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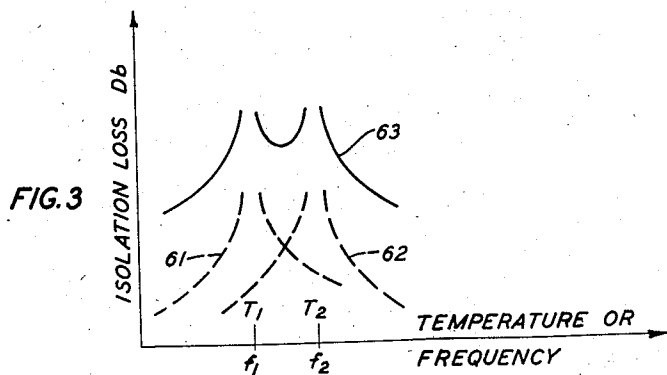
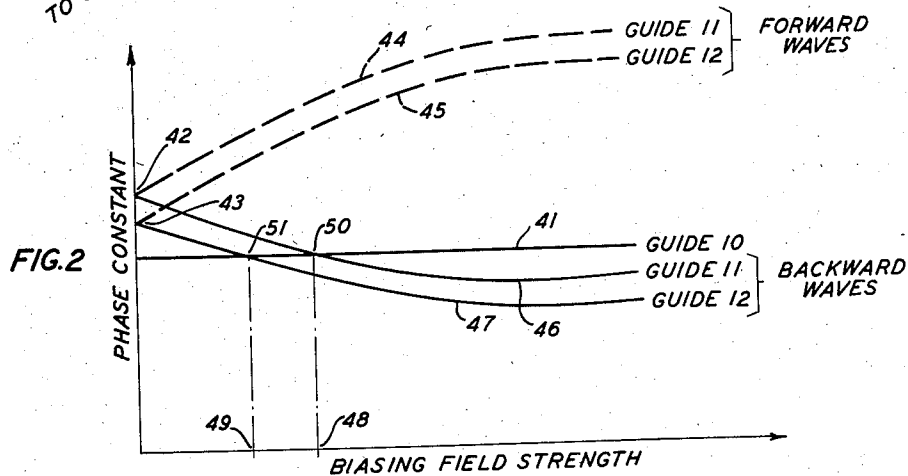
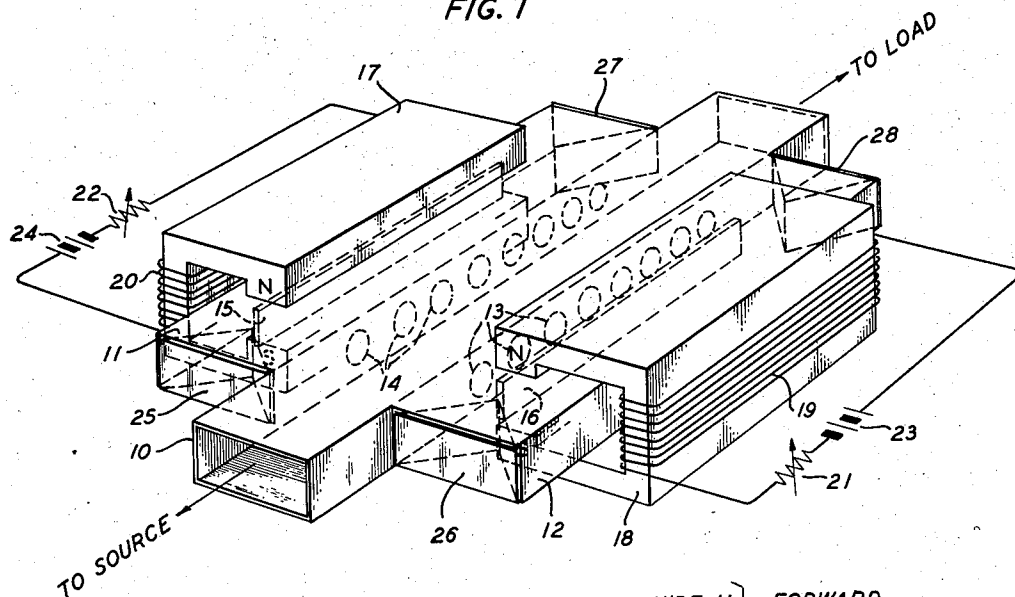
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2,884,604

NONRECIPROCAL WAVE TRANSMISSION

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FIG. 1



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NONRECIPROCAL WAVE TRANSMISSION

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This invention relates to nonreciprocal microwave electromagnetic wave transmission devices and, more particularly, to improved one-way transmission devices employing the properties of gyromagnetic materials to directionally isolate one electromagnetic device from another.

The desirability of directional isolation in electromagnetic wave systems has been apparent for some time. For example, a very simple but particularly useful application of an isolator is found in a system in which wave generation equipment, for example, a frequency modulated oscillator, is to be worked directly into a transmitting antenna. As is well known, serious matching problems are encountered in such a system since any reflection or other return of energy from the antenna has an undesirable effect upon the oscillator. An isolator, therefore, having low loss or attenuation for waves passing from the oscillator to the antenna and high return loss or attenuation for waves passing from the antenna to the oscillator, will greatly simplify the problem. Recently the nonreciprocal properties of polarized elements of gyromagnetic material, often designated ferrites, have been utilized to provide such an isolator. However, the properties of the gyromagnetic material have been found to vary as functions of ambient temperature and operating frequency. Consequently, an isolator employing a gyromagnetic element adjusted for proper operation at one temperature will not operate satisfactorily when the temperature changes. Similar difficulties with frequency variations severely limit the operating bandwidth of the isolators.

It is, therefore, an object of the invention to provide a high degree of attenuation over a broad range of temperature and frequency conditions to wave energy propagating in one direction along a transmission path and to provide substantially free transmission to wave energy propagating in the other direction regardless of the temperature and frequency condition.

It is a further object of the invention to increase the frequency bandwidth and temperature stability of directionally selective attenuators of the gyromagnetic type.

In accordance with the present invention, terminated wave guides are coupled to either side of a center guide interposed in the path requiring isolation. The phase constants of the terminated guides are modified by incorporating within them particularly arranged and polarized members of gyromagnetic material so that each terminated guide has a phase constant that equals the phase constant of the center guide at respectively different predetermined conditions of temperature and frequency for one common direction of propagation therealong and a different phase constant for the opposite direction. Thus wave energy traveling in the common direction along the center guide under either of the predetermined conditions of temperature and frequency will be transmitted into one or the other of the terminated guides for dissipation therein. For conditions of temperature and frequency between the predetermined values, wave energy

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will be transmitted jointly into the two terminated guides, maintaining therefore a high degree of isolation over the broad range between the predetermined conditions. For wave energy propagating in the opposite direction, no energy will be transmitted into the terminated guides maintaining therefore a low forward loss regardless of the conditions of temperature and frequency.

These and other objects, the nature of the present invention, and its various features and advantages, will appear more fully upon consideration of the specific illustrative embodiment shown in the accompanying drawings and described in detail in the following explanation of these drawings.

In the drawings:

Fig. 1 is a perspective view of a principal embodiment of the invention showing three coupled wave guides and the necessary nonreciprocal elements of polarized gyromagnetic material;

Fig. 2, given by way of explanation, shows the relative phase constants of the guides of Fig. 1 versus the biasing magnetic field strength; and

Fig. 3 represents the isolation loss of the isolator of Fig. 1 versus either temperature or frequency.

Referring more specifically to Fig. 1, a non-reciprocal attenuator or isolator is shown as an illustrative embodiment of the present invention. The isolator comprises a center section 10 of electrical transmission line for guiding wave energy which is interposed in the path requiring directional attenuation such as between a source and a load. Guide 10 may be a rectangular wave guide of the metallic shield type having a wide internal cross-sectional dimension of at least one half wavelength of the energy to be conducted thereby and a narrow dimension substantially one half the wide dimension. Located on either side of guide 10 and running for a portion of its length contiguous and parallel thereto are second and third side guide sections 11 and 12 which each have cross-sectional dimensions similar to those of guide 10. One narrow wall of guide 10 is located adjacent to a narrow wall of guide 11, while the other narrow wall of guide 10 is located adjacent to a narrow wall of guide 12. The guides 11 and 12 are coupled electromagnetically to guide 10 over coextensive longitudinal intervals of several wavelengths by one of the several broad band coupling means familiar to the art. This coupling may be, as illustrated, a plurality of apertures 13 extending through the common narrow wall between guides 10 and 12 and a plurality of apertures 14 extending through the common narrow wall between guides 10 and 11. Apertures 13 or apertures 14 are distributed at intervals of less than one half wavelength apart along the length of the coupling interval. Both of guides 11 and 12 are terminated at each end in a reflectionless manner by the characteristic impedance of the guides by means familiar to the art. This means is illustrated, by way of example, by tapered or wedge-shaped terminations 25 and 26 terminating the near ends of guides 11 and 12, respectively, and terminations 27 and 28 terminating the far ends of guides 11 and 12, respectively. Terminations 25 through 28 may be made of electrically high loss material such as polyfoam impregnated with carbon black.

For reference purposes hereinafter, a "forward" direction of propagation is defined as the progression of wave energy away from the viewer from the source toward the load and terminations 27 and 28, while the "backward" direction of propagation is defined as the progression toward the viewer from the load toward the source and terminations 25 and 26. In order to avoid confusion it should be noted that the terms "forward" and "backward" are absolute terms referring to the embodiment as illustrated in the drawing and are not the relative terms sometimes employed in the directional coupler art.

The phase constants of guides 11 and 12 are modified as follows. Located in each of guides 11 and 12 and asymmetrically displaced therein approximately one quarter of the width of the guide to the left-hand side of the center line thereof is a thin vane or septum of gyromagnetic material shown as 15 in guide 11 and 16 in guide 12. This material is, for example, of the type having electrical and magnetic properties of the type described by the mathematical analysis of D. Polder in *Philosophique Magazine*, January 1949, vol. 40, pages 99 through 115. Members 15 and 16 extend across the height of guides 11 and 12, parallel to the narrow walls thereof, and each extends longitudinally in its respective guide along substantially the interval of coupling.

As a specific example of a gyromagnetic medium, members 15 and 16 may be made of any of the several ferromagnetic materials combined in a spinel structure. For example, they may comprise iron oxide with a small quantity of one or more bivalent metals, such as nickel, magnesium, zinc, manganese or other similar material in which the other metals combine with the iron oxide in a spinel structure. This material is known as a ferromagnetic spinel or a ferrite. Frequently, these materials are first powdered and then molded with a small percentage of plastic material, such as Teflon or polystyrene. As a specific example, members 15 and 16 may be made of nickel-zinc ferrite prepared in the manner described in the publication of C. L. Hogan, "The Microwave Gyration" in the *Bell System Technical Journal*, January 1952, and in his copending application Serial No. 252,432, filed October 22, 1951, now United States Patent 2,748,353, issued May 29, 1956.

Members 15 and 16 are biased in the same direction by steady magnetic fields, of the strengths to be described, at right angles to the direction of propagation of the wave energy in guides 11 and 12. As illustrated in Fig. 1, this field is separately supplied to each member by solenoid structures comprising magnetic cores 17 and 18 having pole-pieces bearing on opposite longitudinal edge areas of the wide walls of guides 11 and 12 in the regions of members 15 and 16, respectively. Turns of wire, for example, turns 19 on core 18 and 20 on core 17, are so wound and connected through rheostats 21 and 22 to sources of potential 23 and 24, respectively, that solenoids 17 and 18 produce N magnetic poles on the top sides of guides 11 and 12 and S poles on the lower sides of guides 11 and 12, as illustrated in Fig. 1. These fields may, however, be supplied by an electrical solenoid with a metallic core of other suitable physical design, by a solenoid without a core, by a permanent magnet structure, or the ferromagnetic elements may be permanently magnetized if desired.

It has been determined that a polarized septum of gyromagnetic material located as either member 15 in guide 11 or member 16 in guide 12 will produce a non-reciprocal phase constant for wave energy with respect to opposite directions of propagation along the guide. This phenomenon and related aspects of it are disclosed in the copending applications of W. H. Hewitt, Jr., Serial No. 362,191 filed June 17, 1953; H. Suhl-L. R. Walker, Serial No. 362,176 filed June 17, 1953; S. E. Miller, Serial No. 362,193 filed June 17, 1953; and S. E. Miller, Serial No. 371,594 filed July 31, 1953, now United States Patent 2,849,684, issued August 26, 1958.

This effect will be but briefly re-examined here. It should be recalled that the high frequency magnetic field pattern of a dominant mode wave in a rectangular wave guide forms loops which lie in planes parallel to the wide dimensions of the guide. At points displaced on either side of the center line of the guide this field has a substantial circularly polarized component as the wave propagates along the guide. For a wave propagating away from the viewer in the defined forward direction, a counterclockwise rotating component of the magnetic intensity is presented at a point on the left-hand side of the cen-

ter line and a clockwise rotating component at a point on the right-hand side of the center line. When the direction of propagation is reversed, the circularly polarized components as seen at these points rotate in respectively opposite directions.

Now, if a strip of ferromagnetic material is placed in the guide to extend through one of these regions of circular polarization and magnetized by a transverse biasing field, a wave which has its radio frequency magnetic field at right angles to the biasing field and which rotates counterclockwise as viewed in the direction N to the S pole of the biasing field will encounter a permeability which increases and becomes greater than unity as the intensity of the biasing field is increased. Conversely, a similar wave which has a clockwise rotating magnetic field will encounter a permeability which decreases and becomes less than unity as the intensity of the biasing field is increased. This result is observed for low values of polarizing magnetic field below that field intensity which produces ferromagnetic resonance in the material. Such an element will either decrease or increase the phase constant of the guide in which it is located in proportion to the product of the mass of the element and the strength of the magnetic field by which it is biased.

When these principles are applied to the particular embodiment of the present invention as illustrated in Fig. 1, it will be observed that guides 11 and 12 in the region of coupling each have phase constants which are different for opposite directions of propagation therein. In accordance with the present invention, the parameters of the three guides 10, 11 and 12 and the intensity of the biasing magnetic field are adjusted for one common direction of propagation therealong, so that the separate phase constants of the side guides 11 and 12 are each equal to the phase constant of the center guide 10 for uniquely different conditions of operating frequency and/or ambient temperature. This adjustment will be examined more critically hereinafter with reference to Fig. 2. First, however, it may be briefly stated that for the temperature and/or frequency condition and for the direction of propagation in which the phase constant of guide 10 is equal to the phase constant of guide 12, components of the incident wave applied to guide 10 will be transferred in phase through each of the plurality of apertures 13 into guide 12. Such action relies upon the well-known principles of directional couplers as described in detail in my copending application, Serial No. 325,488 filed December 11, 1952, now United States Patent 2,832,356, issued February 2, 1958, and in my publication "Coupled Wave Theory and Waveguide Applications" in the *Bell System Technical Journal*, May 1954, pages 661 through 719. The coupling parameters are proportioned to result in complete power transfer of all such components from guide 10 into guide 12. In guide 12 the components are completely dissipated in one of the resistive terminations 26 or 28. This results in substantially infinite attenuation for the wave energy applied to guide 10 under the adjusted conditions. Similarly, for the temperature and/or frequency condition for which the phase constant of guide 10 is equal to the phase constant of guide 11 wave energy will be transferred through apertures 14 and dissipated by a termination of guide 11. The combined effect results in substantially infinite attenuation to the wave energy propagating in one direction in guide 10 at two independently controllable temperature and/or frequency conditions. As will be shown hereinafter, the combined effect gives a relatively high attenuation for all frequency and temperature conditions within a broad range. For the opposite direction of propagation at every temperature and frequency, the two side guides 11 and 12 will have phase constants different from guide 10 and the several components transferred through apertures 13 or 14 will experience destructive interference so that substantially no energy will be transferred from guide 10.

This results in a low loss transmission for this direction of propagation.

Referring now to Fig. 2, the relative phase constants of guides 10, 11 and 12 for the forward and backward transmitted waves, respectively, are plotted versus the biasing magnetic field strength for a given condition of temperature and frequency. The reciprocal phase constant of guide 10, which is independent of the biasing field, is represented by a horizontal characteristic 41. For a zero biasing magnetic field, guides 11 and 12 are provided with phase constants which are preferably different from each other and slightly larger than the phase constants of guide 10. The initial phase constants for guides 11 and 12 are represented by points 42 and 43, respectively. Their difference may be obtained in a variety of ways, for example, by using identical wave guides and identical ferromagnetic members, and locating member 15 in guide 11 slightly nearer to the common wall between guides 10 and 11 than member 16 in guide 12. This initial difference in phase constant can also be obtained by employing wave guides of slightly different cross-sectional dimensions and/or by using elements of ferrite of slightly different dimensions. It will be noted that the phase constants for forward waves in guides 11 and 12, represented by curves 44 and 45, respectively, increase as the biasing field is increased. The phase constants for backward waves in guides 11 and 12, represented by curves 46 and 47, respectively, decrease as the biasing field is increased and cross the characteristic 41 at operating points 50 and 51 at different biasing field strengths represented by the points 48 and 49, respectively, on the abscissa of Fig. 2.

As noted above, the conditions represented by Fig. 2 apply only for a given temperature and frequency condition. If the operating temperature is changed, the effect of the gyromagnetic material upon the permeability exhibited to wave energy is the same as if the strength of the biasing field had shifted. This destroys any attempted adjustment to operate the device at the cross-over points 50 and 51. In a more complicated manner, a shift in the operating frequency has as its principal effect a raising or lowering of the ordinate values of curves 44 through 47 and a change in the slopes of all curves. This change again destroys adjustment of the operating points.

In accordance with the present invention the operating point 51 for guide 12 is set, taking into account the cross-sectional dimensions of the guides and the dimensions and location of member 16 therein, by choosing a biasing field strength for member 16 by adjustment of rheostat 21 so that the backward phase constant of guide 12 is equal to the phase constant of guide 10 for a temperature T_1 and/or frequency f_1 . Similarly the operating point 50 for guide 11 is selected, taking into account the parameters of guide cross-sectional dimensions, and the dimensions and location of member 15 in guide 11, any one of which parameters may or may not be the same as the corresponding parameters of guide 10, by choosing a biasing field strength for member 15 by adjustment of rheostat 22 so that the backward phase constant of guide 11 is equal to the phase constant of guide 10 for a second and different temperature T_2 and/or a different frequency f_2 .

In other words, it is a necessary condition for operation of the invention that the phase constants of guides 11 and 12 be equal to that of guide 10 at different frequencies or temperatures under the operating biasing field strength applied thereto. This requires that the relationship between the dimensions of guide 11, the size and/or composition of member 15 therein, its position in the cross section of guide 11 and the strength of the biasing field applied thereto be different from the relationship between the dimensions of guide 12, the size or composition of member 16 therein, its position in the cross section of guide 12 and the strength of the biasing field applied thereto, but this difference may be obtained by having

any one or a combination of the several noted parameters different. Furthermore, in a special case when both the dimensions of guides 11 and 12 and the dimensions of members 15 and 16 are different by specific values from each other, the initial phase constants of guides 11 and 12 may be the same and still have different biased phase constants.

Thus if undesired reflections from the load are received at the far terminal of guide 10 when the ambient temperature is T_1 , successive portions of this energy will be transferred into guide 12 until all this energy has been abstracted from guide 10 and dissipated in termination 26. Any reflection from termination 26 will be absorbed in termination 28. This results in an attenuation or isolation as represented by curve 61 of Fig. 3 which shows the plot of backward isolation loss versus ambient temperature with a point of infinite attenuation centered about the temperature T_1 . As the ambient temperature shifts in the direction of the temperature T_2 successive portions of the energy from guide 10 will now be transferred into guide 11 to be dissipated in terminations 25 and 27. At the temperature T_2 infinite isolation will be provided by the operation of guide 11 as represented by curve 62 on Fig. 3. At temperature values intermediate T_1 and T_2 the isolation is the resultant of curves 61 and 62 such as curve 63, which shows a loss substantially less than infinite but well within acceptable limits for practical applications of the isolator. Obviously, much higher discrimination may be obtained when the temperature range between T_1 and T_2 is small than may be obtained over a wider range in which the temperature spacing T_1 and T_2 is large. In order to simplify the description, the operation has been explained with reference to variations of temperature alone. However, since as noted above, the effect of frequency is much the same as that of temperature, the same broad band characteristics of the isolator are found for variations in frequency or for simultaneous variations in frequency and temperature. Therefore the second abscissa scale of Fig. 3 may be plotted as a function of frequency. For the forward direction of propagation from the source to the load, the loss always remains at its minimum value regardless of the temperature or frequency condition since neither the above described change with temperature nor the change with frequency can cause the phase constants of the forward waves in guides 11 and 12 to approach the phase constant of guide 10.

While the invention has been disclosed in connection with conductively bounded rectangular wave guides, it should be noted that the principles thereof apply and may be used with electromagnetic wave guides of other forms and of other cross-sectional shapes. In this connection, the gyromagnetic element as it is used to obtain a nonreciprocal phase constant will assume the several forms and locations relative to the guides as disclosed in the above noted copending applications and particularly my Patent 2,849,684, issued August 26, 1958. Furthermore, while the particular embodiment as illustrated in Fig. 1 has the outstanding advantage of compactness and short length, it should be noted that the guide sections 11 and 12 may be located along non-coextensive portions of guide 10, either on opposite sides or on the same side thereof.

In all cases it is understood that the above-described arrangements are illustrative of a small number of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can readily be devised in accordance with these principles by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, first and second and third conductively bounded guides for electromagnetic wave energy, coupling means of the phase velocity matching type for

coupling said second and third guides to said first guide along coextensive longitudinal intervals of their lengths, an element of magnetically polarized material exhibiting a gyromagnetic effect at the frequency of said electromagnetic wave energy extending longitudinally in each of said second and third guides along said coupling interval and positioned to affect the phase velocity of waves in said second and third guides respectively in the same sense, and electrical dissipation means coupled to each of said second and third guides for dissipating substantially all of the energy coupled into said second and third guides from said first guide.

2. In combination, first and second and third conductively bounded guides for electromagnetic wave energy, means of the phase velocity matching type for coupling said second and third guides to said first guide along a longitudinal interval of their lengths, a septum of magnetically polarizable material exhibiting a gyromagnetic effect at the frequency of said wave energy located asymmetrically in the cross section of each of said second and third guides and extending longitudinally therein along substantially said interval of coupling and positioned to affect the phase velocity of waves in said second and third guides respectively in the same sense, means for biasing each septum with a magnetizing field, the relationship between the dimensions of said second guide and the dimensions and location and biasing field strength applied to the septum therein being different from the relationship between the corresponding parameters of said third guide and means for dissipating substantially all of the energy coupled into said second and third guides.

3. A nonreciprocal electromagnetic wave component comprising a first transmission path for said wave energy, second and third transmission paths each coupled to said first path by coupling means of the phase velocity matching type along intervals of their lengths, magnetically polarizable material exhibiting a gyromagnetic effect at the frequency of said wave energy extending in the field of wave energy propagated along said second and third paths and positioned to affect the phase velocity of energy in said second and third guides respectively in the same sense, means for applying a biasing magnetic field to said material, said three paths having phase constants that are different when the intensity of said field is zero, means for increasing the intensity of said field to a strength for which said second and third paths have phase constants that are equal to the phase constant of said first path for one common direction of propagation therealong but for different conditions of operating frequency and ambient temperature and means for dissipating substantially all of the energy coupled into said second and third paths.

4. A nonreciprocal electromagnetic wave component comprising first and second and third conductively bounded guides for electromagnetic wave energy, means of the phase velocity matching type for coupling said second and third guides to said first guide along a longitudinal interval of their lengths, a septum of magnetically polarizable material exhibiting a gyromagnetic effect at the frequency of said wave energy located asymmetrically in the cross section of each of said second and third guides to affect the phase velocity of energy in said second and third guides respectively in the same sense and biased by a magnetizing field to modify the phase constants of each of said guides at a given condition of ambient temperature and operating frequency to an extent dependent upon the parameters of size and location and biased strength of the septum in said guide, said param-

eters of said second guide being proportioned to produce in said second guide a phase constant for one direction of propagation that equals the phase constant of said first guide at a first condition of ambient temperature and frequency, said parameters of said third guide being proportioned to produce in said third guide a phase constant for one direction of propagation that equals the phase constant of said first guide at a second condition of ambient temperature and frequency, and resistive means coupled to said second and third guides for dissipating wave energy coupled into said guides.

5. A device for producing nonreciprocal attenuation of electromagnetic wave energy over a wide range of frequencies, said device comprising a first transmission path for said waves, a plurality of other transmission paths coupled by means of the phase velocity matching type to said first path along longitudinal intervals of their lengths, elements of magnetically polarized material exhibiting a gyromagnetic effect at the frequencies of said wave energy interposed in said interval in each of said other paths and positioned to affect the phase velocity of energy in the respective other paths in the same sense for providing a nonreciprocal phase constant substantially equal to the phase constant of said first path for a common direction of transmission in said other paths but for respectively different bands of frequencies within said wide range, and energy dissipating means connected to each of said other paths to dissipate substantially all of the energy coupled thereto.

6. A device for producing nonreciprocal attenuation of electromagnetic wave energy over a wide range of temperatures, said device comprising a first transmission path for said waves, a plurality of other transmission paths coupled by means of the phase velocity matching type to said first path along longitudinal intervals of their lengths, elements of magnetically polarized material exhibiting a gyromagnetic effect at the frequencies of said wave energy interposed in said interval in each of said other paths and positioned to affect the phase velocity of energy in the respective other paths in the same sense for providing a nonreciprocal phase constant substantially equal to the phase constant of said first path for a common direction of transmission in said other paths but for respectively different bands of temperatures within said wide range, and energy dissipating means connected to each of said other paths to dissipate substantially all of the energy coupled thereto.

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