

Aug. 9, 1960

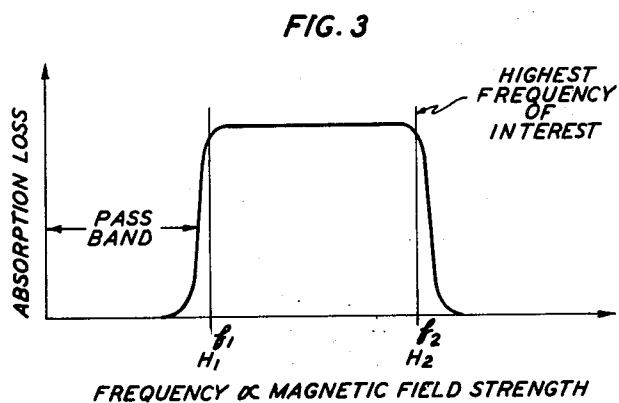
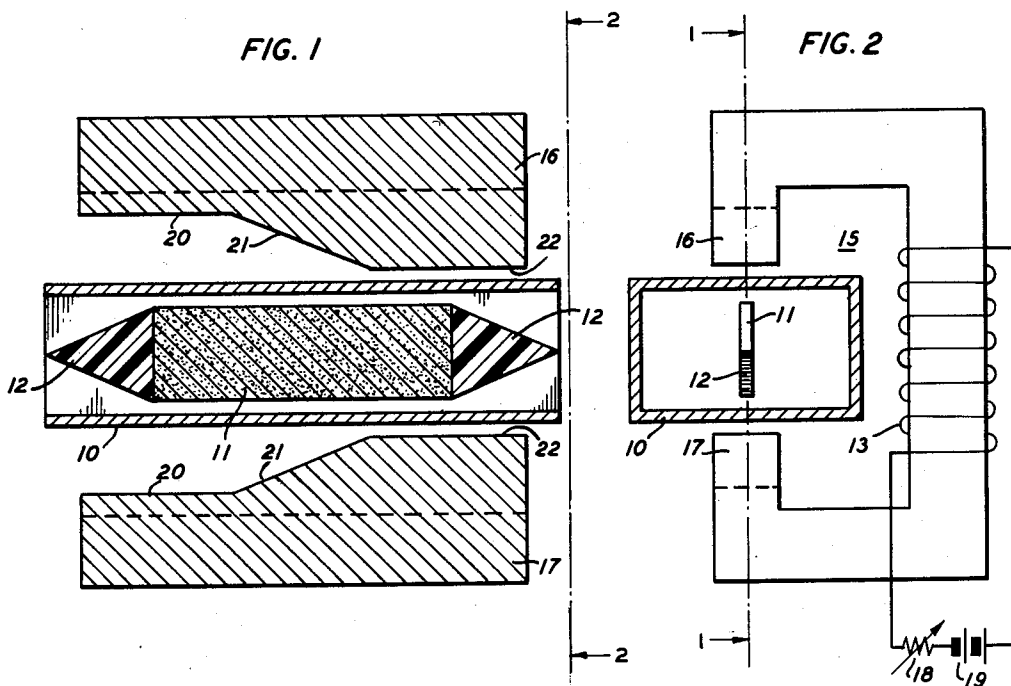
M. L. REEVES

2,948,868

FREQUENCY SENSITIVE ELECTROMAGNETIC WAVE DEVICE

Filed Nov. 14, 1955

3 Sheets-Sheet 1



INVENTOR
M. L. REEVES
BY Roy M. Porter, Jr.

ATTORNEY

Aug. 9, 1960

M. L. REEVES

2,948,868

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FIG. 4

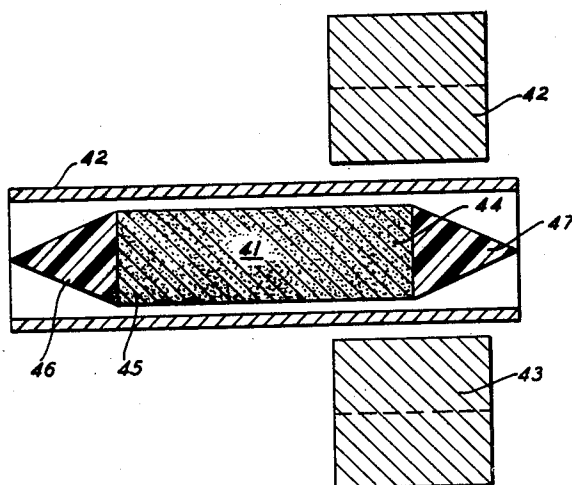
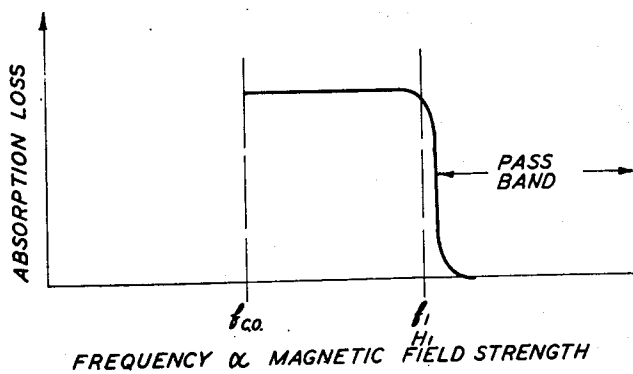


FIG. 5



INVENTOR
M. L. REEVES
BY *Ray M. Portier, Jr.*

ATTORNEY

Aug. 9, 1960

M. L. REEVES

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FIG. 6

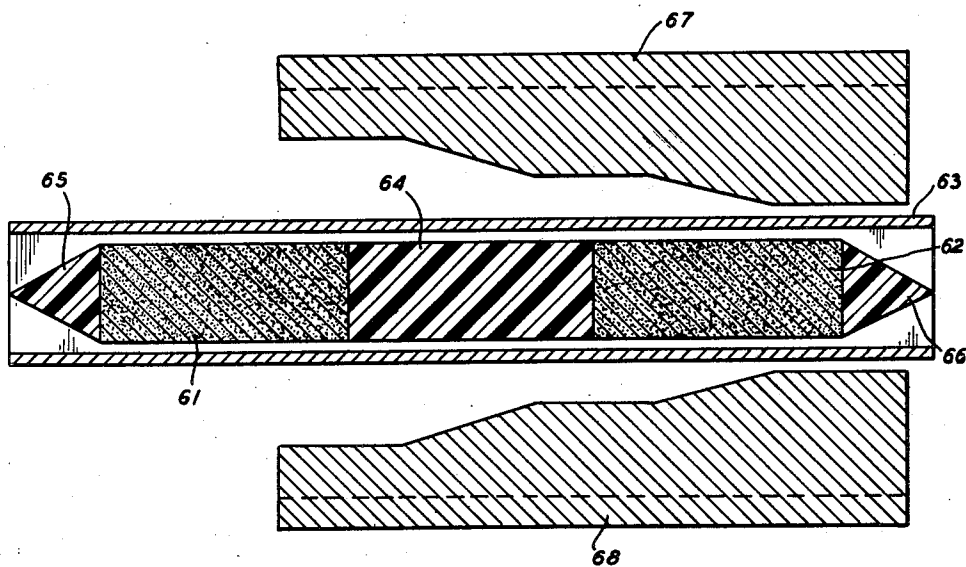


FIG. 7

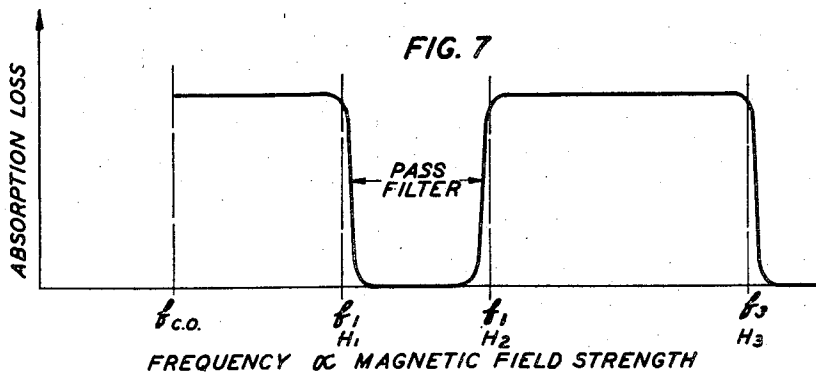
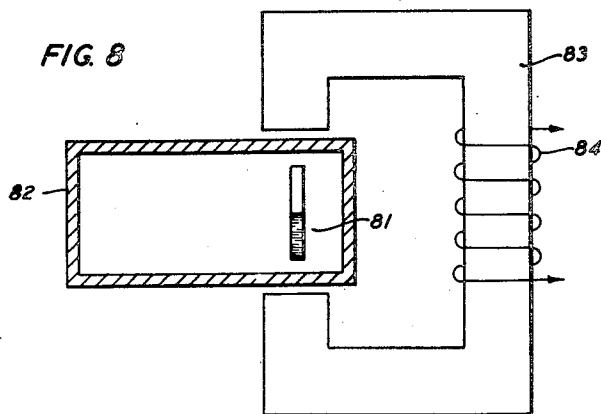


FIG. 8



INVENTOR
M. L. REEVES
BY *Ray M. Porter, Jr.*

ATTORNEY

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2,948,868

FREQUENCY SENSITIVE ELECTROMAGNETIC WAVE DEVICE

Marvin L. Reeves, Seattle, Wash., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

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1 Claim. (Cl. 333—73)

This invention relates to electromagnetic wave transmission systems and, more particularly, to frequency sensitive attenuating means having predetermined and controllable bands of attenuation with respect to the frequency of components of said energy.

It has heretofore been proposed to place an element of gyromagnetic material in the path of and in the field pattern of electromagnetic wave energy and to bias this material to a point at which it becomes resonant in a gyromagnetic sense to the frequency of the applied wave energy. Under this condition certain gyrating electrons within the material couple strongly with clockwise rotating components of the high frequency magnetic field and introduce substantial loss of attenuation to the wave energy. For all field strengths other than that required for resonance, the attenuation will be small. Heretofore the attenuation versus frequency characteristics of such devices have been limited to those of the resonance characteristics inherent in the particular materials used, which in the usual cases have been ferromagnetic materials having relatively broad resonance characteristics. No control existed and no adjustment was possible of the band of these characteristics.

It is an object of the present invention to control the band and frequency selectivity of gyromagnetic attenuating devices.

It is a further object of the invention to filter electromagnetic wave energy by gyromagnetic means in accordance with a predetermined high pass, low pass or band pass characteristic.

In accordance with the present invention, it has been recognized that materials of the type classified as paramagnetic, and, more particularly, as organic free radicals, have very sharp gyromagnetic resonance characteristics. Different finite portions of such an element are subjected to biasing magnetic fields of different intensities. Since the frequency of resonance is directly proportional to the strength of the biasing magnetic field, each finite portion produces resonance at, and therefore introduces attenuation to, wave energy of slightly different frequency. By tapering the magnetic field through all values producing resonance at the frequencies within a given band, the entire band is eliminated. If the highest frequency attenuated is at least as high as the highest frequency of interest, a filter having a low pass characteristic is obtained for which the cutoff frequency is just below the lowest frequency attenuated. Furthermore, in accordance with specific embodiments of the invention, the lowest frequency attenuated is extended down to zero to produce a filter having high pass characteristics. By means of a novel combination of a low pass filter structure and a

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high pass filter structure, a band pass filter is realized. In all embodiments both the bandwidth and the cutoff frequencies are readily designed to predetermined specifications and, if desired, may be made adjustable in the manner to be described.

These and other objects, the nature of the present invention, 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 longitudinal cross-sectional view of a preferred embodiment having low pass filter characteristics in accordance with the invention;

Fig. 2 is a transverse cross-sectional view of Fig. 1 taken as indicated;

Fig. 3, given by way of explanation, is a characteristic of the absorption loss versus frequency or magnetic field strength of the embodiment of Fig. 1;

Fig. 4 is a longitudinal cross-sectional view of an embodiment of the invention having high pass filter characteristics;

Fig. 5, given by way of explanation, is a characteristic of the absorption loss versus frequency or magnetic field strength of the embodiment of Fig. 4;

Fig. 6 is a longitudinal cross-sectional view of an embodiment of the invention having band pass filter characteristics;

Fig. 7 is a longitudinal cross-sectional view of an embodiment of the invention having band pass filter characteristics; and

Fig. 8 is an alternative end view for the embodiment of Figs. 1, 4 or 6, by means of which nonreciprocal filter characteristics are realized.

Referring more particularly to Fig. 1 and the transverse view thereof of Fig. 2, an illustrative embodiment of the invention having low pass filter characteristics comprises a section 10 of conductive rectangular wave guide which is to be interposed in the path of linearly polarized wave energy to be filtered. Located in guide 10 and substantially centered therein is an elongated vane 1 of gyromagnetic material of the type to be described having a width of a small fraction of a wavelength. Van 11 is positioned in guide 10 to extend in a plane parallel to a narrow wall thereof for slightly less than the distance between the wider walls and to extend longitudinally in guide 10 parallel to the narrow walls for several wavelengths. The longitudinal ends of vane 11 are continuous into tapered members 12 of dielectric material to prevent undue reflections from these ends.

Vane 11 is composed of a gyromagnetic material, i.e. a material of the type that exhibits gyromagnetic resonance to electromagnetic wave energy in the frequency range to be filtered and which has a resonance bandwidth that is small compared to the bandwidth of the desired filter characteristic. In accordance with the broadest aspects of the invention, this includes the nonconductive ferromagnetic materials, such as ferrite, and also the nonconductive paramagnetic organic free radical compounds. The phenomenon of gyromagnetic resonance in ferromagnetic materials is well known to the art. Essentially the same principles are involved with the paramagnetic materials and may be explained by the recognition that these materials contain unpaired electron spin

which tend to line up with an externally applied magnetic field. These spins have an associated magnetic moment which may be made to precess about the line of the biasing magnetic field at a resonant frequency dependent upon the intensity of the field. When a field of high frequency wave energy is also applied to the material, the clockwise rotating circularly polarized components of the wave tend to couple strongly with the gyrating electrons when the frequency of the high frequency energy is equal to the resonant frequency of the electrons. This introduces substantial loss or attenuation to the wave. Therefore the frequency of attenuation or the frequency of the high frequency wave that will be resonant with the electrons is directly proportional to the strength of the biasing field and may be varied over a considerable range. For field strengths other than that required for resonance the attenuation will be small.

In accordance with the invention, it has been found that different portions of the same element may be subjected to biasing fields of different intensity and that each portion will produce resonance at, and introduce attenuation to, wave energy of different frequencies. A desired filter characteristic is therefore built up from the resonance absorption of each portion by applying a magnetic field of properly differing intensity to each of the portions to absorb selected frequency components from the total bandwidth of the applied wave energy. This effect can only be taken advantage of if the total bandwidth of the applied energy is substantially greater than the resonance bandwidth of any one portion. Since the ferromagnetic materials have resonance bandwidths that are relatively large compared to the wave energy bandwidths now considered for commercial applications, the use of ferromagnetic materials will only be practical with substantially wider bands than are presently contemplated. On the other hand, the materials classified as paramagnetic and, more particularly, the paramagnetic materials known as organic free radicals because they have an odd number of electrons, have very narrow resonance bandwidths in the order of several oersteds. This compares with the bandwidth of a typical ferrite compound of several hundred oersteds. The fact of the narrow bandwidth means that these materials exhibit a resonance characteristic like that of a very high Q circuit. For example, in a typical organic free radical compound,

Q of from one to ten thousand in a range of interest including the frequency range of ten to fifty-five kilocycles is exhibited, the Q being highest at the higher frequencies.

The following table lists several of the more common organic free radical compounds together with their resonance bandwidths at the half-power points. This listing is by no means to be considered as exclusive of other compounds of this class which may likewise be used to practice the invention.

Compound	Bandwidth at half-power points, oersted
Banfield and Kenyon's radical	18.4
1-para-anisyl nitric oxide	31.4
1-phenyl trinitrophenyl hydrazyl	2.70
orphoxydine	17.0
orphyrindine	25.2
benanthro-phenazinium chlorstannite	6.4
Wurster's Blue (as ferricyanide)	3.7
Wurster's Blue (as picrate)	6.0

Wurster's Blue is a class of dyes derived from the ionization of the compound N,N,N',N'-tetramethyl-p-phenylenediamine, (C₁₀H₁₆N₂) known as Wurster's reagent. When placed in solution with an oxidant, such as picric acid or a ferricyanide, the organic free radical compound Wurster's Blue (as picrate) or Wurster's Blue (as ferricyanide) is formed. (See, The Journal of the American Chemical Society, vol. 53, July-September 1931, pages

2953-2955, and The Concise Chemical and Technical Dictionary by H. Bennett, page 989.) Banfield and Kenyon's radical is the complex compound [β -(phenyl nitric oxide)- β -methyl pentane-3-one oxime N-phenyl ether]. (See Philosophical Magazine, vol. 44, 1953, page 1187.)

Thus, in accordance with a preferred embodiment of the invention, vane 11 is composed of Wurster's Blue (as ferricyanide), being a compound from the preceding table that has one of the narrowest bandwidths and that is also readily available. Vane 11 is then biased by a magnetic field parallel to the plane of vane 11 and perpendicular to the direction of propagation along guide 10, the intensity of which commences at one end of vane 11 with a first value and then increases gradually along vane 11 to a larger value. This field may be supplied as illustrated by a solenoid structure 15 comprising a C-shaped magnetic core which has pole-pieces 16 and 17 spaced apart to form an air gap in which the magnetic field is concentrated and between which guide 10 and vane 11 are received. Turns of wire 13 on core 16-17 are so wound and connected through rheostat 18 to a source potential 19 that north and south poles are produced for pole-pieces 16 and 17, respectively.

The intensity of the field that biases a given portion of vane 11 is determined by the length of the air gap between the portions of the pole-pieces 16 and 17 receiving that part of the vane. Thus the faces of pole-pieces 16 and 17 are tapered over three portions 20, 21 and 22. In portion 20 the air gap is of such distance that a field intensity H₁ is produced in the left hand end of vane 11. H₁ corresponds to the intensity that produces resonance at a frequency f₁ just above the highest frequency to be passed as illustrated in Fig. 3 by the characteristic of absorption loss versus frequency and magnetic field strength, the latter two parameters being proportional to each other. Portion 20 preferably extends for some distance on either side beyond the exact end of vane 11 so that the fringe effects of the field do not decrease its intensity in vane 11 below the desired strength H₁. Thus the band of frequencies below the frequency f₁, representing the cutoff of the filter, will be propagated through guide 10 with substantially no attenuation due to the presence of vane 11. Portion 21 of pole-pieces 16 and 17 comprises a section of progressively decreasing air gap and therefore of progressively increasing biasing intensity. Thus successive portions of vane 11 are resonant to and therefore absorb progressively higher frequency components in the band above f₁. Portion 22 of pole-pieces 16 and 17 produces a field intensity H₂ in the right hand end of vane 11. The intensity H₂ produces resonance at the frequency f₂ which for low pass operation should be at least as high as the highest frequency to be attenuated.

Thus the embodiment of Fig. 1 provides a filter structure that passes all frequency components up to the frequency f₁ and attenuates all components of interest having frequencies between f₁ and f₂. By increasing or decreasing the magnetizing current by adjusting rheostat 18, the value of f₁ may be shifted along the frequency scale thus providing a low pass filter of variable cutoff frequency. If adjustment is not desired it is apparent that the field may be supplied by a suitably shaped permanent magnet structure. It should also be apparent that if the frequency f₂ falls within the band of interest, an equally useful band rejection filter is provided. If band rejection use is contemplated, a solenoid may be provided which allows independent adjustment of the intensity H₂ so that frequency f₂ may be shifted along the frequency scale independently of the frequency f₁. In any event, the sharpness of the cutoff at the frequency f₁ or f₂ is equivalent to the shape of the resonant characteristic of the material used. In the particular case of Wurster's Blue (as ferricyanide), it has been determined that a magnetic field in the order of 4,000 oersteds produces a cutoff frequency in the order of 11,300

megacycles with a very sharp cutoff that corresponds to a resonant line width in the order of 2 to 3 oersteds.

In Fig. 4 a gyromagnetic filter having a high pass characteristic is shown. A vane 41 which is substantially identical to vane 11 of Fig. 1 is located in a rectangular guide 42 in a similar position to vane 11 in guide 10. Dielectric tapers 46 and 47 are provided at the ends of vane 41. Pole-pieces 42 and 43 are provided to supply the biasing magnetic field to vane 41. These pole-pieces have a constant air gap that includes only the end 44 of vane 41 with the end 45 extending beyond the pole-pieces 42 and 43 into the region of progressively decreasing field intensity for a sufficient distance that the end 45 is subject to a magnetic field of zero. The resulting absorption loss characteristic is shown in Fig. 5. Each successive portion of vane 41 starting at end 45 is resonant to and attenuates components having frequencies commencing well below the cut-off frequency f_{co} of the wave guide 10 and extending to successively higher frequencies as the biasing field strength of each portion becomes larger than that of the preceding portion. At end 44, vane 41 is subjected to the maximum biasing field H_1 which is of such strength to produce attenuation at the frequency f_1 . Thus only wave energy having a frequency above f_1 is passed through guide 42. By adjusting the strength of the field H_1 , the cutoff frequency f_1 may be controlled and varied to produce a high pass filter of adjustable pass band.

In the embodiment of Fig. 6 the features of the low pass filter of Fig. 1 and the high pass filter of Fig. 6 are combined to produce a structure having a band pass characteristic. Thus two gyromagnetic vanes 61 and 62 are placed in longitudinal succession in the rectangular guide 63. Vanes 61 and 62 are separated by a vane-like spacer 64 consisting of dielectric material. The separation provided by spacer 64 is sufficient that gyromagnetic vanes 61, 62 may be subjected to biasing fields of different intensities without interaction. The left end of vane 61 and the right end of vane 62 are provided with tapers 65 and 66 of dielectric material as in the preceding embodiments. Magnetic pole-pieces 67 and 68 are located above and below guide 63, respectively, to bias the right hand end of vane 61 and all of vane 62 by a tapered magnetic field. The left hand end of vane 61 extends beyond pole-pieces 67 and 68 at least into a region of zero intensity. As in the preceding embodiments, the air gap between the pole-pieces 67 and 68 controls the biasing intensity of each portion of vanes 61 and 62. The distribution of the field intensity and the resultant band pass characteristic are shown in Fig. 7. Thus, commencing with the left hand end of vane 61, the intensity of this field is zero and increases along vane 61 to an intensity H_1 at its right hand end, increases again in the region of dielectric spacer 64 to an intensity H_2 at the left hand end of vane 62, and then increases to an intensity H_3 at the right hand end of vane 62. Since the frequency of attenuation of each portion of the vane is proportional to the intensity of magnetization, all components having frequencies between the guide cutoff f_{co} and a frequency f_1 , representing the resonant frequency produced by the intensity H_1 , are absorbed in vane 61. Between the frequency f_1 and the frequency f_2 no energy is dissipated since the field strengths between H_1 and H_2 are applied only to dielectric spacer 64. Components having frequencies between f_2 and f_3 , the latter representing the highest frequency of interest, are dissipated in vane 62.

While a single magnetic pole structure is shown for both vanes 61 and 62, it should be apparent that if separate poles are provided the frequencies f_1 and f_2 may be separately selected and adjusted to control the width of the pass band as well as its position along the frequency scale. With a single set of poles as illustrated, the percentage width of the band is fixed and only its position along the frequency scale may be adjusted.

The preceding embodiments as disclosed thus far are all reciprocal with respect to the direction of propagation along the guides and the same attenuation characteristic is presented to wave energy traveling in both directions. In Fig. 8 is shown a transverse cross-sectional view which may represent an alternative cross-sectional arrangement for any of the preceding embodiments by means of which they become nonreciprocal. Thus in Fig. 8 a vane 81 of the type hereinbefore described is located asymmetrically in the cross section of guide 82 and more particularly, at a point displaced approximately one quarter of the guide width away from the narrow wall. As taught in the copending applications of W. H. Hewitt, Serial No. 362,191, filed June 17, 1953, and of S. I. Miller, Serial No. 362,193, filed June 17, 1953, this places vane 81 at a position of circularly polarized components of the high frequency magnetic field of energy traversing guide 82 that rotate clockwise for one direction of propagation along guide 82 and counterclockwise for the opposite direction of propagation. Since the gyrating electrons in the material of vane 81 will couple strongly with only clockwise rotating magnetic field component gyromagnetic resonance will take place for only one direction of propagation and the wave will be substantially unaffected by the presence of vane 81 for the opposite direction of propagation. Core 83 and solenoid 84 represent means for subjecting vane 81 to a biasing magnetic field that may be tapered in accordance with the teachings of the preceding embodiments to obtain a band pass, band rejection, low pass or high pass characteristic for the one direction of propagation. By reversing the sense of the field, the direction of propagation for which the filter characteristic is introduced will be reversed.

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:

In combination, a conductively bounded electromagnetic wave transmission path having an input and an output end and a cutoff frequency f_0 , a source of wave energy including a band of frequencies extending between a lower frequency f_1 higher than f_0 and a frequency higher than f_1 and including a frequency f_2 between f_1 and f_3 connected to said input end, filtering means disposed within said path comprising an element of magnetically polarizable material capable of exhibiting gyromagnetic effects over said band of frequencies and having a sharp gyromagnetic resonance characteristic with respect to said band, said element having a uniform transverse cross section that extends longitudinally along said path, means for inducing gyromagnetic resonance extending from f_1 to f_2 comprising a pair of magnetic pole pieces uniformly spaced to receive a portion only of said element, said pole pieces extending longitudinally beyond one end of said element to produce at said end maximum field intensity in said element that induces gyromagnetic resonance at said one end at frequency f_1 , the remainder of said element extending longitudinally beyond said pole pieces at the other end thereof to produce at said other end a minimum field intensity in said element that induces gyromagnetic resonance at said other end at a frequency no greater than f_0 , and means for utilizing said applied wave energy between the frequencies f_2 and f_3 to the exclusion of said frequencies within said preselected range of frequencies between f_1 and f_2 connected to said output end.

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