

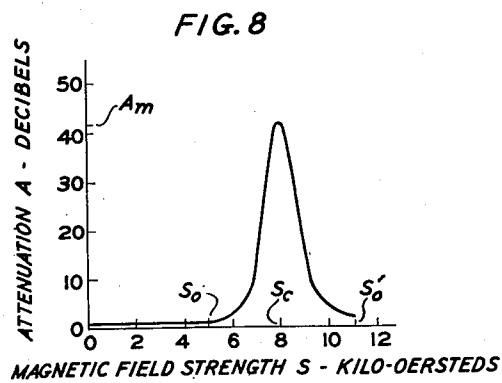
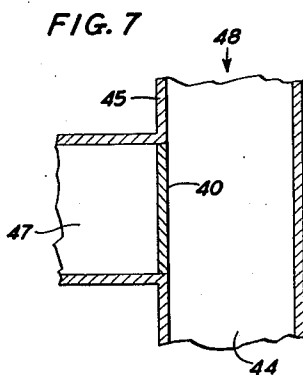
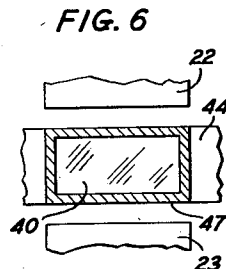
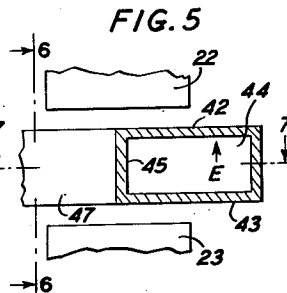
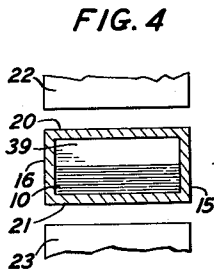
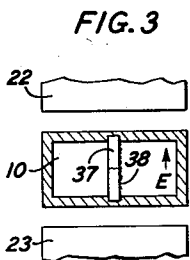
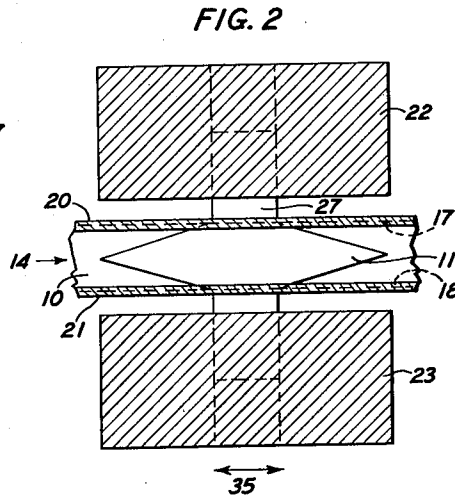
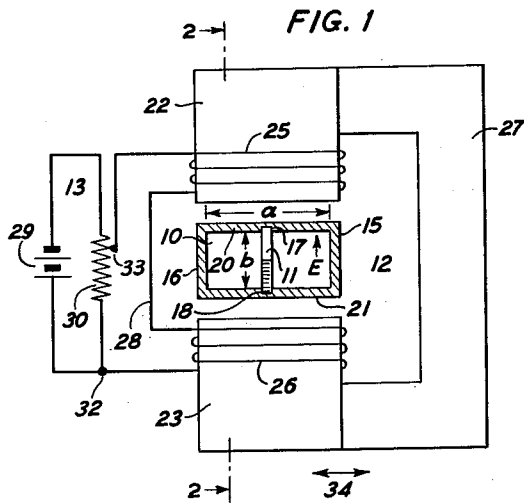
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2,814,783

MAGNETICALLY CONTROLLABLE TRANSMISSION SYSTEM

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MAGNETICALLY CONTROLLABLE TRANSMISSION SYSTEM

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Original application May 17, 1950, Serial No. 162,570, now Patent No. 2,745,069, dated May 8, 1956. Divided and this application January 25, 1956, Serial No. 561,185

14 Claims. (Cl. 333—7)

This application is a division of my copending application Serial No. 162,570, filed May 17, 1950, entitled "Microwave Magnetized Ferrite Attenuator," now Patent 2,745,069, issued May 8, 1956.

This invention relates to wave transmission and more particularly to a magnetically controllable transmission system for electromagnetic waves.

The general object of the invention is to control the transmission of electromagnetic wave energy. A more specific object is to control the attenuation magnetically.

It is often required to vary the attenuation of electromagnetic wave energy which is being transmitted through a wave guide. Heretofore variable attenuators for this purpose have comprised resistive vanes longitudinally positioned within the guide parallel with the electric field of the waves. The attenuation is varied by moving the vane transversely to a region of greater or less field strength.

In the variable electromagnetic wave attenuator in accordance with the present invention the attenuating element remains in a fixed position. The attenuation is controlled magnetically by making use of the ferromagnetic resonance effect, which is a property of all magnetic material. A comprehensive description of this property will be found in the paper by Charles Kittel, entitled "Ferromagnetic Resonance," published in *Le Journal de Physique et le Radium*, Tome 12, Mars 1951, page 291, and the numerous references cited therein. In the embodiments disclosed herein, by way of example only, the attenuator comprises a wave guide of the hollow-pipe type adapted for the transmission of electromagnetic waves of a particular orientation, an attenuating element of magnetic material located within the guide, means for subjecting the element to a magnetic field parallel to the electric field of the waves, and means for varying the strength of the field through a range of values in the neighborhood of the value require to produce exact ferromagnetic resonance in the element. The guide may be rectangular in cross section, with unequal cross-sectional dimensions, in which case the electric field will be parallel to the narrower sides.

The attenuating element may, for example, be in the form of a longitudinally positioned vane, a block, or a window in a side of the guide. The vane or block is preferably tapered at each end to reduce reflection effects. The vane is arranged parallel with the electric field and may extend all or only part of the way across the guide in the direction of the electric field. The block may only partly fill the cross section of the guide, but when considerable power is to be dissipated the block, at least for a portion of its length, preferably entirely fills the guide. A branch wave guide may be connected to the main guide at the window.

The magnetic material used in the attenuating element may be a ferrite or a magnetic metal, reduced to a powder and mixed with a suitable dielectric medium or ap-

plied as a coating to a dielectric carrier. When the material is a ferrite, it may constitute the entire element.

The magnetic field is preferably supplied by a horseshoe magnet between the pole pieces of which the attenuating element is located. This may be a permanent magnet, an electromagnet, or a combination of the two. The strength of the magnetic field to which the attenuating element is subjected may be varied by moving the magnet away from or toward the element. If an electromagnet is employed, its field strength may be varied conveniently by adjusting the current through the winding. The attenuator is preferably operated near the field strength which produces exact ferromagnetic resonance in the attenuating element because, in this region, the change in attenuation with field strength is much greater than elsewhere.

The nature of the invention will be more fully understood from the following detailed description and by reference to the accompanying drawings, of which:

Fig. 1 is an end view of a variable electromagnetic wave attenuator in accordance with the invention in which the attenuating element is a vane;

Fig. 2 is a longitudinal sectional view of the attenuator taken at the plane 2—2 in Fig. 1 in the direction of the arrows;

Fig. 3 shows a partial end view of a modified form of the attenuator in which the attenuating element is a dielectric vane coated on one side with magnetic powder;

Fig. 4 is a partial end view of another modification in which the attenuating element is a block entirely filling a cross section of the guide;

Fig. 5 is a partial end view of another embodiment of the invention in which the attenuating element appears as a window in the side of the main wave guide;

Fig. 6 is a partial side view of the attenuator of Fig. 5, taken at the plane 6—6 in the direction of the arrows;

Fig. 7 is a horizontal sectional view, taken at the plane 7—7 in Fig. 5 in the direction of the arrows, of the main and branch wave guides used in the structure shown in Figs. 5 and 6; and

Fig. 8 shows a typical characteristic of attenuation versus field strength obtainable with the attenuator of Figs. 1 and 2.

Taking up the figures in more detail, the embodiment of the variable electromagnetic wave attenuator in accordance with the present invention shown in Figs. 1 and 2 comprises a wave guide 10, an attenuating element 11, a horseshoe magnet 12, and a source of variable voltage 13. The wave guide 10 is of the hollow-pipe type and is rectangular in cross section, with unequal cross-sectional dimensions a and b . It is supplied at one end with electromagnetic wave energy, as indicated by the arrow 14 in Fig. 2. The longer dimension a preferably falls between λ and $\lambda/2$ where λ is the wavelength within the guide 10 at the maximum operating frequency of the attenuator, so that the guide will transmit the fundamental mode but will not support higher modes, and generally is made approximately equal to $3\lambda/4$. The shorter dimension b is preferably less than $\lambda/2$, so that the guide will not support a fundamental mode with its electric field oriented perpendicular to the b dimension, and is generally made approximately equal to $a/2$ or less. The electric field of the transmitted fundamental mode is, therefore, oriented parallel to the narrower sides 15, 16 of the guide, as indicated by the arrow E in Fig. 1.

The attenuating element 11 is in the form of a comparatively thin, flat, longitudinally positioned vane, preferably centrally located between and parallel with the narrower sides 15, 16 so that it will be in the strongest part of the electric field. In the operating range of the attenuator the attenuation corresponding to a given applied field depends upon the volume of the attenuating element 11

within the field. The element may extend only part or all of the way between the sides of the guide. The embodiment in which the element extends all the way across the guide and makes physical contact with two or more of the sides is to be preferred, when comparatively large amounts of power are to be dissipated, because the heat generated in the attenuating element is more easily conducted to the walls of the guide, from which it may be radiated into the surrounding atmosphere. As shown in Figs. 1 and 2 the vane 11 extends all the way between the wider sides 20, 21 and is held in place by the grooves 17 and 18. These grooves extend the entire length of the guide 10 so that the vane 11 may be inserted into the end of the guide and slid into place. The vane is tapered at each end, as shown in Fig. 2, for a distance at least equal to $\lambda/2$ in order to reduce reflection effects.

The vane 11 comprises magnetic material, such as a ferrite or a magnetic metal. If a ferrite is used, it may be molded into the required shape before receiving the heat treatment or it may be machined to shape from a block of ferrite. Either the ferrite or the magnetic metal may be reduced to a fine powder or dust and mixed with a suitable dielectric medium. The dielectric constant and the loss factor of the dielectric medium should be as low as possible. Keeping the dielectric constant and the loss factor low minimizes, respectively, the reactance and the attenuation associated with the dielectric medium. A dielectric constant not exceeding 2.5 and a loss factor of not more than 0.0006 have been found to be satisfactory. If the vane 11 is comprised entirely of a ferrite, its resistivity should be as high as possible to keep the minimum attenuation small. For a minimum attenuation of less than one decibel a resistivity of at least 100,000 ohm-centimeters has been found to be satisfactory. All ferrites contain iron and have the general chemical formula MFe_2O_4 , where M denotes one or two bivalent metals in almost any proportion. An example is zinc manganese ferrite with the formula $Zn_{1/2}Mn_{1/2}Fe_2O_4$, which may also be written $(ZnO)(MnO)2Fe_2O_3$. Magnetic metals suitable for mixing with the dielectric medium are nickel, iron, or an alloy of nickel and iron. A preferred alloy is composed of 45 percent by weight of nickel and 54 percent by weight of iron, known as Perm-alloy 45. Other percentages may, of course, be used.

The transverse magnetic field is furnished by the horseshoe magnet 12, which comprises two pole pieces 22, 23, with windings 25, 26 thereon, and a magnetic yoke 27 providing a path of low reluctance between the pole pieces. The inner ends of the windings 25 and 26 are connected by the strap 28. The pole pieces 22 and 23 are located as close as possible to the wider sides 20 and 21 of the guide 10 so that the attenuating element 11 may be subjected to the highest possible magnetic field intensity. Also, in order to provide the strongest possible field, the dimension b of the guide may be reduced to the smallest value consistent with the power to be transmitted.

The source of variable voltage 13 is a potentiometer or voltage divider comprising a battery or other source of constant direct electromotive force 29 across which is connected a resistor 30 of high resistance. The outer end of the winding 26 is connected to one end of the resistor 30, as shown at the point 32, and the outer end of the winding 25 is adjustably connected to a point 33 on the resistor 30. The magnetic field corresponding to the desired attenuation is obtained by properly selecting the point of connection 33. It will, of course, be understood that the magnetic field corresponding to the minimum desired attenuation may be provided by permanently magnetizing the magnet 12, thus permitting a corresponding reduction in the required magnitude of the voltage supplied by the source 29. Another way in which the strength of the magnetic field may be varied is to move the magnet 12 transversely with respect to the attenuating element 11, as indicated by the double-pointed arrow 34

in Fig. 1, or longitudinally, as indicated by the arrow 35 in Fig. 2, by any suitable means, not shown. In this case, if the magnet 12 is permanently magnetized to a sufficient strength, the source of variable voltage 13 and the windings 25, 26 are not required.

Referring to the typical attenuation-field strength curve of Fig. 8, the following theory is offered to explain the operation of the variable attenuator shown in Figs. 1 and 2. When the strength S of the magnetic field applied to the vane 11 is sufficiently greater or less than the critical value S_c required to produce exact ferromagnetic resonance in the magnetic material in the vane 11, the resulting attenuation A is very small, approaching zero. As S is gradually increased from zero, a value such as S_0 is reached beyond which the attenuation rises rapidly to a maximum value of A_m at the value S_c and thereafter drops rapidly to a comparatively small value at the field strength S_0' . The portion of the characteristic between S_0 and S_0' may be termed the region of ferromagnetic resonance. Ferromagnetic resonance occurs because of the action of the magnetic field upon the unpaired electrons associated with the metallic elements of the vane 11. The spin axes of the free electrons precess around the direction of the applied magnetic field. The frequency of these oscillations depends upon the strength S of the field and their magnitude is damped as the electron axes line themselves up with the field. When the magnetic field associated with the electromagnetic wave being propagated along the guide 10 is properly oriented with respect to the field of the magnet 12, the axes of the electrons will continue to precess instead of being damped, because of the absorption of electromagnetic energy by the oscillating electrons. The amount of energy thus absorbed depends upon the difference between the frequency at which the electron axes want to oscillate, which is a function of the applied field, and the frequency of the electromagnetic waves within the guide 10. This absorption of energy by the vane 11 causes an attenuation the magnitude of which is under the control of the field strength S . The maximum attenuation A_m occurs when S has the value S_c which causes exact ferromagnetic resonance. It will be evident, however, that the magnitude of A_m is dependent upon the frequency of the waves. The frequency sensitivity of the attenuator will be reduced if the distance between the vane 11 and either of the narrower sides 15, 16 of the guide 10 is less than $\lambda/2$. Furthermore, when this distance is less than $\lambda/2$ the maximum attainable attenuation A_m is increased. This is due to the fact that, as ferromagnetic resonance in the vane 11 is approached, the resistivity of the vane is reduced and the vane acts more and more like a low-resistance wall dividing the guide 10 effectively into two guides, neither of which is wide enough in the direction of the dimension a to support the wave being propagated.

The curve in Fig. 8 shows a typical attenuation characteristic obtainable at a frequency of 24,000 megacycles per second with the variable attenuator of Figs. 1 and 2. The attenuation A in decibels is plotted against the magnetic field strength S in kilo-oersteds applied to a vane 11 made of zinc manganese ferrite having a resistivity of a million ohm-centimeters. The vane has a length of 2 inches, with a $3/4$ -inch taper at each end, and a thickness of 0.037 inch. The guide 10 has inside dimensions a and b equal, respectively, to 0.42 inch and 0.17 inch. A maximum attenuation A_m of 41.5 decibels occurs at a critical field strength S_c of 7.95 kilo-oersteds. As S is varied in either direction from this value, by changing the point of connection 33 to the resistor 30, the attenuation correspondingly decreases, reaching a minimum value of 0.3 decibel at zero field strength. Any desired attenuation between these limits may be obtained by a proper selection of the tapping point 33. A decrease of S to a value S_0 of 5:1 reduces the attenuation to the minimum value of 0.3 decibel, at which it remains as S is further reduced to zero. Increasing the field strength from

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S_0 to a value S_0' of 11.16 decreases the attenuation from 41.5 to 0.5 decibel. As mentioned above, the field strength S_0 can be supplied by permanently magnetizing the magnet 12. At any other frequency the maximum attenuation A_m will, in general, be somewhat different, and the corresponding critical field strength S_0 will also be different. At a frequency of 23,600 megacycles, for example, A_m is 39.5 decibels at a value of S_0 of 7.85, and the attenuation at zero field strength is 0.5 decibel. When the vane 11 has a high resistivity, the reflection effects caused by its presence within the guide are, in general, small enough to be unobjectionable for most applications. When the resistivity of the vane is reduced by using a ferrite with lower resistivity or by using a mixture of powdered ferrite or powdered magnetic metal and a dielectric medium, the reflections and the minimum attainable attenuation are increased and the maximum attenuation is decreased.

Fig. 3 shows a modified form of the attenuator in accordance with the invention, similar in all respects to the one shown in Figs. 1 and 2 except that the vane 11 is replaced by a similarly shaped and mounted attenuating element comprising a vane 37 of dielectric material with a thin coating or film 38 of magnetic material, indicated by stippling, on one side. Only the wave guide 10, the attenuating element 37, 38 and the ends of the pole pieces 22, 23 are shown in Fig. 3. It is to be understood that the rest of the structure is the same as shown in Figs. 1 and 2, and that the operation of the attenuator is the same. The function of the vane 37 is to provide support for the magnetic film 38. If the material from which the vane is made has a sufficiently high resistivity, its thickness is not important. A resistivity of 10^{10} ohm-centimeters or greater has been found to be satisfactory. The film of magnetic material 38 may comprise a mixture of powdered ferrite, magnetic metal, or magnetic alloy and an acrolloid or phenolic resin binder.

Fig. 4 is a partial end view, similar to the one shown in Fig. 3, of a third embodiment of the variable attenuator in accordance with the invention. In Fig. 4 the attenuating element 39 is a block of magnetic material which, at its central portion, entirely fills the transverse cross section of the guide 10, and is in physical contact with all of the sides 15, 16, 20 and 21. The block 39 is preferably tapered at each end for a distance equal to $\lambda/2$ or more, in the same manner as is the vane 11 shown in side view in Fig. 2. The block 39 may be made of any of the materials suggested for the vane 11 described above in connection with Figs. 1 and 2. The attenuator of Fig. 4 is particularly adapted to handle relatively high power, because the heat generated in the attenuating element 39 is readily conducted on all sides to the walls of the guide 10, from which it is radiated into the surrounding air. The attenuation is varied in the same manner as described above in connection with the attenuator of Figs. 1 and 2.

Figs. 5, 6 and 7 show another embodiment of the variable attenuator in accordance with the invention in which the attenuating element 40 is a plate extending between the wider sides 42, 43 of the main wave guide 44 and forming a window in one of the narrower sides 45 flush with the inner side thereof. A branch wave guide 47 is connected to the main guide 44 at the window, so that the element 40 closes the end of the branch guide. The structure for providing the variable magnetic field may be the same as shown in detail in Figs. 1 and 2. The pole pieces 22 and 23, only the ends of which appear in Figs. 5 and 6, are preferably centered about the element 40 so that it will be in the strongest and most uniform portion of the applied magnetic field. The element 40 may be made of any of the materials suggested above for the vane 11. Part of the electromagnetic wave energy fed into one end of the main guide 44, as indicated by the arrow 48 in Fig. 7 will be diverted from the main guide through the window 40 and into the branch guide 47.

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When the field applied to the element 40 is well below or well above its critical value S_0 , the energy diverted into the branch guide is substantially unaffected as it passes through the window. However, as the field strength S is varied in the direction of the value S_0 , a value such as S_0 or S_0' is reached beyond which the element 40 increasingly attenuates the energy in the branch, without substantially altering the transmission down the main guide 44. The maximum attenuation of the energy in the branch is reached when the field attains the value S_0 at which exact ferromagnetic resonance occurs in the element 40. Therefore, as to the energy in the branch guide 47, the arrangement operates as a variable attenuator, under the control of the applied field strength S . The characteristic is of the same type as the one shown in Fig. 8. The magnitude of the maximum attenuation A_m is dependent upon the thickness of the element 40, increasing as the thickness increases. As in the other embodiments, the desired attenuation may be obtained by a proper choice of the point of connection 33 to the resistor 30.

What is claimed is:

1. In combination, a conductively bounded wave guide for linearly polarized electromagnetic waves, an aperture in a conductive side wall thereof, an element comprising ferrite closing said aperture, and means for applying a unidirectional magnetic field to said element in a direction parallel to that of the polarization of said waves.
2. The combination in accordance with claim 1 and a conductively bounded microwave structure coupled to said guide through said aperture.
3. The combination in accordance with claim 2 in which said structure is a second wave guide.
4. In combination, a conductively bounded wave guide for transmitting linearly polarized electromagnetic waves from a source to a load, an aperture in a conductive side wall of said guide, an element comprising ferrite closing said aperture, and means for applying a magnetic field to said element in a direction parallel to that of the polarization of said waves.
5. The combination in accordance with claim 4 and a conductively bounded microwave structure coupled to said guide through said aperture.
6. The combination in accordance with claim 5 in which said structure is a second wave guide.
7. The combination in accordance with claim 4 in which the strength of said field falls within the region of ferromagnetic resonance for said element at a frequency within the operating range.
8. In combination, a wave guide for linearly polarized electromagnetic waves, a ferrite element forming part of a conductive side wall thereof, and means for applying a unidirectional magnetic field to said element in a direction parallel to that of the polarization of said waves.
9. The combination in accordance with claim 8 and a second wave guide coupled to said first guide through said element.
10. In combination, a conductively bounded wave guide, means for introducing linearly polarized electromagnetic waves into said guide, an element comprising ferrite forming a window in a conductive side wall of said guide, means for applying a unidirectional magnetic field to said element in a direction parallel to that of the polarization of said waves, and a second wave guide coupled to said first guide through said window.
11. The combination in accordance with claim 10 in which said second guide is coupled at its end to said first-mentioned guide.
12. The combination in accordance with claim 10 in which the strength of said field falls within the region of ferromagnetic resonance for said element at a frequency within the operating range.
13. The combination in accordance with claim 12 and means for varying the strength of said field.

14. The combination in accordance with claim 10 in which said first-mentioned guide is rectangular in cross section with unequal cross-sectional dimensions and said window is in one of the narrower side walls.

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