

July 21, 1959

A. G. FOX

2,896,174

NONRECIPROCAL WAVE TRANSMISSION

Filed Jan. 27, 1955

3 Sheets-Sheet 1

FIG. 1

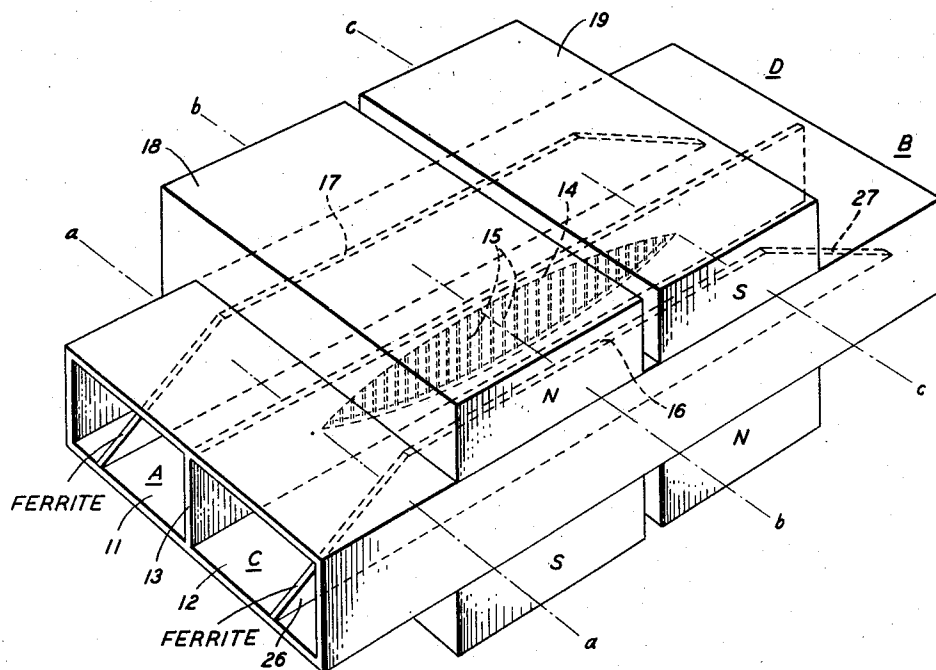
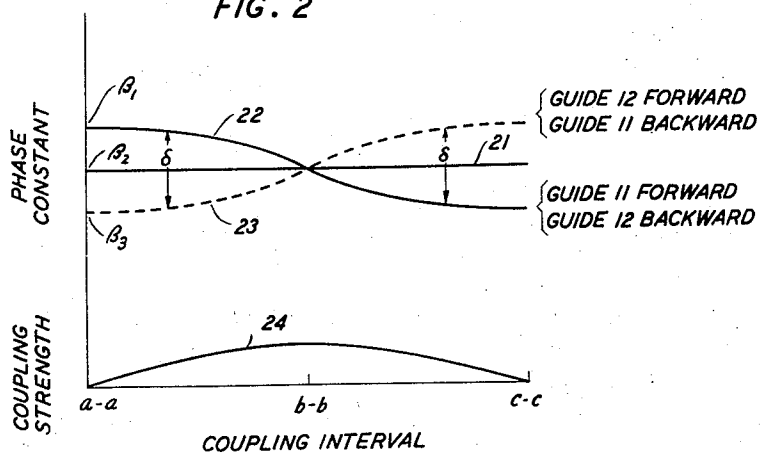


FIG. 2



INVENTOR
A. G. FOX

BY *Ray M. Porter*

ATTORNEY

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A. G. FOX

2,896,174

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FIG. 3

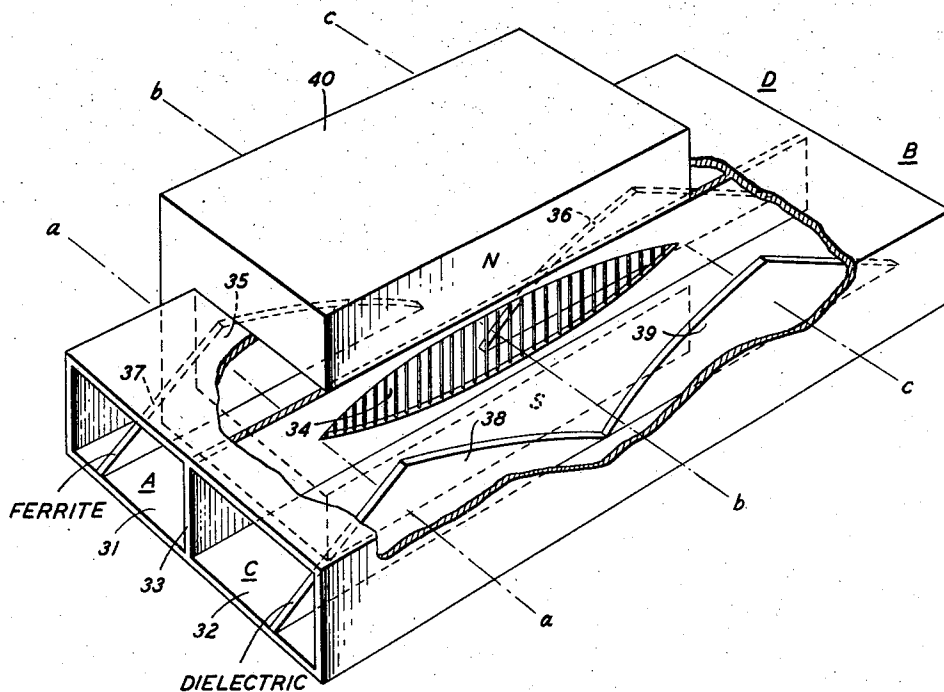
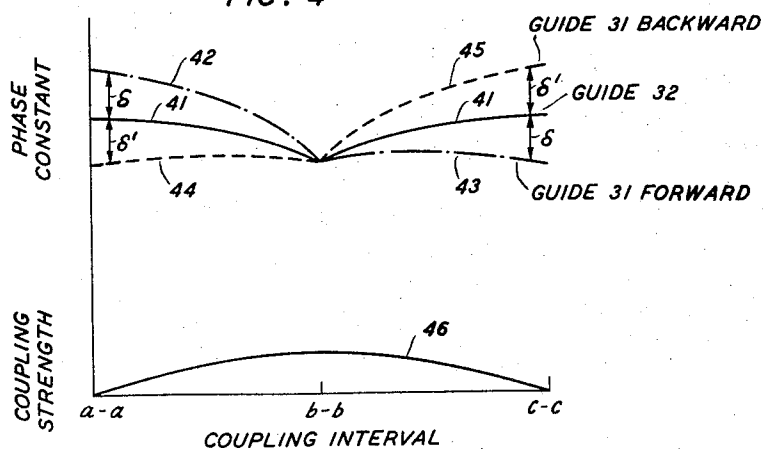


FIG. 4



INVENTOR
A. G. FOX

BY *Ray M. Porter, Jr.*

ATTORNEY

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A. G. FOX

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FIG. 5

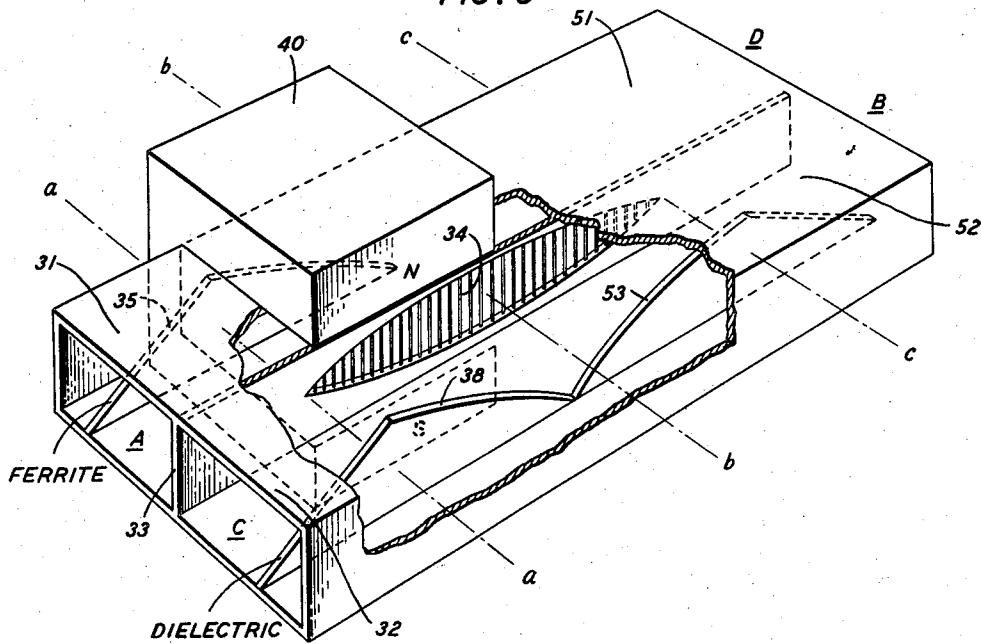


FIG. 7

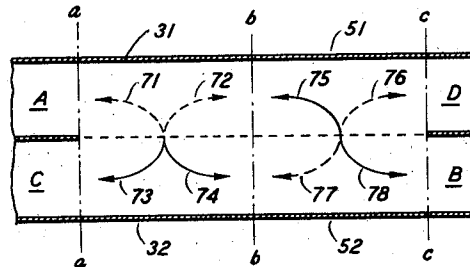
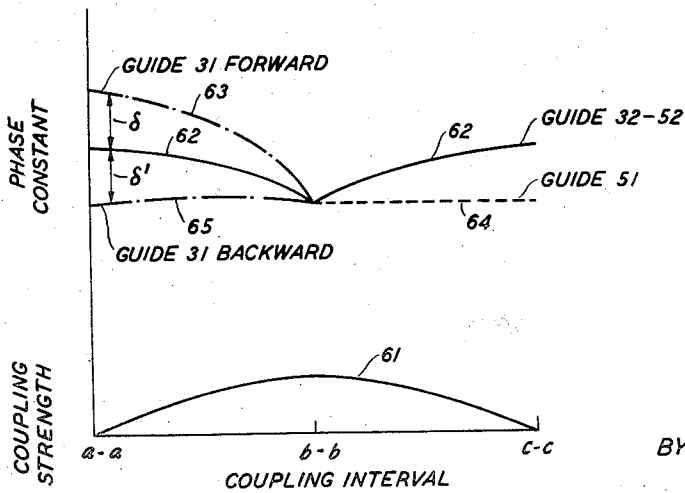


FIG. 6



INVENTOR
A. G. FOX
BY *Ray M. Porter, Jr.*

ATTORNEY

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2,896,174

NONRECIPROCAL WAVE TRANSMISSION

Arthur G. Fox, Rumson, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Application January 27, 1955, Serial No. 484,498

15 Claims. (Cl. 333—10)

This invention relates to electrical transmission systems and, more particularly, to multibranch circuits having nonreciprocal transmission properties for use in said systems.

A group of nonreciprocal transmission components has been recently developed for electromagnetic wave transmission systems utilizing one or more of the nonreciprocal properties of gyromagnetic materials, often designated ferromagnetic materials or ferrites. Important classes of these components include directional coupler-like structures that have nonreciprocal phase shift characteristics and new coupling components known as circulators. As the operation of these components relies upon critical adjustments relative to specific characteristics of the ferrite, they are influenced by inherent variations of the characteristics of the ferrite with variations in ambient temperature and also with variations in operating frequency. Obviously, the temperature variation is a disadvantage since it is impractical in most applications to operate the device in a temperature controlled medium. Likewise, the frequency variation has the effect of limiting the operating bandwidth of the device.

It is therefore an object of the present invention to increase the operating temperature and frequency bandwidth of nonreciprocal microwave components.

In my copending application Serial No. 465,579, filed October 29, 1954, now Patent No. 2,834,944 and in the copending application of J. S. Cook, Serial No. 465,578, filed October 29, 1954, there is disclosed for reciprocal devices a new principle of coupling between related transmission systems known as "normal mode tapering." Broadly stated, normal mode tapering operates by exciting one of the normal modes in a coupled wave guide system, and by tapering the phase constants and the coupling coefficient for the wave guides so as to cause the cross-sectional energy distribution, characterizing the normal modes at any point, to change from point to point along the structure in a desired manner. The manner in which the normal mode energy pattern is varied will hereinafter be referred to as the "normal mode syntax," meaning the order or arrangement of parameter variation that produces the desired change of energy distribution. Further definition of the normal mode and its characteristics will be found hereinafter. For more detailed consideration reference may be had to my above mentioned copending application.

It is important to realize that the desired shift of energy depends upon the syntax of the tapered parameters and not upon any absolute or fixed value of either the individual phase constants of the coupled wave guides, the phase constant difference, or the coupling coefficient, although certain relationships appear to give optimum performance in a given coupling interval. Therefore, a normal mode shift of energy is broad band and variations which may affect the absolute values of the parameters, but which do not alter their relative patterns, will not affect the normal mode operation.

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In one aspect, it is an object of the invention to produce a nonreciprocal normal mode shift of electromagnetic wave energy between coupled wave guiding paths.

In accordance with the present invention the phase constants of a pair of coupled transmission lines are modified by incorporating within the lines particularly located, shaped and polarized members of gyromagnetic material to nonreciprocally produce the phase constant variation required for the desired normal mode syntax. In a first embodiment of the present invention the nonreciprocal characteristics are arranged so that in one direction of propagation between a given pair of wave guide terminals, a shift of energy occurs in what is referred to and which will be defined hereinafter as the "in-phase" normal mode, while in the opposite direction of propagation the shift is produced in the "out-of-phase" normal mode. This results in a broad band nonreciprocal directional coupler or hybrid type structure capable of abstracting all or part of the wave energy traversing a first transmission path and launching this energy directionally in a second transmission path. It is nonreciprocal since energy is transmitted between the paths in-phase in one direction but out-of-phase in the opposite direction. This nonreciprocal phase characteristic is not found in any conventional directional coupler or hybrid structure.

A principal feature of the present invention resides in the four-terminal "circulator circuit" that results from combining a nonreciprocal normal mode coupler in accordance with the first embodiment with a reciprocal normal mode coupler. "Circulator circuit" is the generic designation of a group of nonreciprocal multibranch networks for which numerous applications have been devised. All circulators have the electrical property that energy is transmitted in circular fashion around the branches of the network so that energy appearing in one branch thereof is coupled to only one other branch for a given direction of transmission but to another branch for the opposite direction of transmission. The circulators in accordance with the present invention are extremely broad band, being limited only by the inherent frequency limitations of the wave guide components themselves and are substantially independent of effects of temperature and frequency upon the gyromagnetic element.

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

In the drawings:

Fig. 1 is a perspective view of a nonreciprocal directional coupler, in accordance with a first embodiment of the invention, showing a pair of wave guides each including a nonreciprocal, phase constant modifying element of polarized gyromagnetic material to produce coupling by normal mode tapering;

Fig. 2, given by way of explanation, shows the variation of the relative phase constants and the coupling coefficients along the interval of coupling in the embodiment of Fig. 1;

Fig. 3 is a perspective view of a second embodiment of the invention wherein the phase constants of the guides are modified by tapered elements of uniformly polarized gyromagnetic material;

Fig. 4, given by way of explanation, shows the variation of the relative phase constants and the coupling coefficients along the interval of coupling in the embodiment of Fig. 3;

Fig. 5 is a perspective view of a circulator circuit, in accordance with the invention, comprising a reciprocal section and a nonreciprocal section of guides coupled by normal mode tapering;

Fig. 6, given by way of explanation, shows the variation of the relative phase constants and the coupling coefficients along the interval of coupling in the embodiment of Fig. 5; and

Fig. 7 shows schematically the coupling and phase characteristics for the purpose of explaining the operation of the circulator of Fig. 5.

Referring more specifically to Fig. 1, a non-reciprocal directional coupler embodying the principles of normal mode tapering is shown as an illustrative embodiment in accordance with the invention. In some respects this circuit is a directional coupler structure of conventional design having specially modified phase constants. The directional coupler portion comprises a first section 11 of electrical transmission line for guiding wave energy, which 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 adjacent guide 11 and running for a portion of its length contiguous and parallel thereto, is a second section 12 of transmission line which has cross-sectional dimensions similar to those of guide 11 and which has a narrow wall 13 in common with guide 11.

Guides 11 and 12 are coupled electromagnetically over an interval of several wavelengths between sections *a-a* and *c-c* by a divided aperture 14 in common wall 13. Divided aperture 14 has a transverse dimension which is zero in section *a-a*, tapers to a maximum in section *b-b* and decreases again to zero in section *c-c*. It is divided by a plurality of parallel wires 15 in accordance with the teachings of applicant's copending application, Serial No. 236,556, filed July 15, 1951, now Patent No. 2,701,342. Suitable coupling may also be provided by a plurality of discrete apertures of tapered sizes spaced relatively close together in common wall 13.

For reference purposes hereinafter the ends of guide 11 are labeled branch A and branch D, respectively, and the ends of guide 12 are labeled C and B, respectively. The forward direction of propagation is defined as the progression of wave energy from branch A to D or from branch C to B while the backward direction of propagation is defined as the progression from D to A or from B to C. In order to avoid confusion, it should be noted that the terms "forward" and "backward" as used herein are absolute terms referring to the embodiments as shown in the drawings and are not the relative terms sometimes employed in the directional coupler art.

The phase constants of the structure are modified as follows. Located in guide 12 and asymmetrically displaced therein approximately one quarter of the guide width to the right-hand side of the center line of guide 12 is a thin vane or septum 16 of gyromagnetic material. 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 *Philosophical Magazine*, January 1949, vol. 40, pages 99 through 115. Member 16 extends across the height of guide 12, parallel to the narrow walls thereof, and extends longitudinally therein at least along the region of coupling from section *a-a* to *c-c*. The ends of member 16 beyond section *a-a* or *c-c* may be provided with tapers 26 and 27 to prevent reflections of wave energy therefrom. A similar member 17 is located in guide 11 asymmetrically displaced to the left-hand side of the center line of guide 11.

As a specific example of a gyromagnetic medium, members 16 and 17 may be made of any of the several ferro-magnetic 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 ferromag-

netic 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 16 and 17 may be made of nickel-zinc ferrite prepared in the manner described in the publication of C. L. Hogan, "The Microwave Gy-rator," in the *Bell System Technical Journal*, January 1952, and in his copending application Serial No. 252,432, filed October 22, 1951, now Patent No. 2,748,353.

Members 16 and 17 are biased by a steady magnetic field applied at right angles to the direction of propagation of wave energy in guides 11 and 12. The strength of this field is tapered longitudinally along the coupling interval so that it is maximum in one sense at section *a-a*, is zero at section *b-b*, and is maximum in the opposite sense at section *c-c*. As illustrated in Fig. 1, this field may be supplied by the novel arrangement of two permanent magnet structures 18 and 19 having pole pieces N and S bearing oppositely upon the top and bottom wide walls, respectively, of guides 11 and 12 between the sections *a-a* and *c-c*. In other words, permanent magnet 18, as shown, has its N pole bearing against the top wide walls of guides 11 and 12 between the cross sections *a-a* and *b-b*, while permanent magnet 19 has its S pole bearing against the top walls between the sections *b-b* and *c-c*. Thus in the vicinity of section *b-b* the fields from magnets 18 and 19 are oppositely directed and cancel to produce a net magnetic field of zero. This field increases gradually between the section *b-b* and the section *a-a* to the maximum strength produced by magnet 18 and similarly increases gradually in the opposite sense between the sections *b-b* and *c-c* to the maximum strength produced by magnet 19. This field may, however, be supplied by a permanent magnet structure of other suitable physical design, by an electrical solenoid, or members 16 and 17 may be permanently magnetized if desired.

It has been determined that a polarized septum of gyromagnetic material located as either member 17 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 Patent No. 2,849,684.

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 center 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, the relative phase constants of guides 11 and 12 vary along the coupling interval between sections $a-a$ and $c-c$ in the manner shown in Fig. 2. In the absence of magnetic field, guides 11 and 12 will have equal uniform phase constants as represented by characteristic 21 on Fig. 2. These constants are equal to some value β_2 which is determined by the dielectric and unmagnetized permeability constants of members 16 and 17 and the fixed parameters of the guides themselves. When the magnetic field from magnets 18 and 19 is applied in the specific senses indicated on Fig. 1, a wave traveling in the forward direction from branch A to branch D in guide 11 will be presented at section $a-a$ with a phase constant β_1 larger than β_2 by an amount representing the increase in the permeability of member 17 caused by the magnetic field strength at the section $a-a$. As the field strength decreases, passes through zero, and increases in the opposite sense between sections $a-a$ and $c-c$, the phase constant presented to a wave in guide 11 follows the characteristic represented by curve 22 of Fig. 2. Between section $b-b$ and $c-c$ the effect of the permeability is to reduce the phase constant represented by curve 22 so that it is less than that represented by curve 21.

A wave applied at branch C of guide 12 will be presented at section $a-a$ with a phase constant equal to β_2 , smaller than β_1 by an amount representing the decrease from unity of the permeability of member 16 under the influence of the magnetic field at section $a-a$. The phase constant of guide 12 will increase along the coupling interval as the field decreases and will equal that of guide 11 at section $b-b$, as represented by curve 23, and will continue to increase between the sections $b-b$ and $c-c$, as further represented by curve 23. It will be noted that curve 23 varies inversely to curve 22 since the positions of the gyromagnetic members 17 and 16 are on opposite sides of the longitudinal center lines, respectively, of guides 11 and 12 and therefore have permeabilities that vary oppositely under the influence of the same magnetic field.

For waves propagating in the backward direction, i.e., for waves applied to terminal D of guide 11 or terminal B of guide 12, the characteristics are reversed since the senses of rotation of the circularly polarized components of the backward traveling wave are reversed from the senses of the forward traveling wave. Therefore for a backward traveling wave, curve 22 represents the phase constant of a wave propagating from branch B to branch C in guide 12 and curve 23 represents a wave propagating from branch D to branch A in guide 11. On Fig. 2 is also shown the variation of the coupling coefficient k along the interval from section $a-a$ to section $c-c$ as represented by curve 24.

It is therefore noted that for either direction of propagation, guides 11 and 12 in the region of coupling have phase constants that are different by an amount δ from each other. At the positions of minimum coupling factor the difference δ is maximum, and this difference decreases to zero at the position of maximum coupling factor in the middle of the coupling region. The phase difference is of opposite sign on opposite sides of the middle so that the individual phase characteristics cross over each other at the middle. These characteristics comprise the pattern or order and arrangement of parameter

variation disclosed in my said copending application to produce a shift of energy distribution for the normal modes of the system. In addition, the characteristics are nonreciprocal since, in the regions of different phase constants, one of the two coupled guides has a larger phase constant for one direction of propagation, while the other has the larger phase constant for the opposite direction of propagation.

Thus, if a microwave signal is applied to branch A of guide 11 it will excite in the coupled system comprising guides 11 and 12 the field distribution defined in my said copending application as a "normal mode" of propagation. As there defined for a coupled wave guide system, a "normal mode" is that field distribution of the wave energy propagated jointly in a pair of coupled guides that remains unchanged during propagation along a coupling region in which all characteristics remain unchanged including the phase, coupling coefficient, characteristic impedance and the attenuation constant. In a system having two modes of propagation between which power transfer is to be effected, there are two normal modes into which wave energy propagating in one direction along the pair of coupled guides can be resolved. One of these modes is designated the "in-phase" mode, or the low phase velocity mode, since the total field pattern of the mode comprises two portions of electrical intensity on opposite sides of the conductive boundary separating the two guides, which portions are maximum at the same instant of time and in the same direction, and propagate together at a lower velocity than would a conventional wave in either of the guides alone. The other normal mode is designated the "out-of-phase" or high velocity normal mode since the two portions of its intensity are in opposite directions and propagate at a higher velocity than would a wave in either guide alone. The two portions of either mode will propagate jointly along the coupled guides without change in field distribution so long as the coupling and phase constants of the guides remain constant. However, as demonstrated in detail in said copending application, the two portions need not have equal amplitudes. Rather, a particular distribution of the normal mode energy between the two guides at a given cross section is uniquely determined by the relationship between the phase constant difference and the coupling coefficient at that cross section. In a coupled system comprising a pair of wave guides having substantially different phase constants and negligible coupling, the normal modes will have all of their energy in either one or the other of the guides. Therefore if energy is introduced into one of the wave guides it will excite only one of the normal modes. As the phase constant difference is gradually decreased and the coupling increased, a shift of energy in the normal mode will take place into the other guide. When the phase constants of the guides are equal the normal mode will have its energy equally divided between the guides. If the phase constant difference is increased again, but in the opposite sense to produce a "cross-over" in the individual guide phase constants, and the coupling decreased, the shift will continue until all energy will appear in the second guide at the point of negligible coupling. It is a further characteristic of such a system that when energy is initially delivered to the branch having the larger phase constant it will excite in the coupled system the in-phase normal mode. Similarly, if the energy is initially delivered to the branch having the smaller phase constant, it will excite the out-of-phase normal mode. All this is demonstrated in detail in said copending application with the aid of illustrations showing typical field distributions. Also, desirable rates of variation of the phase constant difference and the coupling coefficient are defined, and optimum relationships between the phase difference and the coupling coefficient are given which may be employed in optimum adjustment of the present invention. For these and other details reference is made to said copending application.

In view of what has been restated here, it is apparent that the energy applied to branch A of guide 11 will excite the in-phase normal mode in the coupled system since for the forward direction of propagation β_1 in guide 11 is greater than β_3 in guide 12. At the cross section $a-a$ all energy in the normal mode will be in guide 11, but between sections $a-a$ and $b-b$ a normal mode shift of energy will take place into guide 12 until in the sections $b-b$ equal, in-phase, portions will be found in guides 11 and 12. Since the phase constant characteristics of the guides cross over, the shift of energy will continue until at section $c-c$ all energy will be in guide 12 for delivery to branch B.

If wave energy is instead applied to branch B, the energy will now excite the out-of-phase normal mode in the coupled system since for the backward direction of propagation the relative phase characteristics of the guides are reversed from those for the forward direction. In section $b-b$ equal out-of-phase portions of the mode will be found in guides 11 and 12. At section $a-a$ all energy will be in guide 11 for delivery to branch A. In addition, the phase delay for propagation from B to A will be less than was the phase delay for propagation from A to B, because the velocity of the out-of-phase mode is higher than for the in-phase mode. Thus, for propagation between A and B, the coupler acts like a directional phase shifter, owing to the nonreciprocal properties of the ferrite. Similarly transmission from branch C to D will take place by means of a shift in the distribution of the out-of-phase normal mode, whereas transmission from D to C will be made in the in-phase normal mode. Since the directions in which the relative in-phase or out-of-phase normal mode conditions are observed depend upon whether a relatively high or relatively low phase constant is exhibited by the guide initially excited, which in turn depends upon the sense of biasing magnetic field relative to the direction of propagation, reversing the field has the effect of reversing the direction through the coupler in which the above described phase relations are found.

The above described operation assumes complete power transfer. However, coupling aperture 14 may be closed off starting from section $c-c$, for example, to obtain any desired division of power between branches B and D for energy initially applied at either branch A or C. If the portion of aperture 14 is closed between sections $b-b$ and $c-c$ wave energy will be divided equally and in-phase between branches B and D. If however, wave energy is applied to branch C instead, the energy will be divided equally but out-of-phase between branches B and D. This unusual phase characteristic is not found in any conventional directional coupler or hybrid structure. One novel combination making particular use of this property will be considered hereinafter with respect to Fig. 5.

The independence of operation of the coupler from the effects of temperature and frequency variations on the ferrite material should now be apparent. Any variation that changes the magnetized permeability of the ferrite will have the effect of changing the specific value of the phase constant difference by slightly increasing or decreasing β_1 or β_2 . However, this variation will be substantially uniform along the coupling interval so that the function according to which the phase constant difference δ varies along the interval will not be substantially changed, and more particularly, the pattern that the variation follows will be unaffected. Since the absolute value of the phase constants of neither guide is important with respect to normal mode tapering, these variations will in no way effect or change the broad band operation of the invention. This is true also of the alternative embodiments now to be described.

In the embodiment of Fig. 1, the necessary taper of the phase constants characteristic of the normal mode syntax is obtained by tapering the intensity of the biasing magnetic field. Since the resulting phase constant is proportional to the product of the biasing intensity and

the mass of the material, the phase constants of the guides may also be tapered by tapering the mass of the gyromagnetic material itself. Referring to Fig. 3, an illustrative embodiment of the invention is shown in which the guides are loaded by tapered members of ferrite and dielectric. Guides 31 and 32 are rectangular wave guides which are located side by side to provide a common wall 33 having a divided aperture 34 several wavelengths long. Aperture 34 produces a tapered coupling characteristic as in Fig. 1. Located in guide 31 are tapered members 35 and 36 of gyromagnetic material the cross sections of which, and therefore the masses, increase from zero to a maximum and then decrease to zero. Member 35 is located to the left of the longitudinal center line of guide 31 with its maximum mass at section $a-a$ and its minimum mass at section $b-b$. Taper portion 37 provides a reflectionless transition between the unloaded portion of guide 31 and the maximum mass of member 35. Member 36 is located to the right of the center line of guide 31 with its maximum mass at section $c-c$ and its minimum mass at section $b-b$. Located in guide 32 are counterpoises 38 and 39 of dielectric material having tapers and masses that produce dielectric loading in each cross section of guide 32 equal to the dielectric loading produced by members 35 and 36 in guide 31.

Members 35 and 36 are biased by a magnetic field of uniform strength along the coupling interval by permanent magnet structure 40 having its N pole bearing against the top wide wall of guide 31 and its S pole bearing below guide 31.

The resulting relative phase constants of guides 31 and 32 are shown on Fig. 4. Also shown on Fig. 4 is the coupling strength coefficient represented by curve 46. In the absence of magnetic field, guides 31 and 32 will have equal phase constants, as represented by curve 41, that vary along the coupling interval in accordance with the variation of the dielectric constants of elements 35 and 36 in guide 31 and of dielectric counterpoises 38 and 39 in guide 32. When the magnetic field from magnet 40 is applied in the specific sense indicated, a wave traveling in the forward direction from branch A to branch D will be presented with a phase constant at section $a-a$, as represented by curve 42, that is initially greater than the phase constant of guide 32, as represented by curve 41. The amount of this difference corresponds to the increase in permeability of member 35 caused by its magnetization. As the mass of member 35 decreases, the phase constant of guide 31 decreases to a value equal to the phase constant of guide 32 in section $b-b$. Between sections $b-b$ and $c-c$, guide 31 has a phase constant, as represented by curve 43, that becomes increasingly less than the phase constant of guide 32 since the effect of the magnetization is to decrease its permeability. The size, taper and location of members, 35, 36, 38 and 39 are adjusted relative to each other and to the strength of the magnetizing field so that the difference δ between the phase constants of guides 31 and 32 for the forward direction of propagation tapers along the coupling interval in the proper way to produce a normal mode shift of energy, as described above. Therefore, energy applied to branch A of guide 31 will excite the in-phase normal mode in the coupled system and will be transferred as an in-phase portion into guide 32 for delivery to branch B.

A wave traveling in the backward direction in guide 31 will be presented with a phase constant at section $c-c$ that is different by an amount δ' from the phase constant of guide 32. This phase constant of guide 31, as represented by curve 45, is initially greater than, and progressively approaches, the phase constant of guide 32 since for this direction of propagation the effect of the permeability of member 36 now reinforces the effect of its dielectric constant. Between sections $b-b$ and $a-a$, guide 33 has a phase constant represented by curve 44.

that becomes increasingly less than curve 41. For this direction of propagation wave energy applied at branch B of guide 32 will be transferred into guide 31 in the out-of-phase normal mode. As in the embodiment of Fig. 1 a broad band transfer of energy is produced with a nonreciprocal phase shift for the backward and forward directions of propagation.

Comparing Figs. 2 and 4, important differences in the two embodiments will be seen. Note that in Fig. 2 the average phase velocity between the two guides is a constant and is the same for both directions of transmission through the structure. On the other hand, in Fig. 4 the average phase velocity varies along the length of the coupling interval and is different for opposite directions of propagation therealong. However, it is the phase constant difference δ or δ' , depending upon the direction of propagation, that is important with respect to normal mode tapering. This difference may easily be made to vary, if desired, according to the same characteristic along the coupling interval in both embodiments and for both directions of propagation regardless of the average phase velocity. It should also be noted that in both embodiments the purpose of the dielectric counterpoises is to balance the dielectric loading produced by the gyromagnetic member. This equalization might have been accomplished also by tapering the wide dimension of one or both of the guides so that in the absence of magnetic field both guides have the same phase constant characteristic along the length of the coupling interval.

One particularly useful combination making use of the nonreciprocal property of the gyromagnetically controlled normal mode coupler of either Fig. 1 or Fig. 3 is illustrated in Fig. 5 in which the nonreciprocal portion is ended at the point producing equal division of power between two of its branches. These branches are connected to a 3 decibel reciprocal directional coupler or hybrid junction. As particularly illustrated in Fig. 5, a preferred embodiment of this combination comprises a nonreciprocal portion that is structurally similar to the portion of the embodiment of Fig. 3 between the sections $a-a$ and $b-b$ and on which corresponding reference numerals have been employed to designate corresponding components. The extensions 51 and 52 of guides 31 and 32, respectively, comprise a reciprocal 3 decibel tapered mode coupler of the type disclosed and claimed in my above mentioned copending application. The phase constant difference between guides 51 and 52 is produced by loading guide 52 by dielectric member 53 extending from a minimum mass at section $b-b$ to a maximum at section $c-c$, and by providing no loading in guide 51. The guides are coupled by a single divided aperture 34 tapering from a minimum transverse dimension at sections $a-a$ and $c-c$ to a maximum at section $b-b$.

The resulting phase constant characteristics along the coupling interval are shown in Fig. 6 along with the coupling characteristic represented by curve 61. The phase constant for guide 32—52, as represented by curve 62, is determined by the dielectric loading of members 38 and 53 and is the same for either direction of propagation. As noted above for the forward direction of propagation between sections $a-a$ and $b-b$, the increased permeability of member 35 causes guide 31—51 to have a phase constant represented by curve 63. Between sections $b-b$ and $c-c$, the unloaded portion of guide 31—51 has a constant phase constant represented by curve 64. For the backward direction of propagation the decrease in permeability of member 35 results in a phase constant for guide 31—51 as represented by curve 65. Thus, for the forward direction of propagation between sections $a-a$ and $b-b$ a phase constant difference of δ is provided between guides 31—51 and 32—52, with guide 31—51 having the larger phase constant. For the backward direction of propagation be-

tween sections $b-b$ and $a-a$ a phase constant difference of δ' is provided with guide 32—52 having the larger phase constant.

These phase characteristics produce a broad band nonreciprocal coupling between branches A, B, C and D that is typical of the class of coupling networks known as circulators. This characteristic will now be examined with reference to Fig. 7 in which guides 31—51 and 32—52 are schematically represented. The shifts of energy between the guides for the in-phase and out-of-phase normal mode in each direction of propagation are indicated by the arrows 71 through 76. Broken line arrows 71, 72, 76 and 77 represent that transfer of energy between the guides in the indicated directions, being those directions determined by the normal mode syntax in which energy is initially applied to the guide having the smaller phase constant and is shifted into the guide having the larger phase constant, is made in the out-of-phase normal mode. The solid line arrows 73, 74, 75 and 78 represent that transfer of energy between the guides in the indicated directions, being those directions in which the normal mode shift is from the guide of the higher phase constant into the guide of the lower phase constant, is made in the in-phase normal mode.

Thus, if a microwave signal is applied to branch A of guide 31, one half of it will be transferred in-phase into guide 32 as indicated by arrow 74. Between sections $b-b$ and $c-c$ the remaining portion of energy will be transferred from guide 51 into guide 52 in-phase as indicated by arrow 78. Therefore, the two portions of the energy in guide 52 at branch B thereof will be in-phase and will combine. No energy will appear at branch D of guide 51 since the voltage in the portion of the energy which came straight through guides 31 and 51 is out-of-phase with the voltage which was returned to guide 51 by way of the coupling represented by arrow 76. Substantially free transmission is, therefore, afforded from branch A to branch B.

Tracing the phase shifts of wave energy applied to branch B will show an in-phase transfer in the energy from guide 52 into guide 51, as indicated by arrow 75, and an in-phase transfer back to guide 32 from guide 31, as indicated by arrow 73, so that the two portions of energy are in-phase to combine at branch C of guide 32. The energy will not appear at branch A of guide 31 since the portion transferred from guide 32 to guide 31, as indicated by arrow 71, is out-of-phase with the energy which was transferred into guide 51, as indicated by arrow 75.

To a limited extent the structure of Fig. 5, as shown schematically in Fig. 7, is symmetrical so that the same coupling characteristic is found between branch C and branch D as was described between branch A and branch B. Likewise, the same coupling is experienced from branch D to branch A as was described above from branch B to branch C.

In all cases, it is to be understood that the above described arrangements are simply 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. A coupling device comprising a pair of electromagnetic wave guides, means for distributively coupling said guides along an interval of their lengths, said coupling versus distance along said interval defining a continuous function, gyromagnetic material extending in at least one of said guides longitudinally along at least a portion of said interval and asymmetrically located in the transverse cross section of said guide to modify the phase constant of said guide in said portion, and means for applying a transverse magnetic field to said

gyromagnetic material, the product of the strength of said field and the mass of said gyromagnetic material being tapered along said portion so that said guides have phase constants that are substantially equal at at least one point along said portion and substantially different along the major part of said portion.

2. A coupling device according to claim 1 wherein said product is zero in a center region of said coupling interval and maximum at at least one end of said coupling interval.

3. A coupling device according to claim 1 wherein said portion consists of substantially one-half of said coupling interval and wherein said product is zero at one end of said portion and maximum at the other end of said portion.

4. A coupling device according to claim 1 wherein said portion comprises substantially all of said coupling interval and wherein said product is zero at the center of said portion and is maximum at either end of said portion.

5. A coupling device according to claim 4 wherein said product is of opposite sign at said either end.

6. A coupling device comprising a pair of electromagnetic wave guides, means for distributively coupling said guides along an interval of their lengths, said coupling versus distance along said interval defining a continuous function, an element of gyromagnetic material asymmetrically located in the transverse cross section of at least one of said guides and extending within said guide longitudinally along at least a portion of said interval, and means for applying a magnetizing field to said element, the strength of said field tapering smoothly from a maximum at one longitudinal point to zero at another longitudinal point along said portion.

7. A coupling device in accordance with claim 6 wherein the strength of said field is zero at the center of said portion and tapers to maximum values of opposite polarities on either side of said center.

8. A coupling device according to claim 6 including a second element of gyromagnetic material in the other of said guides wherein said elements are located in opposite asymmetrical locations in the transverse cross sections of each of said guides.

9. A coupling device comprising a pair of electromagnetic wave guides, means for distributively coupling said guides along an interval of their lengths, said coupling versus distance along said interval defining a continuous function, a member of gyromagnetic material asymmetrically located in the transverse cross section of at least one of said guides and extending therein longitudinally along at least a portion of said interval, the mass of said member being tapered with distance along said interval from a minimum mass at the center of said coupling interval to a maximum mass at one end of said coupling interval, and means for applying a magnetizing field to said member along the length of said taper.

10. A coupling device in accordance with claim 9 including a second member of gyromagnetic material extending in said one guide along a second portion of said interval, the mass of said second member being tapered with distance along said interval from a minimum mass at the center of said coupling interval to a maximum mass at the other end of said coupling interval.

11. A coupling device in accordance with claim 10 wherein said members are located on respectively opposite sides of the longitudinal center line of said one guide.

12. A coupling device in accordance with claim 9 including a member of dielectric material located in the other of said guides, said dielectric member being tapered in mass along said interval relative to the taper of said gyromagnetic member to render the phase constant of said other guide substantially equal in each cross section along said portion to the phase constant of said one guide when magnetization of said gyromagnetic member is zero.

13. A coupling device comprising a pair of electromagnetic wave transmission lines, means for distributively coupling said lines along an interval of their length, said coupling versus distance along said interval defining a continuous function, said lines having phase constants that are equal to each other in the center of said interval and substantially different in the portions of said interval on either side of said center, said difference being of opposite senses respectively on either side of said center for at least one direction of propagation along said lines, said difference on at least one side of said center being of opposite sense for opposite directions of propagation along said lines.

14. A coupling device as recited in claim 13 wherein said difference on one side of said center is of the same sense for opposite directions of propagation along said lines.

15. A coupling device as recited in claim 13 wherein said difference is of the same sense on either side of said center for one direction of propagation along said lines.

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