

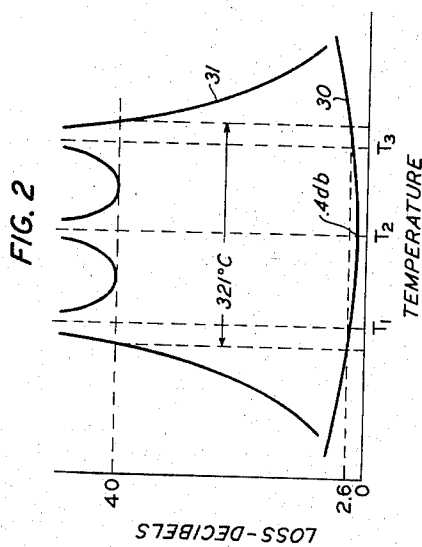
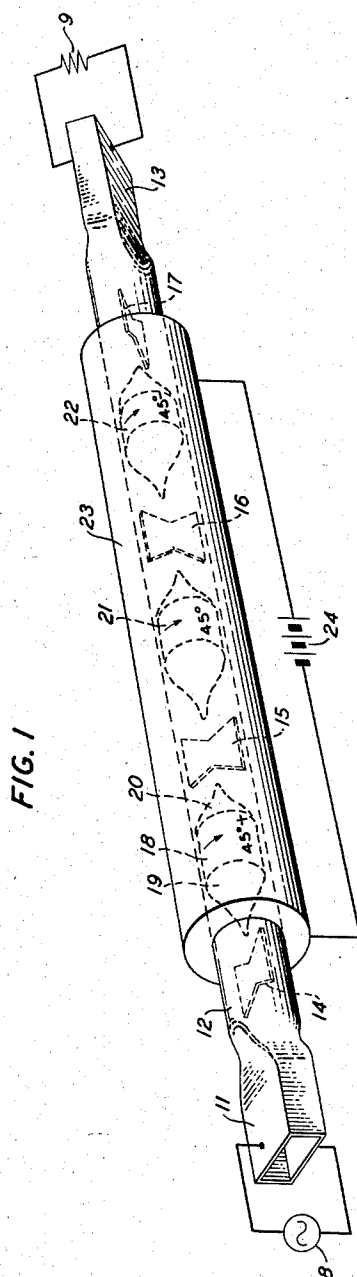
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NON-RECIPROCAL WAVE TRANSMISSION

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NON-RECIPROCAL WAVE TRANSMISSION

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7 Claims. (Cl. 333—24)

This invention relates to non-reciprocal electrical wave transmission devices, and more particularly, to improved one-way transmission devices employing an anti-reciprocal rotation of the polarization of electromagnetic wave energy which may directionally isolate one electrical circuit from another. This is a division of my co-pending application Serial No. 362,243, filed June 17, 1953, now United States Patent 2,802,184, granted August 6, 1957.

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, would greatly simplify the problem. Until recently, such a non-reciprocal transmission medium was unknown.

Lately, the antireciprocal Faraday-effect rotation of a magnetized element of ferromagnetic material has been exploited to provide such an isolator. The Faraday-effect element is combined with a polarization-selective attenuator so that in the forward direction of transmission the polarization of the wave is rotated by the Faraday-effect element into the plane of minimum loss in the attenuator, while in the return direction the polarization of the wave is rotated into the plane of maximum attenuation. Such a system is disclosed in the copending application of C. L. Hogan, Serial No. 252,432, filed October 22, 1951 now United States Patent 2,748,353, granted May 29, 1956, and in his publication, "The Microwave Gyrator," in the Bell System Technical Journal, January 1952.

It has been shown experimentally that Faraday rotation obtained in known ferromagnetic materials varies as a function of ambient temperature and to some extent also as a function of frequency. Consequently, an isolator employing a ferromagnetic element adjusted for the proper rotation at one temperature will be capable of a maximum return loss only at that temperature for which the adjustment was made. At temperatures either above or below this, the Faraday rotation will no longer rotate the return waves into the plane of maximum loss of the attenuator, and some undesired power will return to the sending end of the isolator. One solution to this would be to operate the ferromagnetic element in a temperature controlled medium, but the necessary complications thereby involved would seriously limit the extent of feasible application of the device. Similar difficulties are presented by the frequency variations of the amount of rotation in the ferromagnetic element.

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It is an object of the present invention to attenuate, by new and improved apparatus, wave energy propagated in one direction along a transmission path to a substantially greater degree than wave energy propagated in the other direction along said path.

Further objects of the invention are to reduce the effects of ambient temperature and to reduce the operating frequency variations in connection with ferromagnetic isolators.

In accordance with a specific embodiment of the present invention a plurality of Faraday-effect rotators and a plurality of polarization-selective attenuators are arranged along a wave energy transmission path. Each rotator is adjusted for maximum return loss with respect to one or more of the attenuators at slightly different operating temperatures and/or operating frequencies. The combined effect gives a relatively high attenuation for return wave energy and a relatively low forward loss at all temperatures and frequencies within the range of the temperatures and frequencies for which the over-all device is adjusted.

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

In the drawing:

Fig. 1 is a perspective view of a first specific isolator in accordance with the invention, showing the physical relationship of three Faraday-effect rotators and four polarization-selective attenuators;

Fig. 2 represents the loss or attenuation versus temperature characteristic of the isolator of Fig. 1.

Referring to Fig. 1, a one-way transmission device in accordance with the first embodiment of the invention is illustrated which connects an oscillator 8 to a load 9 with relatively low loss, and which isolates oscillator 8 by a relatively high loss from energy which might be reflected from load 9. As illustrated, this isolator comprises a rectangular wave guide 11 which will accept and support only plane polarized dominant mode waves from oscillator 8 for which the electric vector, which determines the plane of polarization of the wave, is parallel to the short side of rectangular wave guide 11. Guide 11 tapers into a round wave guide 12 to the opposite end of which is joined another rectangular wave guide 13. Guide 13 will accept and support only plane waves polarized at an angle, illustrated as 135 degrees clockwise as viewed from and with respect to the polarization of waves in guide 11. By means of the smooth transition from the rectangular cross-section of either guide 11 or guide 13 to the circular cross-section of guide 12, the dominant mode in either guide 11 or guide 13 is coupled to and from the dominant mode in circular guide 12 having a parallel polarization. The diameter of guide 12 is preferably chosen so that only the several polarizations of this dominant mode can be propagated.

Spaced along the length of guide 12 are a plurality of polarization-selective attenuators comprising resistive vanes 14 through 17, respectively. Vane 14 is positioned in the end of guide 12 adjacent guide 11 and is diametrically disposed in guide 12 in a plane perpendicular to the electric polarization in guide 11 so as to absorb and dissipate waves having their plane of polarization perpendicular to the plane of polarization of waves in guide 11. The other resistive vanes 15, 16 and 17, respectively, are each disposed in guide 12 in a plane inclined 45 degrees (clockwise as viewed from guide 11) to the plane of the immediately preceding vane. The sense of this progressive inclination is the same as that of the angle between guides 11 and 13.

Except for their respective angles of disposition, vanes

14, 15, 16 and 17 may be identical and may each be a thin sheet of low dielectric constant material, for example, polystyrene, coated with a film of resistive material, for example, carbon black, or may consist solely of carbon or other resistive material. In order to prevent reflections from the edges of vanes 14 through 17, these edges may be tapered over a distance of several wavelengths, thus making the plane of each half of vanes 14 through 17 a trapezoidal shape. Thus, a wave polarized perpendicular to the plane of any vane will suffer only negligible attenuation, while a wave polarized parallel to the plane of the vane will induce currents in the resistive material and will be dissipated thereby. It is obvious to one skilled in the art that other means of absorbing wave energy of selected polarization may be employed.

Interposed between vanes 14 and 15 in the path of the electromagnetic wave passing therebetween in guide 12 is suitable means of the type which produces an antireciprocal Faraday-effect rotation of the plane of polarization of these waves such that an incident wave impressed upon a first side of the rotator emerges on the second side polarized at a different angle from the original wave, and an incident wave impressed upon the second side emerges upon the first side with an additional rotation of the same angle. As illustrated by way of example in Fig. 1, this means comprises a ferromagnetic element 18, with conical transition members 19 and 20 in accordance with usual practice, mounted inside guide 12 approximately mid-way between vanes 14 and 15. Similar ferromagnetic elements 21 and 22 are located in guide 12 between vanes 15 and 16 and 16 and 17, respectively.

Elements 18, 21 and 22 may be made of any of the several ferromagnetic materials which each comprise an iron oxide with a small quantity of a bivalent metal 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, elements 18, 21 and 22 may be made of nickel-zinc ferrite prepared in the manner described in the above-mentioned publication and copending application of C. L. Hogan. As there disclosed, this material has been found to operate satisfactorily as a directionally selective Faraday-effect rotator of polarized electromagnetic waves when placed in the presence of a longitudinal magnetizing field of strength below that required to produce ferromagnetic resonance in the material.

Suitable means for producing the necessary longitudinal magnetic field surrounds elements 18, 21 and 22, which means may be, for the purposes of illustration, a single solenoid 23 mounted upon the outside of guide 12 and supplied by a source 24 of energizing current. The polarity of the field is chosen so that the direction of rotation for a wave propagated from left to right through elements 18, 21 and 22 (as indicated by the arrows on the elements) is clockwise when viewed from the left and thus in the same sense as the angles between vanes 14 and 15, 15 and 16, 16 and 17, and between guides 11 and 13. It should be noted that elements 18, 21 and 22 may be magnetized to the proper strength alternatively by separate solenoids, by permanent magnet structures, or they may be permanently magnetized if desired.

As an alternative, the required Faraday-effect rotation may be obtained by employing three antireciprocal rotators of the type disclosed in the copending application of E. H. Turner, Serial No. 339,289, filed February 27, 1953, and in my copending application Serial No. 360,795, filed June 10, 1953.

Whatever form of Faraday-effect element is employed,

the magnitudes of rotation of the three elements are adjusted for a given mid-band frequency and at the center of a range of ambient temperature variation so that one of said elements produces substantially a 45-degree rotation of the plane of polarization for a single passage of electromagnetic wave energy, and the other two of said elements produce an angle somewhat larger, and somewhat smaller, respectively, than 45 degrees. Considerations involved in selecting the amount of this difference will be considered hereinafter. For the particular type of rotator illustrated in Fig. 1, the magnitude of rotation produced by elements 18, 21 and 22 is approximately directly proportional to the thickness of the material traversed by the waves and to the intensity of the magnetization of the material. If elements 18, 21, and 22 are each subject to the same intensity of magnetization by solenoid 23, the above-described difference in rotation is obtained by varying or properly choosing the thickness of the material comprising each element. However, by suitably winding solenoid 23 so that a different magnetic field intensity is provided for each element, the intensity of the individual fields may be adjusted either with or without differences in the physical dimensions of the elements.

For convenience in the explanation that follows, assume that for a given temperature T_2 and a given frequency, element 18 produces a rotation greater than 45 degrees; element 21 produces a rotation of 45 degrees; and element 22 produces a rotation less than 45 degrees. Thus, element 21 may be somewhat shorter than element 18, and element 22 somewhat shorter than element 21. This means that at some temperature T_1 lower than T_2 element 22 will produce precisely a 45-degree rotation while both elements 21 and 18 will produce a rotation, respectively, larger than 45 degrees. Similarly, at a temperature T_3 higher than both T_1 and T_2 , element 18 will have a rotation of 45 degrees, while elements 21 and 22 will rotate the polarization less than 45 degrees. A similar analysis applies to frequencies above and below the given mid-band frequency.

The operation of the isolator of Fig. 1 may easily be seen by tracing the path of energy from oscillator 8 to load 9 and the return path of a wave reflected by load 9 for the mid-band frequency and at the mid-range temperature T_2 . Thus, a vertically polarized wave introduced from oscillator 8 into guide 11 travels past vane 14 unaffected thereby inasmuch as the plane of the vane is perpendicular to the polarization of the wave, and past transition member 19 to element 18. Element 18 rotates the wave slightly more than 45 degrees in the same sense as the angle existing between guide 11 and guide 13 (in a clockwise direction as indicated by the arrow on element 18 in the drawing).

The rotated wave may be resolved into two components with respect to vane 15, i. e., a major component of the wave at right angles to the plane of vane 15 and a very small component of the wave parallel to the plane of vane 15, representing the amount the rotation exceeded 45 degrees. The small component will be dissipated by vane 15. The major component of the wave will pass vane 15 unaffected and will be rotated 45 degrees by element 21 in the direction of the arrow thereon. This brings the wave into a polarization perpendicular to the plane of vane 16 past which the wave travels unaffected to element 22. Element 22 rotates the polarization of the wave somewhat less than 45 degrees in the direction of the arrow thereon, bringing the polarization of the major component of the wave into a plane perpendicular to vane 17 past which the wave travels unaffected through guide 13 to load 9. A small component of the wave rotated by element 22 will lie in the plane of vane 17 (representing the amount that the rotation falls short of 45 degrees), and will be dissipated by vane 17.

Curve 30 of Fig. 2 represents the loss versus temperature for the forward traveling wave just described. At

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the temperature T_2 the loss represented by curve 30 accounts for the two small components lost in vanes 15 and 17 and the incidental loss in the ferromagnetic material of elements 18, 21 and 22. In a typical embodiment, this loss will not exceed about 1 decibel. As the temperature is increased or decreased from this value, the loss will increase as shown by curve 30 only slightly due to the additional power lost in vane 16. Within the range between T_1 and T_3 the increase in power lost by one of vanes 15 or 17 is compensated by the decrease in power lost in the other.

Assume now that a substantial return component of the wave energy is reflected by load 9. This reflected wave travels past vane 17 unaffected thereby, inasmuch as the plane of the vane is perpendicular to the polarization of the wave, to element 22. Element 22 rotates the return wave slightly less than 45 degrees in the direction indicated by the arrow on element 22. The rotated wave may be resolved into two components with respect to vane 16, i. e., a major component in the plane of vane 16 and a small component perpendicular to the plane of vane 16. The major component will be dissipated by vane 16. The small component will pass vane 16 and will be rotated 45 degrees by element 21 in the direction of the arrow thereon. This brings the small component into the plane of vane 15 by which it is dissipated. Thus, at the temperature T_2 all energy in the reflected wave is dissipated either in vane 16 or vane 15. This results in substantially infinite discrimination between the forward wave and the return wave through the isolator of Fig. 1 as represented by the infinite loss portion of curve 31 of Fig. 2 at the temperature T_2 .

At the temperature T_3 , for which the rotation of both elements 21 and 22 is greater than 45 degrees, a small component perpendicular to the plane of vane 15 will pass on to element 18 to be rotated 45 degrees into the plane of vane 14 and dissipated thereby. Thus, at the temperature T_3 as indicated by curve 31 on Fig. 2, infinite discrimination will be found for the isolator. At the temperature T_1 for which the rotation of element 22 is precisely 45 degrees, all wave energy will be dissipated in vane 16. Again, infinite discrimination, as represented by curve 31 of Fig. 2, is found for the isolator. At intermediate temperatures, the discrimination is substantially less than infinite but is well within acceptable limits for practical applications of the isolator.

Specific design data of an isolator for any given application depends upon the maximum return loss required, the range of ambient temperature variation over which this loss must be maintained and the number of 45-degree sections of the isolator. Obviously, for a given number of sections, a much higher discrimination may be obtained over a limited range than may be obtained over a wider range. In a typical embodiment, it has been determined that each 45-degree section will produce 40 decibels of return attenuation over a temperature range of substantially 9.35 degrees centigrade. However, for a given specific embodiment employing three such sections as in Fig. 1, with the temperatures T_1 , T_2 and T_3 at which each section produces a 45-degree rotation, respectively, spaced substantially 138 degrees centigrade apart, a return loss of at least 40 decibels will be maintained over a temperature range of 321 degrees as shown in Fig. 2. The forward attenuation or loss at the extreme temperature values under this condition would only be 2.6 decibels greater than the loss due to the ferrite elements alone. This is represented on an exaggerated scale by curve 30 of Fig. 2. It has been found that in a typical sample of ferromagnetic material, the rotation changed 0.28 percent per degree centigrade. Thus, on the basis of the above specific values, element 18 should be adjusted to produce a rotation of approximately 62.4 degrees, element 21 of approximately 45 degrees and element 22 of approximately 27.6 degrees, all at the center

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range temperature T_2 . Obviously, these adjustments need not be accurately made.

Three 45-degree sections have been illustrated in Fig. 1 as a typical embodiment. Two sections, however, will give substantial improvement over a single section and the number of sections may be further increased to increase the operating band and/or the minimum discrimination within the band, if desired. It should be noted in this connection that a multiple of four sections or multiples of two sections in which the direction of rotation of alternate rotators is reversed, or combinations thereof will place the output polarization in the same plane as the input polarization.

In order to simplify the description above, operation of the isolator of Fig. 1 has been explained with reference to variations of temperature alone. However, since as noted above, the effect of frequency upon the rotation of ferromagnetic materials is similar to the effect of temperature, i. e., it has been observed that substantially a 3 percent change in rotation occurs for a 1 percent change in frequency; therefore, the same compensating effects of the isolator are found for variations in frequency or for simultaneous variations in frequency and temperature. Thus, on the basis of specific values given above, the isolator would maintain a return loss of at least 40 decibels over a change in frequency of substantially 30 percent. From the standpoint of actual use this extremely broad stability with respect to frequency is of far more practical significance than the broad temperature range since such a frequency band would not be unusual in a broad band transmission system, whereas so great a temperature variation would be exceptional.

In all cases, it is understood that the above-described arrangement is simply illustrative of one 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 by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. An electromagnetic wave transmission isolator for maintaining between wave energy propagating in opposite directions therethrough a given substantial degree of isolation over a range of significantly different operating conditions determined by the ambient temperature and operating frequency, said isolator comprising a plurality of coupled individual isolators each adjusted to provide maximum isolation at successively different optimum operating conditions within said range over which said isolation is maintained, each of said individual isolators having an isolation response decreasing from said maximum and being greater than said given degree of isolation over a small fraction of said range, said successive optimum operating conditions being uniformly spaced from each other in temperature and frequency by an amount large enough to provide said given degree of isolation at the limits of said range and at the same time uniformly spaced from each other by an amount small enough that at a single operating condition between successive pairs of optimum operating conditions the sum of the isolation contributed by the decreasing isolation response of each said individual isolators is substantially equal to said given degree of isolation.

2. An electromagnetic wave transmission isolator for maintaining between wave energy propagating in opposite directions therethrough a given substantial degree of isolation over a range of significantly different operating conditions determined by the ambient temperature and operating frequency, said isolator comprising a waveguide section adapted to support electromagnetic wave energy in a plurality of polarizations, means at each end of said section for coupling a linearly polarized wave to and from said section in a predetermined polarization, a plurality of dissimilar Faraday-effect rotators for

rotating wave energy propagated from one end of said section to the other end from the predetermined polarization in said one end through intermediate polarizations into the predetermined polarization in said other end, said rotation being antireciprocal, means for attenuating wave energy of a selected polarization to a substantially smaller degree than wave energy polarized perpendicular to said selected polarization, said selected polarization being substantially parallel to at least one of said intermediate polarizations of said rotated wave for propagation from said one end to said other end and thereby also perpendicular to at least one intermediate polarization of wave energy propagated from said other end to said one end, said rotators and said attenuating means being adjusted to provide maximum isolation for successively different optimum operating conditions within said range over which said isolation is maintained, said successive optimum operating conditions being spaced from each other in temperature and frequency by an amount such that at a single operating condition between successive pairs of optimum operating conditions the sum of the isolation contributed by each of said individual isolators is equal to said given degree of isolation.

3. An electromagnetic wave transmission isolator for maintaining between wave energy propagating in opposite directions therethrough a given substantial degree of isolation over a range of significantly different operating conditions determined by the ambient temperature and operating frequency comprising a section of electromagnetic wave guide of circular cross section, a vane of resistive material disposed in a diametrical plane in said guide in each of at least three regions along said section and angularly displaced with respect to each other, an antireciprocal Faraday-effect element for rotating the polarization of wave energy propagated along said guide interposed between said regions, said angular displacement between the diametrical plane in the region on one side of each of said elements and the diametrical plane in the region on the other side of each of said elements differing from the angle of rotation imparted to said energy by said interposed element for providing maximum isolation at successively different optimum operating conditions within said range over which said isolation is maintained, each of said combinations of ele-

ments and adjacent vanes having an isolation response decreasing from said maximum and being greater than said given degree of isolation over a small fraction of said range, said successive optimum operating conditions being uniformly spaced from each other by an amount large enough to provide said given degree of isolation at the limits of said range and at the same time uniformly spaced from each other by an amount small enough that at a single operating condition between successive pairs of optimum operating conditions the sum of the isolation contributed by the decreasing isolation response of each of said individual combinations of vanes and elements is substantially equal to said given degree of isolations.

4. The combination according to claim 3 wherein each of said vanes is diametrically disposed in said guide in a plane inclined by 45 degrees to the plane of the immediately adjacent vane, and wherein said Faraday-effect rotation for each element is substantially 45 degrees for different conditions of ambient temperature and operating frequency within said range.

5. The combination according to claim 2 wherein said means for attenuating and said means for rotating are located in respectively alternate regions along said section and wherein said selected polarization in each region is substantially parallel to the polarization of wave energy leaving the immediately preceding rotating region for propagation from said one end to said other end under a given temperature and frequency condition.

6. The combination according to claim 3 wherein said angular displacement is the same for each of said vanes and wherein the rotation produced by at least one of said elements is equal to said angular displacement for a predetermined temperature and frequency condition said predetermined condition being different from the temperature and frequency condition for which said rotation is produced by every other element.

7. The combination according to claim 4, wherein each of said rotating elements comprises a magnetized ferromagnetic member, and wherein each element has a different relationship of physical dimension and strength of magnetization.

No references cited.