line of said guide.

4. The combination according to claim 1 wherein said guiding path is a coaxial transmission line having concentric inner and outer conductors, wherein said conductive element extends between said inner and outer conductors and wherein said gyromagnetic element is disposed transversely to one side of said conductive element.

5. In an electromagnetic wave system supportive of a range of operating frequencies, means for selectively transmitting a band of frequencies within said range comprising a pair of parallel elongated conductive members, a shorting stub of low loss highly conductive material conductively connected to and extending between said members having transverse dimensions that are small compared to the wave length of wave energy within said range, an element of magnetically polarizable material capable of exhibiting gyromagnetic effects over said band of frequencies located between said members adjacent to said stub, and means for magnetically polarizing said element to gyromagnetic resonance at a frequency within said band.

6. The combination according to claim 5 wherein said stub lies in a transverse plane normal to the axes of said members.

7. The combination according to claim 5 wherein said element is small compared to the length of said stub.

8. The combination according to claim 6 wherein said element is located in the transverse plane of said stub.

9. The combination according to claim 5 wherein the distance between said element and said stub is substantially less than the distance between said members.

10. The combination according to claim 5 wherein said magnetic polarizing field is directed normal to the axes of said members.

11. In an electromagnetic wave system supportive of a range of operating frequencies, means for selectively transmitting a band of frequencies within said range comprising a pair of parallel elongated conductive members, a plurality of shorting stubs each of low loss highly conductive material conductively connected to and extending between said members longitudinally distributed along said members, an element of magnetically polarizable material capable of exhibiting gyromagnetic

effects over said band of frequencies located between said members adjacent to each of said stubs, and means for magnetically polarizing said elements to gyromagnetic resonance at a frequency within said band.

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