Nov. 6, 1962 W. A. HUGHES 3,063,029

FERRORESONANT MICROWAVE ATTENUATOR

Filed March 11, 1954

2 Sheets-Sheet 1

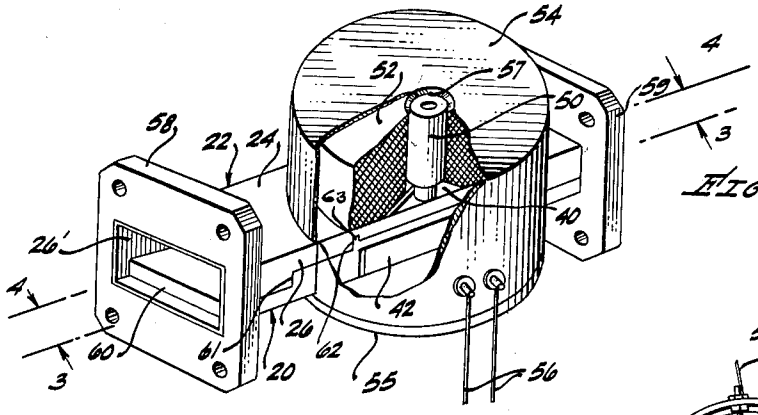


FIG. 1.

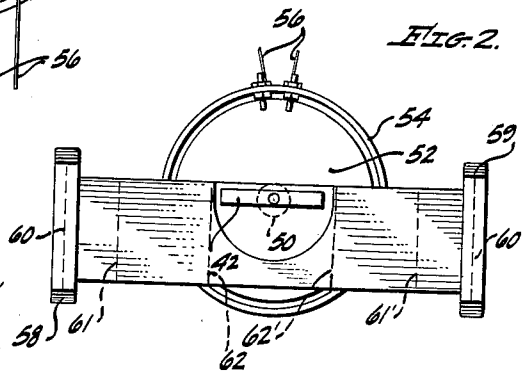
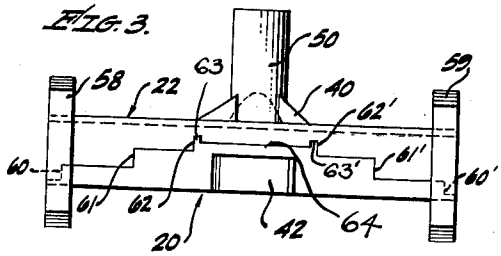


FIG. 2.

FIG. 3.



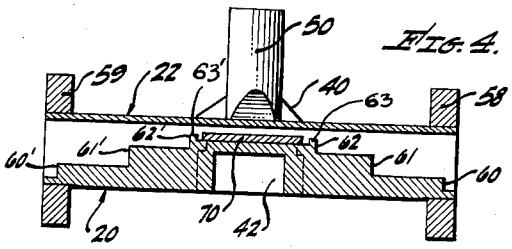


FIG. 4.

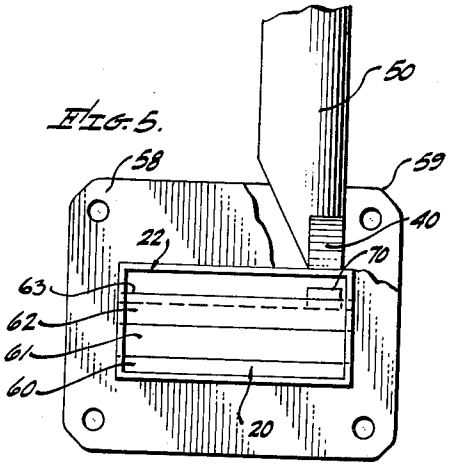


FIG. 5.

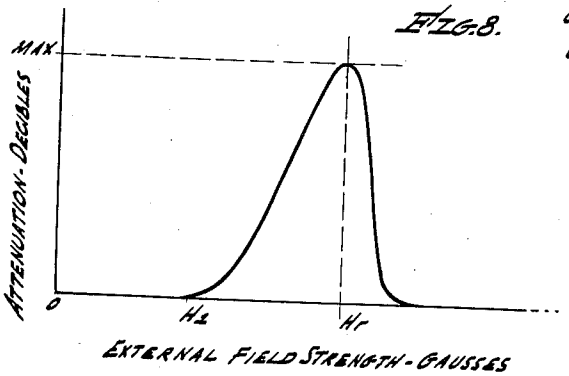


FIG. 8.

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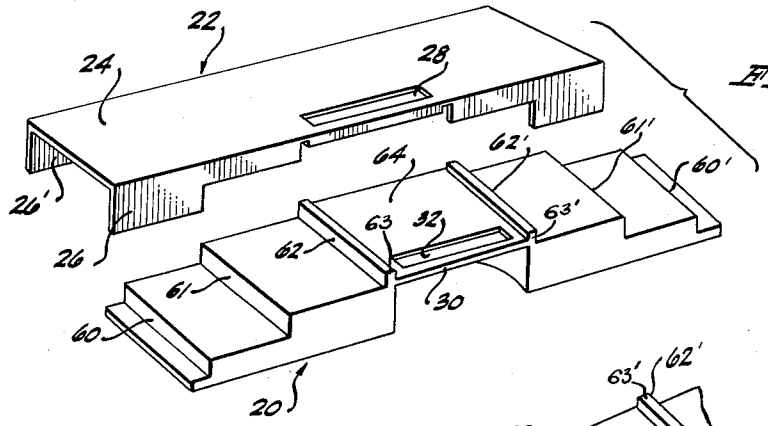


FIG. 6.

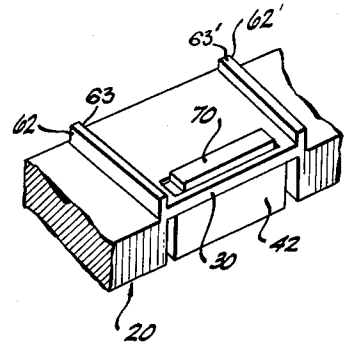


FIG. 7.

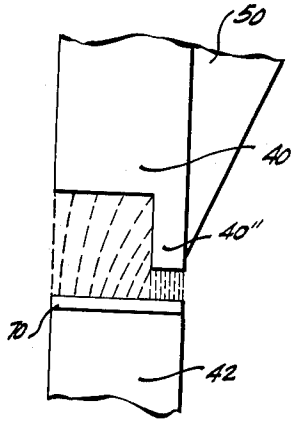


FIG. 10.

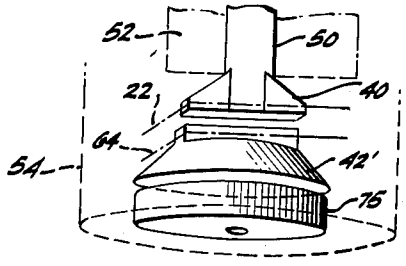


FIG. 9.

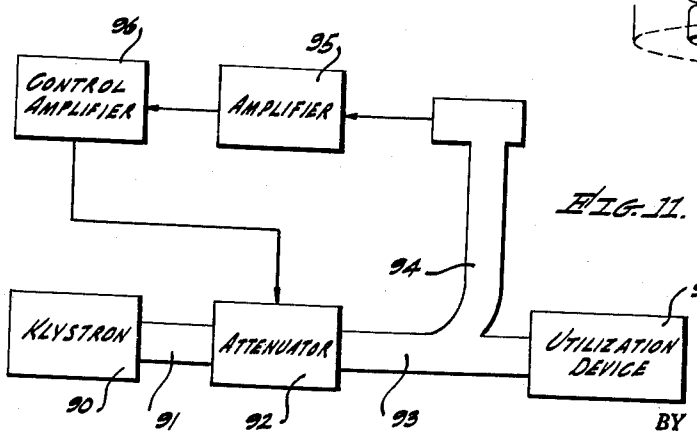


FIG. 11.

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FERRORESONANT MICROWAVE ATTENUATOR

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Filed Mar. 11, 1954, Ser. No. 415,475
12 Claims. (Cl. 333—81)

This invention relates to waveguides for microwave transmission, and more particularly to an improved microwave attenuator of a type in which the amount of attenuation is controlled electromagnetically.

Electromagnetic control of attenuation in a waveguide is achieved by inserting ferromagnetic material in the waveguide and applying an external magnetic field perpendicularly to the axis of the waveguide. The structure and behavior of some waveguide attenuators filled with ferromagnetic material are discussed in an article entitled, "Magnetically Controlled Waveguide Attenuators," by Theodore Miller, Journal of Applied Physics, vol. 20, pp. 878–82 published by American Institute of Physics, Inc., 1949. A number of difficulties are inherent in attenuators of this type and have inhibited their use in practical devices. The difficulties include undesirable reflection of microwave energy in the waveguide, high insertion loss and abnormally large physical structures. In both mechanical and magnetic attenuators of the prior art, effective attenuation is restricted to a relatively narrow frequency band. It is sometimes desirable that microwave attenuators be effective over a broad spectrum of frequencies.

It is therefore an object of this invention to provide an electromagnetically controlled waveguide attenuator in which reflection of transmitted or driving energy is substantially negligible.

It is another object of this invention to provide a waveguide attenuator in which attenuation is electromagnetically controlled, wherein insertion losses are minimized and attenuation is effective over a wider range of frequencies than has been possible with prior art waveguide attenuators.

It is still another object of this invention to provide an attenuator which is remotely controllable.

It is another object of this invention to provide a waveguide attenuator structure of the electromagnetically controlled type, in which the physical dimensions of the structure are a practical minimum.

It is still a further object of this invention to provide a miniaturized waveguide attenuator structure employing a minimum number of component parts of simple design, capable of being easily reproduced and assembled.

In accordance with a preferred embodiment of this invention, a pair of rectangular pole pieces are embedded in opposite walls of a waveguide with their pole faces disposed in opposition with respect to each other. These pole pieces are located on one side of the longitudinal center-line of the waveguide. A rectangular shaped ferromagnetic dielectric element is positioned between the pole pieces. The pole pieces are magnetically coupled to an external core, which supports an exciting coil. When the coil is energized to establish a sufficiently strong field between the pole faces, substantially all microwave power inserted in the waveguide flows through the ferrite. When the ferromagnetic dielectric element is subjected to the external magnetic field, part of the microwave power is converted to heat energy which is dissipated in the walls of the waveguide. The degree of attenuation is directly related to the degree of such conversion. In the device of the present invention, there is substantially no reflection of the microwave energy, insertion losses

are a minimum, and substantially unity ratio of voltage standing waves is realized over a relatively wide range of microwave frequencies.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawings in which several embodiments of the invention are illustrated by way of example. It is to be understood, however, that the drawings are for the purpose of illustration and description only, and are not intended as a definition of the limits of the invention. Referring to the drawings, which are made a part of this specification,

FIG. 1 is a perspective view, including a cut-away portion, of a waveguide attenuator in accordance with this invention;

FIG. 2 is a bottom view of the device shown in FIG. 1;

FIG. 3 is a view taken along the line 3—3 of FIG. 1;

FIG. 4 is a sectional view taken along line 4—4 of FIG. 1;

FIG. 5 is an end elevation view of the device of FIG. 1;

FIG. 6 is an exploded view of certain portions of the device of FIG. 1;

FIG. 7 is a fragmentary perspective view of a portion of the device of FIG. 1;

FIG. 8 is a curve showing attenuation characteristics of the device of FIG. 1, for the purpose of explanation;

FIGS. 9 and 10 illustrate different modifications of a portion of the device of FIG. 1 to obtain distinct results, further in accordance with this invention; and

FIG. 11 is a block diagram of a servo system to illustrate a practical use of the attenuator of this invention.

Referring to the drawings, in which like reference characters indicate like parts throughout, and more particularly to FIGS. 1–7, a rectangular waveguide is formed essentially of two pieces, a bottom member **20** and top member **22**. Bottom member **20** has an inner surface of step formation and preferably is solid metal in which steps are milled. Top member **22** has a broad wall **24** and downwardly depending side portions **26**, **26'** which are cut to match the steps of bottom member **20**. The broad walls or surfaces of the waveguide thus are the broad wall **24** of top member **22** and the surfaces of the steps of bottom member **20**. The side walls of the waveguide are formed by the side portions **26**, **26'** of top member **22**. The members **20**, **22** can be readily assembled and secured together, for example, by silver-soldering. Insertion losses due to eddy currents are substantially negligible by this construction, as will be made more evident hereafter.

A rectangular slot **28** extends through the wall **24** of top member **22** (see FIG. 6), and is located adjacent to one side of the waveguide. A portion of bottom member **20** is removed to provide a thin section **30** directly opposite slot **28**. A rectangular slot **32** to match slot **28** is provided in this thin section **30**. A pole piece **40** is fixed within slot **28**, and its pole face registers flush with the inner surface of the broad wall **24**. Similarly, a pole piece **42** is fitted in slot **32**, and its pole face is flush with the inner surface of the portion **30**.

Pole piece **40** forms the shoe of a magnetizable core **50** and supports a coil **52** which is placed over the core. A permeable cup or shield **54** is positioned over coil **52**, and external leads **56** are connected through shield **54** to the ends of coil **52**. Shield **54** is fixed to core **50**, as by a screw **57**. A permeable plate **55** is affixed to the open end of shield **54** to provide a complete magnetic circuit.

Flanges **58**, **59** fixed to the opposite ends of the wave-

guide provide conventional means for connecting the ends of the waveguide to other waveguide apparatus.

When the waveguide is assembled as shown, the steps previously mentioned constitute a conventional microwave impedance transformer. For the purposes of this invention, such a transformer is of the type which has a broadband impedance match. This is conventionally achieved with an odd number of steps, succesive steps being spaced a quarter of a wavelength apart. In the embodiment shown here, referring to FIG. 6, three steps **60**, **61**, **62** lead up from the bottom of the waveguide at its input end to the center section **64** of member **20**. Center section **64** includes the thin section **30**. The impedance transformation is the ratio of the height of the waveguide at its input end to the height of the waveguide at center section **64**.

Although the transformer above described has a broadband impedance match, there may be an undesirable amount of inductive susceptance in the plane of the highest step **62**. The inductive susceptance tends to cause impedance mismatch at this point and consequent reflection of energy. Steps **62** and **62'** are provided respectively with thin cells **63** and **63'**, each of which project above the surface of center section **64**, and this is known in the art as a "capacitive iris." This iris provides sufficient additional capacitance to cancel the inductive susceptance and provide effective impedance match over the desired band. The transformer above described serves to provide a minimum height of waveguide at center section **64**. Accordingly, a relatively small amount of power is required to establish a desired magnetic field between the pole pieces **40** and **42**. This is a factor of considerable importance, in that the saving in material and space to obtain the necessary external magnetic field strength is quite large compared with the requirements for waveguide attenuator structures of similar type hitherto known. In addition, the reduction in waveguide height is effective to minimize the possibility of the existence of modes in the vertical direction; the importance of this aspect will be made more evident hereafter.

If the output of the attenuator waveguide is to be applied to a waveguide of the same height as the input waveguide, a second transformer similar to that above described includes successive descending step **62'**, **61'** and **60** leading from center section **64** to the bottom of the waveguide at its output end. The impedance transformation is the reverse of that for the transformer previously described.

Fixed between the pole faces of pole pieces **40**, **42** is an elongated rectangular shaped attenuator vane, or element, **70**. Element **70** is a ferronmagnetic dielectric element, the dielectric characteristics of which determine the insertion loss. Such a ferromagnetic dielectric, or ferrite, may be composed of a ferric-oxide combined with a bivalent metal, as XFe_2O_3 and XFe_2O_4, where X represents the bivalent metal. Magnesium and manganese represent a suitable bivalent metal.

The length of element **70** is sufficiently less than the length of center section **64** to permit highly reactive fields (i.e., higher order modes), which may exist in the center section **64** on account of the step transitions to be suppressed by the waveguide itself in the regions between the ends of the element **70** and the adjacent steps **62**, **62'**. The thickness of element **70** is less than the internal height of the waveguide at center section **64** to minimize any impedance changes which occur in teh region of the ferrite.

The arangement of pole pieces **40**, **42**, and the element **70** locates the element **70** out of the region of high electric field intensity and in the region of the circularly polarized alternating magnetic fields which form a part of the microwave power passing through the waveguide.

Referring to FIGS. 4 and 5, the portion of core **50** adjacent pole piece **40** tapers from its outer diameter to the bottom of pole piece **40**. In this manner, substantially all the magnetic flux is focused in pole piece **40** and directed through the element **70**.

The operation of the structure above described will now be explained for the waveguide excited in the TE_{10} mode, In the absence of an externally applied magnetic field, the electric and magnetic fields are set up as usual, with the transverse electric field across the height of the waveguide and the alternating magnetic fields extending across the width and along the length of the waveguide. In the absence of a static magnetic field, element **70**, because of its location and size as previously explained has substantially negligible effect on the power propagated.

The electrons in the element **70** have an average magnetic moment which is random in the absence of the external field. When coil **52** is energized to establish the transverse external field, the average magnetic moment tends to line up with the external field established. In addition, the alternating magnetic fields in the ferrite cause this average magnetic moment to precess. The precessing of the average magnetic moment is attended by the production in the ferrite of magnetic fields which tend to reinforce the alternating magnetic fields. This results in a shift of the microwave power over to the region of the ferrite. The precession and shift of microwave power depend upon the strength of the external field. Further, the microwave power is absorbed in attendant precessional damping losses, manifested as heat dissipated through the walls of the waveguide.

The degree of attenuation of the microwave power depends upon the extent to which it is absorbed, and maximum absorption occurs at the value of external field strength at which precessional, or gyromagnetic, resonance exists. Precessional resonance occurs when the frequency of precession of the average magnetic moment is the same as the frequency of the alternating magnetic fields, i.e., the same as the so-called driving frequency.

FIG. 8 illustrates the variation of attenuation with external field strength. A value H_1 of the external field strength is reached before precession of the average magnetic moment is sufficient to realize any appreciable absorption and attenuation. Attenuation then increases with the field strength until, at a field strength H_r, the attenuation is maximum; this is the point of precessional resonance. For greater field strengths, the attenuation falls off sharply, as indicated. Accordingly, depending upon the attenuation desired, the external field strength should not exceed H_r.

In one practical embodiment of a waveguide attenuator of the type above described, the waveguide was 0.4" high at its ends. A transformer of the type described was used in which the successive steps changed the height of the waveguide in the relation 1:2:1 to make the height of the waveguide 0.1" at center section **64**. Further, impedance match covered 20% of the X-band. Other specifications were: The impedance transformation was thus 4:1.

Body members **20**, **22** and flanges **58**, **59**: brass.
Core **50**: soft iron, 0.375 in. diameter.
Pole pieces **40**, **42**: soft iron, 0.800 in. by 0.150 in.
Coil **52**: 27,000 turns, number 38 copper wire.
Shield **54**: soft iron, 2-in. diameter, 1.60 in. high.
Element **70**: Ferrite composed of 51% iron, 11% magnesium, 4.80% manganese, 33.20% oxygen, 0.825 in. x 0.25 in. x 0.050 in.

In this arrangement, a field of 4,000 gauss was sufficient for maximum attenuation at a given frequency in the X-band. Three watts of control power were required to energize coil **52** to obtain the 4,000 gauss field strength. In the absence of the external field, insertion loss is of the order of 0.05 db. Maximum attenuation is over 40 db, or more than double that obtained by attenuators heretofore known. In addition, the VSWR (voltage standing wave ratio) was maintained at approximately 1.12 for driving frequency changes of $\pm 12\%$, or 24%, of the

X-band. It has not been possible heretofore to maintain a VSWR less than 2.0 over more than 8% of the X-band.

FIG. 9 illustrates a modification of the magnetic circuit previously described. Referring to FIG. 9, the bottom pole piece 42' has a circular base from which there is a transition to a rectangular parallelepiped. The rectangular portion is positioned in the waveguide opposite pole piece 40, in the maner previously described for pole piece 42. Positioned under the base of pole piece 42' is a short, cylindrical permanent magnet 75 to be affixed to the shield 54. The magnet 75 provides a fixed flux density between pole pieces 40, 42'. The preferred value of this fixed field is that which the coil 52 alone would have to provide before attenuation would be effective, i.e., H_1 in FIG. 8. The size of coil 52 and the power required to establish the desired flux density is thus less than would be required without the permanent magnet 75.

As pointed out previously, the waveguide attenuator arrangement of FIG. 1 provides maximum attenuation when the external field strength is sufficient to cause precession of the average magnetic moment at the driving frequency. Thus, if the driving frequency varies with the external field strength remaining the same, the attenuation at the different frequency will not be exactly the same because precessional resonance is not as pronounced. An arrangement for insuring precessional resonance over a range of frequencies for one value of the external field strength is obtained by shaping at least one of the pole pieces to effect a variation of flux density across the width of the ferrite element 70, as illustrated in FIG. 10.

Referring to FIG. 10, a modified upper pole piece 40' has an irregularly configured pole face. The thickness of the portion of the pole face registering with the inner surface of wall 24 is less than the width of the pole piece 40'. This is a depending portion 40'', illustrated as an extension of the side of the pole piece 40' nearest the axis of the waveguide. The greatest concentration of the external field is between portion 40'' and bottom pole piece 42. The field varies between pole piece 42 and the more widely spaced parts of the pole face. Lines drawn from pole piece 40' indicate generally the flux paths set up. This construction makes use of the shifting with driving frequency of the longitudinal plane containing the circularly polarized alternating magnetic fields. Although the element 70 is located in the region of these fields, the plane of circular polarization obviously will move across the width of the element, from its inner edge to its outer edge, as the frequency decreases. The configuration of pole piece 50 insures a variation in flux density across the width of element 70, so that the plane of circular polarization at any point across element 70 is located in the flux path which is of the proper strength to maintain precessional resonance. In this manner, precessional resonance is maintained in spite of variations in the driving frequency, and hence maximum attenuation is maintained.

It is to be understood that it is not required to use external field strengths which will give precessional resonance. The attenuator of this invention can be set to provide less than maximum attenuation, as desired.

FIG. 11 illustrates a servo system employing the attenuator of this invention. Included in the system is a klystron oscillator 90 having a waveguide 91 connected to its output, the attenuator 92 of this invention connected between waveguide 91 and an output waveguide 93, a directional coupler and detector 94 connected to waveguide 93, an amplifier 95 and control amplifier 96 coupled between coupler 94 and attenuator 92. Control amplifier 96 supplies current to the attenuator control coil to control the external magnetic field. Voltages in waveguide 93 are applied through coupler and detector 94, amplified, and fed through control amplifier 96 to the attenuator control coil. For voltages tending to exceed a predetermined value, the external magnetic field automatically increases to maintain the output from waveguide 93 constant. Similarly, output voltages tending to fall below the desired value, give rise to a decrease in the external magnetic field strength to decrease the attenuation by a sufficient amount to maintain a constant output. Thus an output utilization device 98, which requires a constant input voltage, can be connected to waveguide 93.

What is claimed is:

1. In a microwave component wherein at least one ferrite vane is mounted entirely in a rectangular waveguide and is subjected to an externally applied static transverse magnetic field, a pair of conductive ferromagnetic pole pieces built into opposite broad sides of the waveguide for mounting the ferrite vane to channel the magnetic field through the ferrite vane while maintaining substantially unimpaired the conductivity of said broad sides of the waveguide.

2. In a microwave component which utilizes the ferroresonant properties of a ferrite vane mounted entirely within a waveguide and positioned in a static magnetic field for altering a microwave signal, the combination comprising: a section of waveguide; at least one conductive ferromagnetic pole piece built into a side wall of said waveguide, an end of said pole piece lying essentially flush with the inner surface of said waveguide wall; a ferrite vane mounted within said waveguide on said pole piece; and a static magnetic field source having first and second poles and positioned around at least a portion of said waveguide for producing a static magnetic field in the interior of said waveguide, said first pole of said source engaging said pole piece whereby said field is channeled through said ferrite vane.

3. The combination defined in claim 2 wherein said waveguide is rectangular in cross section and which further includes a second pole piece built into the wall of said waveguide opposite said one pole piece and surfacing both within and without said waveguide, said second pole of said source engaging said second pole piece.

4. The combination defined in claim 3 wherein said static magnetic field [sic.] source includes a permanent magnet.

5. The combination defined in claim 2 wherein said static magnetic field source comprises an electromagnet, whereby said microwave signals are altered upon energization of said electromagnet.

6. An absorption type microwave component comprising: a rectangular waveguide; first and second ferromagnetic pole pieces built into opposite walls of said waveguide, said pole pieces being parallel to each other and to the longitudinal axis of said wave guide and surfacing both within and without said waveguide, said pole pieces substantially preserving the electrical conductivity of the walls of which they [sic.] form a part; at least one ferrite vane mounted within said waveguide on at least one of said pole pieces, the electrical conductivity of said vane being relatively low compared to that of said pole pieces; and a magnetic field source positioned around at least a portion of said waveguide and having first and second poles, said first and second poles engaging said first and second pole pieces, respectively, for producing a magnetic field through said ferrite vane.

7. In a microwave component which utilizes the ferroresonant properties of a ferrite vane mounted entirely within a waveguide and positioned in a static magnetic field for altering a microwave signal, the combination comprising: a section of rectangular waveguide; at least one conductive ferromagnetic pole piece built into the wall of said waveguide and in electrical contact therewith; said pole piece surfacing both within and without said waveguide; a ferrite vane mounted within said waveguide on said pole piece; and a magnet positioned adjacent the exterior of said waveguide and having first and second poles, said first pole of said magnet engaging said pole

piece whereby said ferrite vane is included in a low reluctance path with said magnet.

8. An absorption type microwave component comprising: a rectangular waveguide; first and second ferromagnetic pole pieces built into opposite walls of said waveguide and being composed of material whose conductivity is of the same order of magnitude as that of said waveguide, said pole pieces being parallel to each other and to the longitudinal axis of said waveguide and surfacing both within and without said waveguide; at least one ferrite vane mounted within said waveguide on at least one of said pole pieces; and a static magnetic field source positioned adjacent said waveguide and having first and second poles engaging said first and second pole pieces, respectively, for producing a magentic field through said ferrite vane.

9. A waveguide attenuator comprising a length of rectangular waveguide having an input end of predetermined height, a broad band impedance transformer in said waveguide extended from said input end increasing in height in discrete steps to provide a waveguide section having a minimum height proportional to said predetermined height, at least one pole piece of ferromagnetic material extending into a wall of said waveguide section, the end of said pole piece lying essentially flush with the inner surface of said wall, a thin elongated attenuation strip of ferrite disposed in said section and contacting said pole piece with the longitudinal axis parallel to the sides of said section and a broad surface parallel to a broad wall of said section at least substantially between the center line and one side of such broad wall, said strip having a thickness substantially less than said minimum height and a width less than half the width of said waveguide, and means for establishing a static magnetic field through said pole piece and said ferrite transverse to said broad surface and along the length thereof of a value producing gyromagnetic resonance at the frequency of microwave energy propagated through said waveguide whereby resonance absorption of energy by said ferrite occurs.

10. A microwave attenuator comprising a length of rectangular waveguide having an input end of predetermined height between broad walls for propagating microwave energy in a plane polarized magnetic field mode parallel to the broad walls, impedance transformer structure included in said waveguide and extended the width of said waveguide for a predetermined length from said input end for providing a waveguide section having a height between broad walls proportionately less than said predetermined height whereby an impedance proportional to the relative heights at the respective ends of said structure is provided with an impedance match minimizing reflections, at least one pole piece of ferromagnetic material extending into a wall of said waveguide section, the end of said pole piece lying essentially flush with the inner surface of said wall, an elongated segment of ferrite material mounted in said section entirely on said pole piece with its longitudinal axis parallel to the narrow walls of said section between the longitudinal center line and one narrow wall to include a plane of circular polarization of said magnetic field mode, means for establishing a static magnetic field through said pole piece and said segment parallel to the narrow walls of said section of a value to produce gyromagnetic resonance at said plane of circular polarization at the frequency of energy propagated through said waveguide whereby energy is absorbed by resonance absorption in said ferrite and resultant heat dissipated through adjacent walls of said waveguide.

11. In a length of rectangular waveguide for propagating microwave energy in the TE_{10} mode having a magnetic field parallel to the broad walls and including impedance matching transformer structure proportionately decreasing the height of the narrow walls to provide a ssection of reduced height with minimum reflection, at least one pole piece of ferromagnetic material extending into a broad wall of said section, the end of said pole piece lying essentially flush with inner surface of said broad wall, an attenuator structure comprising an elongated ferrite element mounted against said pole piece and in said section between the longitudinal center line and one side of said section to include a plane of circular polarization of said magnetic field, said element having a thickness less than half said reduced height and a width less than half the dimension of the broad walls of said section, and means for establishing a static magnetic field through said pole piece and said element parallel to the narrow walls of a value producing gyromagnetic resonance at the frequency of said energy along said plane of circular polarization whereby energy is absorbed in said ferrite by resonance absorption and resultant heat is dissipated by adjacent walls of said waveguide.

12. A waveguide attenuator comprising a length of rectangular waveguide having impedance transformer means at input and output ends and a central section of reduced internal height, at least one pole piece of ferromagnetic material extending into a broad wall of said section, the end of said pole piece lying essentially flush with the inner surface of said broad wall, a thin elongated ferrite strip mounted within said center section in contact with said pole piece and with its broad surface parallel to said broad wall of said center section and disposed at least substantially at one side of the longitudinal center line of said broad wall, said ferrite strip having a thickness substantially less than said reduced internal height whereby insertion losses are minimized, and means for establishing a static magnetic field through said pole piece and said ferrite strip transverse to said broad surface of a value to produce gyromagnetic resonance at the frequency of microwave energy propagated through said waveguide whereby said energy is attenuated by resonance absorption in said ferrite.

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