

Aug. 9, 1960

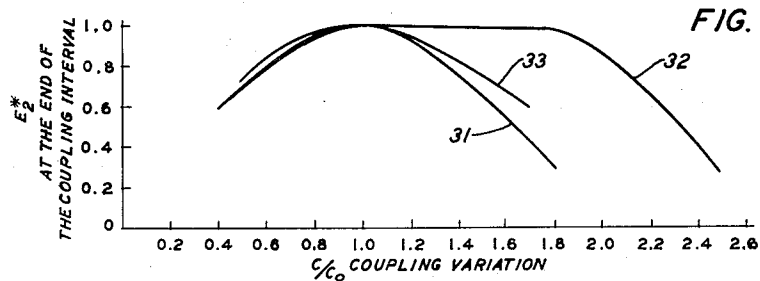
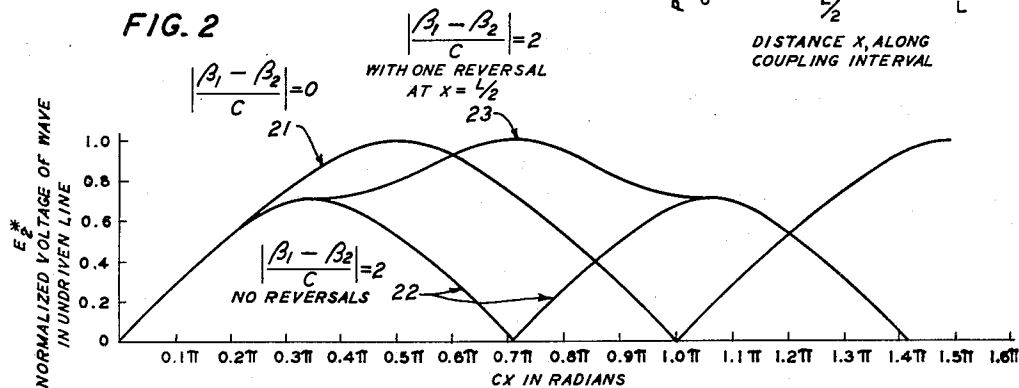
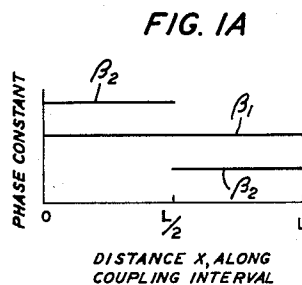
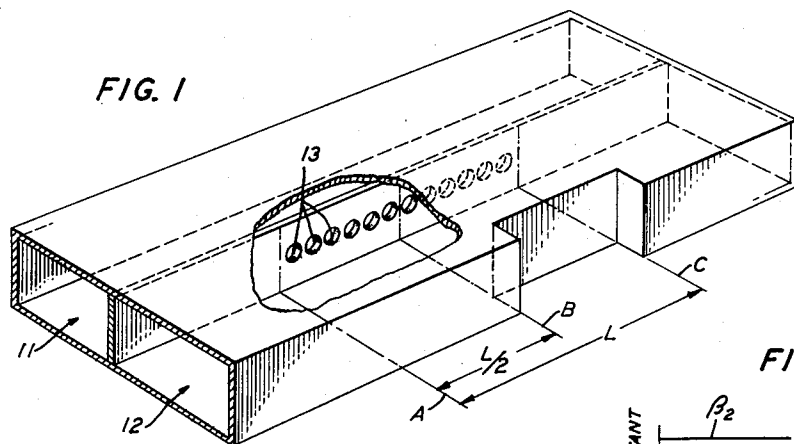
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2,948,864

BROAD-BAND ELECTROMAGNETIC WAVE COUPLER

Filed Oct. 2, 1957

4 Sheets-Sheet 1



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BROAD-BAND ELECTROMAGNETIC WAVE COUPLER

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FIG. 4

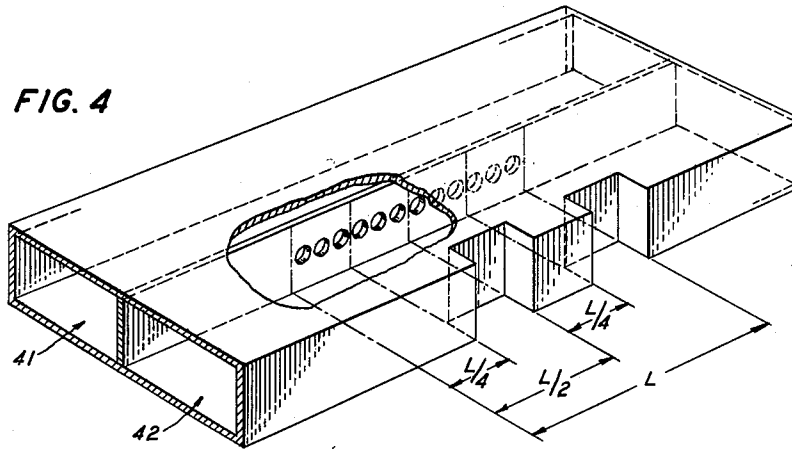
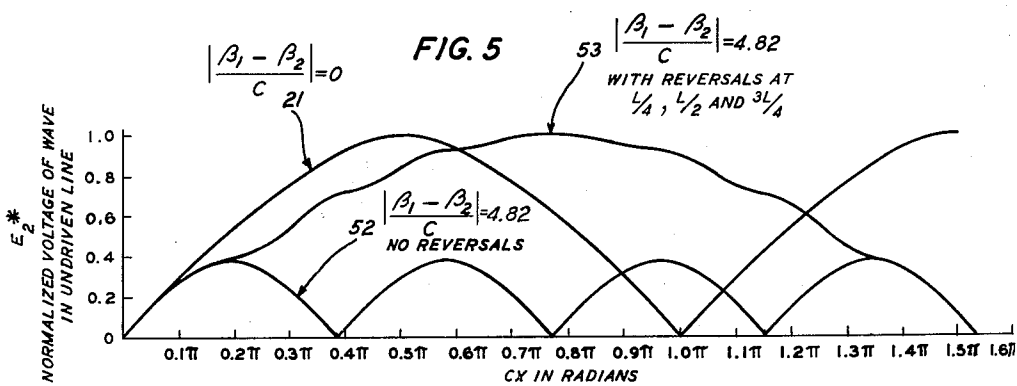
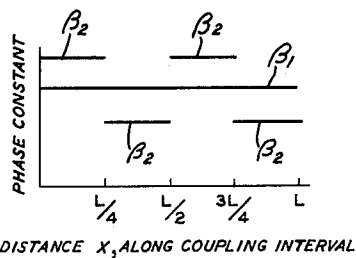


FIG. 4A



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FIG. 6

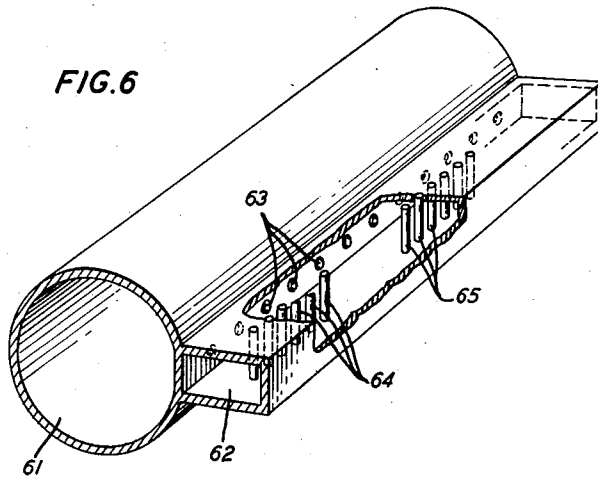


FIG. 7

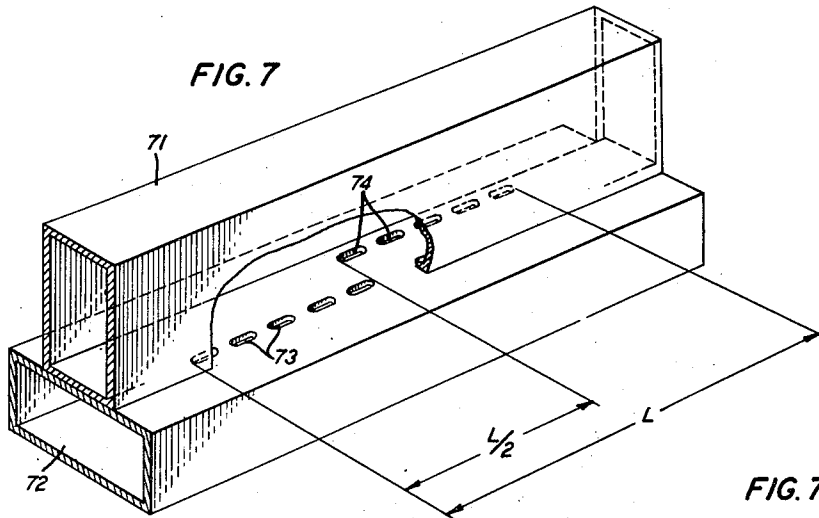
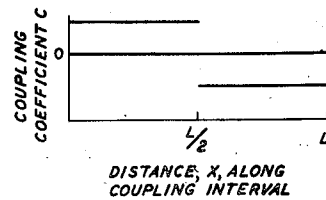


FIG. 7A



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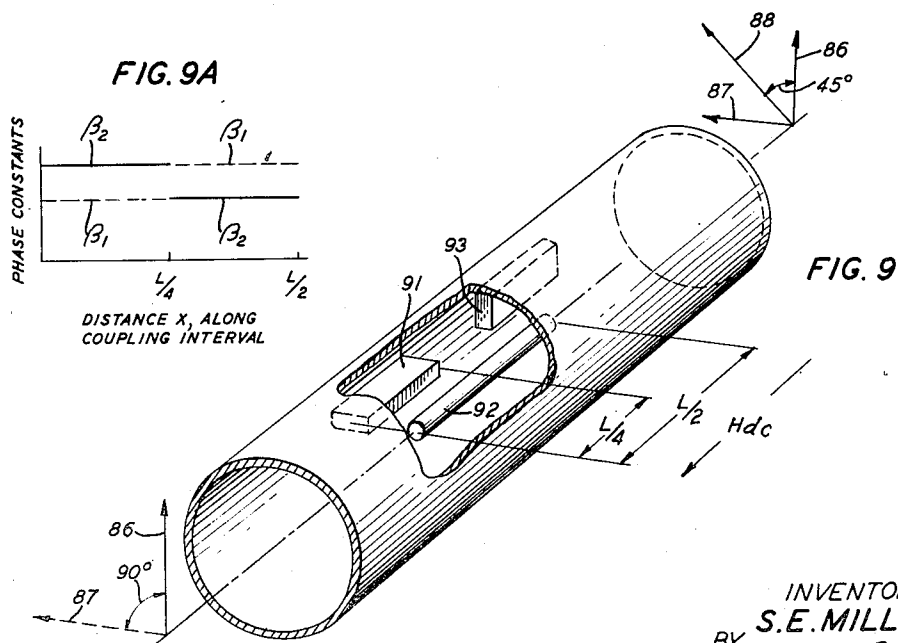
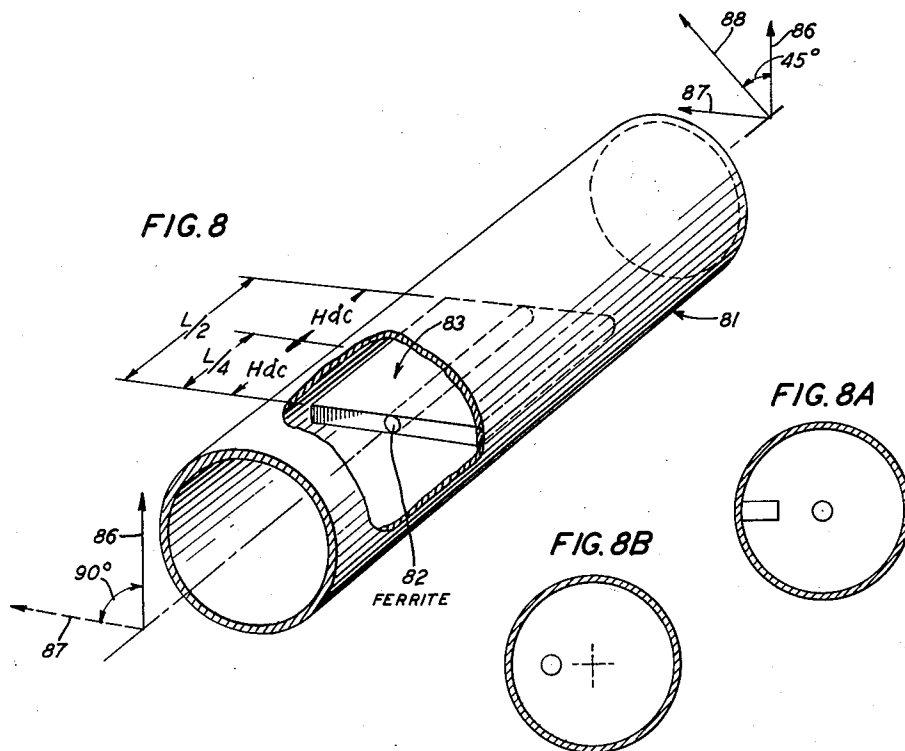
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4 Sheets-Sheet 4



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BROAD-BAND ELECTROMAGNETIC WAVE COUPLER

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Filed Oct. 2, 1957, Ser. No. 687,729

11 Claims. (Cl. 333—10)

This invention relates to means for coupling electromagnetic wave channels and more particularly for providing such coupling over a broad frequency band.

It is understood that "wave channels" may be considered to include not only physical wave guides but also distinct modes of electromagnetic wave propagation. Thus, not only may two physical wave guides carrying information bearing microwave signals be coupled together but so also may two different modes of electromagnetic wave energy propagated in the same physical wave guide be capable of carrying separate information in their respective modes and by analogy coupling may be accomplished therebetween.

It is often important in microwave systems to insure that the mechanism for coupling between the channels is substantially frequency insensitive over the band of interest so that energy and information is not lost as a result of providing the coupling. Numerous arrangements and devices have been developed in the art which satisfy this requirement with varying degrees of efficiency and with varying degrees of structural simplicity.

It is the primary object of this invention to provide uniform coupling between wave guiding channels over a broad frequency range in a physically simple structure.

The most common type of wave guiding channel in the microwave region is the hollow, metallic, sheath type guide. One of the common means for coupling between wave guides of this type is the directional coupler, well known in the art. It is a specific object of this invention to broadband the operation of wave guide directional couplers.

Another category of wave guiding channels, not as commonly considered as such, is the various modes or patterns of electromagnetic fields propagating wave energy. Thus, for example, in various types of ferrite devices, such as the Faraday rotator, nonreciprocal effects are produced on wave energy by virtue of differentially treating orthogonally polarized wave components in a manner such that energy is transferred from one component to the other to provide a different over-all resultant effect. This too, of course, is coupling between microwave channels. It is, therefore, an additional specific object of this invention to provide broad-band operation of ferrite devices.

In order to completely transfer the wave energy from a driven wave guiding channel to an undriven channel, it is well known in the art to equalize the phase constants of the two channels over the frequency band of interest. In my publication, "Coupled Wave Theory and Waveguide Applications," Bell System Technical Journal, volume 33, May 1954, it is demonstrated that for two channels having substantially equal attenuation constants, the maximum amount of power that can be transferred from a driven channel to an undriven channel depends upon the difference between the phase constants of the channels. As the phase constants become more and more unequal, the maximum amount of energy transferable decreases.

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More specifically, the maximum amount of energy transferable is a function of

$$\left| \frac{\beta_1 - \beta_2}{c} \right|$$

where β_1 is the phase constant of the driven channel, β_2 the phase constant of the undriven channel, and c is the coupling coefficient or coupling strength of the coupling mechanism between channels. Thus, if this ratio is 0 and the length of the coupling interval is appropriate, complete transfer of wave energy between channels is provided. If, on the other hand, the magnitude of this ratio equals the value 2, the maximum amount of power that can be transferred to the undriven line is only one-half the power that the driven line supports, i.e., 3 db division between the coupled channels.

Furthermore, the amount of energy transferred between the lines varies cyclically along the coupling interval and if the coupling interval is infinite the cyclical transfer of energy between the lines will continue on indefinitely with distance. Accordingly, for a given frequency, the length of the coupling interval will ascertain the division of power between the channels. Thus, in the case of

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 0$$

complete power transfer may be provided by having a coupling length equal to a value such that the coupling is terminated at the point whereat total transfer of energy has occurred; this is the distance equal to one-half the period of the cyclical transfer of energy. If, however, 3 db division is desired, the coupling length would accordingly be made one-quarter the period of cyclical transfer of energy.

In the case of

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 2$$

wherein the maximum transfer of energy is one-half, the cyclical transfer of energy varies as a rectified sine function from 0, to $\frac{1}{2}$, and then back to 0 to complete a cycle. Thus, in this arrangement, a coupling length equal to one-half the period would result in a one-half division of power rather than complete transfer; in order to have a transfer of one-quarter of the power to the undriven line, the interval would accordingly be one-quarter that of the cyclical period.

It can be seen that for a fixed coupling interval a variation in frequency will change the designed amount of energy to be transferred. Since, as is well known in the art, the phase constants of microwave channels and the coupling coefficient therebetween are frequency dependent parameters, it is apparent that the magnitude of

$$\frac{\beta_1 - \beta_2}{c}$$

will change with frequency and thus the length of the coupling interval appropriate to provide a given amount of energy transfer for the former frequency will be at the wrong point in the cycle for the new frequency; in addition, the total amount of energy subject to transfer is changed.

The frequency dependence thus inherent in coupling between channels has been substantially overcome in accordance with the invention. Since, as will be seen in more detail below, the frequency dependence is a function of the rate of change of power transferred to the driven line with distance, a means for making this rate of change more gradual, i.e., decreasing the slope of the cyclical transfer of energy curve, will result in less frequency sensitivity and thus broadbanding of the coupling mech-

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anism. Consequently, if the curve is flattened out, a change in frequency will result in a transfer of energy which is substantially the same as at the previous frequency, or at least the magnitude of the transferred energy will change by a much smaller amount than in the case of the arrangement where the rate of change of transferred energy versus distance was greater.

Consider an arrangement wherein it is desired to transfer all of the power from the driven to the undriven line. Ordinarily the device would have to satisfy the condition

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 0$$

However, in accordance with the invention, the coupling arrangement is instead made such that

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 2$$

for half the distance along the coupling interval and the same value is utilized for the second half of the distance along the coupling interval except that the sense of the coupling coefficient is reversed, or alternatively the sense of the difference between β_1 and β_2 is reversed, i.e., the sign of

$$\left(\frac{\beta_1 - \beta_2}{c} \right)$$

is reversed. This effectively results in having two 3 db couplers in tandem. Because of the reversal in sense of either of the two above-mentioned parameters the energy from the driven line is completely transferred to the undriven line. This may be understood by considering the fact that at the end of the first 3 db section, the vector relationship of the electromagnetic fields which had been reinforcing up until that point in the undriven line and which would ordinarily switch to an interfering relationship at that point, continues to reinforce by virtue of the fact that either the coupling sense or the sense of $(\beta_1 - \beta_2)$ is reversed. As a consequence, rather than having the energy which was transferred to the undriven line during the first half of the coupling interval return back to the driven line, this energy remains in the undriven line and the other half of the energy from the driven line proceeds also to transfer to the undriven line. The coupling length in such an arrangement would of necessity be longer for a complete transfer than for a situation wherein

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 0$$

(i.e., the ordinary situation for complete transfer) assuming the same value for c . However, this arrangement results in a flattening of the transferred energy versus coupling distance curve and as a consequence a change in frequency will effect the amount of energy transfer much less than would otherwise be the case.

The invention is by no means restricted to providing complete energy transfer but can provide 3 db division, or any other power division desired, by appropriately fixing the length of the coupling interval. In general, the greater the number of reversals provided in c or $(\beta_1 - \beta_2)$ along the coupling interval, the more gradual the slope of the transfer energy curve and accordingly the less frequency sensitive will be the coupling device. It is to be understood, as will be more fully explained below, that the significant factors providing frequency independence in accordance with the invention are the reversals in the sense of these parameters and not in the specific magnitude of

$$\frac{\beta_1 - \beta_2}{c}$$

In accordance with certain embodiments of the invention, reversals are provided with respect to the sense of $(\beta_1 - \beta_2)$. Thus, in coupled wave guides wherein the driven line initially has a value β_1 greater than β_2 of the

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undriven line, the reversal is accomplished by making β_1 of the driven line smaller than β_2 . This can be provided by abruptly constricting the transverse dimension of one wave guide so as to change the value of its phase constant relative to that of the other wave guide, or by properly loading the wave guide with dielectric material or periodic reactances to accomplish the same purpose. Where the wave channels are modes of wave energy propagation, the reversal of the sense of the phase constant difference may be accomplished by presenting an element of dielectric material to one mode which does not effect the other mode because of its particular electromagnetic field configuration. Although the sign of $(\beta_1 - \beta_2)$ is thus changed, the magnitude of this quantity remains constant along the entire coupling interval in accordance with the invention.

Other embodiments of the invention utilize reversals in the sense of coupling coefficient c . Thus, where the wave channels are coupled modes as in a Faraday rotator, the reversal is accomplished by reversing the polarity of the magnetic field biasing the ferrite element. Where the wave channels are hollow pipe wave guides, this may be accomplished by coupling in one region to field components in the driven guide having a given polarity and then abruptly discontinuing that coupling and reestablishing the coupling to field components in the driven line having an opposite polarity. However, the magnitude of c remains constant over the entire coupling interval.

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

In the drawings:

Fig. 1 is a perspective view of two coupled rectangular wave guides arranged to provide complete energy transfer;

Fig. 1A presents illustrative curves showing the relationship between the phase constants of the guides of Fig. 1;

Fig. 2, given for purposes of illustration, presents curves exemplifying the difference between the transferred energy versus coupling distance characteristic of a directional coupler in accordance with the invention and that of the prior art;

Fig. 3 presents illustrative curves demonstrating the improvement in the broad-band characteristics provided by the invention;

Fig. 4 is a perspective view of two coupled wave guides wherein two reversals in the sense of phase constant difference are utilized;

Fig. 4A is a graphical representation for purposes of illustration of the phase constant relationship between the wave guides of the embodiment of Fig. 4;

Fig. 5 is a graphical representation of the improvement in performance provided by the embodiment of Fig. 4;

Fig. 6 is a perspective view of a rectangular wave guide coupled to a circular wave guide in accordance with the invention;

Fig. 7 is a perspective view of two coupled rectangular wave guides wherein the sense of the coupling coefficient is reversed along the coupling interval;

Fig. 7A is a graphical illustration of the coupling coefficient variation of the directional coupler of Fig. 7;

Fig. 8 is a perspective view of a Faraday rotator in accordance with the invention wherein the sense of the coupling coefficient is reversed;

Figs. 8A and 8B are transverse cross sectional views of modifications of the Faraday rotator of Fig. 8;

Fig. 9 is a perspective view of a Faraday rotator in accordance with the invention utilizing a reversal in the sense of the phase constant difference; and

Fig. 9A is a graphical illustration of the phase constant relationship of the two wave channel modes supported in the embodiment of Fig. 9.

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In more detail, Fig. 1 represents an example, for purposes of illustration, of a directional coupler in accordance with the invention wherein complete transfer of wave energy occurs between two wave guides over a broad frequency range. Wave guide 11, which is the driven line, i.e., has energy applied to it at its input, is of the hollow, metallic, sheath type having a rectangular cross section whose wide dimension is proportioned to support solely the dominant mode of wave energy propagation in the operating frequency band. The wide dimension of guide 11 determines its phase constant β_1 . Disposed parallel to guide 11 is rectangular wave guide 12 which is the undriven line in this illustrative example. Guide 12 is disposed relative to guide 11 such that they share a narrow wall in common. A series of circular apertures 13 through the common narrow wall extends longitudinally along said wall for the purpose of providing communication between the two guides. This series of apertures 13 provides distributed coupling, as is obvious to one skilled in the art, between the two guides along the longitudinal extent of series 13. Imaginary planes A and C, transverse to the longitudinal axis of the guides, define the left hand and right hand extremities of the coupling interval, respectively. This length is designated L. Throughout the discussion, L designates the coupling distance, x, required to provide complete power transfer, L/2 the distance needed for equal division, L/4 for one-quarter power transfer, etc. Thus a 3 db coupler would have a coupling length of

$$x = \frac{L}{2}$$

Imaginary plane B, parallel to planes A and C, is located midway between planes A and C at a distance

$$x = \frac{L}{2}$$

from plane A. In the region of guide 12 between A and B, the width of guide 12 and thus its phase constant β_2 is greater than that of guide 11 in the same region. In the region between B and C the width of guide 12 and its phase constant β_2 is smaller than that of guide 11. This is accomplished by abruptly constricting the width of guide 12 in the form of an abrupt corrugation. In both regions, however, the two widths are proportioned such that solely the dominant mode of wave energy in the rectangular guide may be supported. The relationship of the phase constants of the two guides is graphically represented in Fig. 1A. It may be noted that the phase constant β_1 of guide 11 remains constant along the coupling interval for the entire distance L. The phase constant β_2 of guide 12 is greater in value in the region of the coupling interval defined by the distance from A to B, and is thus represented above the curve β_1 . From B to C, however, β_2 abruptly diminishes in value and is represented as a curve below that of β_1 . It may be noted that there is a sharp discontinuity of the β_2 curve at the point

$$x = \frac{L}{2}$$

Furthermore, it may be noted that the distance of β_2 above β_1 in the A to B region is equal to the distance of β_2 below β_1 in the B to C region. As a consequence, the magnitude of $(\beta_1 - \beta_2)$ is constant along the entire coupling interval but the sign of this parameter is reversed at

$$x = \frac{L}{2}$$

The dimensions of coupling apertures 13 are selectively chosen for the frequency at the middle of the operating

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band of the directional coupler jointly with the values of β_1 and β_2 , such that

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 2$$

In order to comprehend the operation of the device of Fig. 1 reference should properly be had to Fig. 2. As disclosed in my above-mentioned publication the variation of wave amplitude in an undriven line of a directional coupler, wherein the attenuation constants of the two lines are substantially equal and the phase constants differ by any amount or not at all, may be represented by the relationship

$$E_2^* = \left[\frac{(\beta_1 - \beta_2)^2}{4c^2} + 1 \right]^{-\frac{1}{2}} i \sin \left[\frac{(\beta_1 - \beta_2)^2}{4c^2} + 1 \right]^{\frac{1}{2}} cx \quad (1)$$

where E_2^* is the normalized voltage of the wave in the undriven line such that when all the energy from the driven line is transferred to the undriven line the voltage of the wave in the undriven line is equal to unity, x is the distance along the coupling interval, and c is the coupling coefficient of the directional coupler whose magnitude is a function both of the dimensions of the coupling apertures and frequency. Based upon this equation, curve 21 of Fig. 2 represents the plot of E_2^* versus the integrated coupling strength cx, for the case where the phase constants of the driven and undriven lines are equal. It may be noted that when these phase constants are equal, complete transfer from the driven line to the undriven line is possible, and this maximum occurs for curve 21 at $cx = .5\pi$. If the coupling interval is extended beyond this point, the energy commences to decrease in the undriven line by virtue of its retransfer to the driven line up to the point $cx = \pi$, whereat a complete retransfer to the driven line is accomplished. It may be noted that this transfer occurs cyclically. For the case where the phase constants β_1 and β_2 of the two lines are unequal, we see from Equation 1 that it is impossible, without more, to provide a complete transfer from the driven line to the undriven line (a necessary condition for $E_2^* = 1$, is $\beta_1 - \beta_2 = 0$). Thus, for example, curve 22 represents a case where

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 2$$

and wherein the sign associated with this quantity remains the same over the entire coupling interval. It may be seen that in this situation the maximum value of E_2^* is .707 and thus such a coupling arrangement would provide a maximum of 3 db power division between the driven and undriven line. It may be noted that this maximum value occurs at a different point along the cx axis than does the maximum value of curve 21 and that the period of the cycle of curve 22 is smaller than that of curve 21. The maximum points and the periods for different values of phase constant difference and coupling coefficient are readily determined from Equation 1 and are, respectively,

$$\text{Maxima at } cx = \pi \left[\frac{(\beta_1 - \beta_2)^2}{4c^2} + 1 \right]^{-\frac{1}{2}} \quad (2)$$

$$\text{Periods at } cx = \frac{\pi}{2} \left[\frac{(\beta_1 - \beta_2)^2}{4c^2} + 1 \right]^{-\frac{1}{2}} \quad (3)$$

Since in Fig. 1,

$$\left| \frac{\beta_1 - \beta_2}{c} \right|$$

is made equal to 2, one would ordinarily expect that complete transfer of energy is impossible on the basis of the description provided by curve 22 of Fig. 2. However, in accordance with the invention, the sense of the phase constant difference is reversed at the middle of the coupling interval. The first half of the coupling

interval corresponds to a distance in Fig. 2 of $.354\pi$ along the cx axis which provides the maximum point of curve 22 in the first cycle. Ordinarily then one would expect in Fig. 1, retransfer of energy from line 12 to line 11 commencing at

$$x = \frac{L}{2}$$

However, because the sense of the phase constant difference is reversed by virtue of the abrupt constriction in the wide dimension of guide 12, the vector relationship of the electromagnetic fields beyond the middle of the coupling interval is the opposite from what it would ordinarily be without the reversal. Accordingly rather than having a retransfer of energy, the remaining half of the energy in guide 11 continues to be transferred into guide 12. Thus, curve 23 of Fig. 2 demonstrates the coupling effect of the directional coupler when

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 2$$

with one reversal at

$$x = \frac{L}{2}$$

i.e., at the midpoint of the coupling interval of Fig. 1. Comparison of curves 21 and 23 demonstrates that the slope of the E_2^* versus cx curve is on the average more gradual over the entire coupling interval for curve 23 than for curve 21. A concomitant effect of course is that the coupling length for complete power transfer in curve 23 is greater than that for curve 21, assuming that the coupling coefficient is the same.

As a consequence of this more gradual slope, a change in frequency would have a smaller effect on the transfer characteristics of a coupler built in accordance with the parameters of curve 23 than one built in accordance with curve 21. This is readily understandable since with a change in frequency there is a change in the phase constants and coupling coefficient of the directional coupler. Thus, the fixed coupling length of a coupler in accordance with curve 21 would not coincide with the maximum point of the curve and would thus fall at some other point in the cycle wherein some value less than total transfer would result. Furthermore, the maximum of the curve at the changed frequency would be of a different magnitude than that of curve 21. This would also be true of a coupler in accordance with curve 23, except that it would require a much greater change in frequency to produce as much of a change in the transfer effect than would be the case for the coupler of curve 21 by virtue of the more gradual slope of curve 23.

The broad-banding effect thus provided by the coupler of Fig. 1 is dramatically demonstrated in Fig. 3 which represents a graph of the wave amplitude in undriven guide 12 (at the end of the coupling interval) versus coupling variation. The coupling variation axis is represented as

$$\frac{c}{c_0}$$

wherein c_0 is the coupling coefficient for the directional coupler at the midband frequency, while c is the coupling coefficient at any frequency under investigation. Thus, as frequency is changed in the driven line, c will vary relative to c_0 and thus the abscissa of Fig. 3 represents frequency variation. However, since c is inversely related to frequency (and nonlinearly), as the ratio

$$\frac{c}{c_0}$$

increases, frequency decreases to the right.

Curve 31 accordingly represents the frequency response of a directional coupler wherein

$$\frac{\beta_1 - \beta_2}{c} = 0$$

Curve 32 represents the frequency response of the directional coupler of Fig. 1. Comparison of the two curves demonstrates the much greater frequency insensitivity of the directional coupler in accordance with the invention. Curve 33, which also demonstrates greater frequency insensitivity than that of curve 31 will be discussed in greater detail below wherein it is demonstrated that it is the reversal along the coupling interval that is fundamentally responsible for broad-banding and not the specific phase constant relationship.

Turning now to Fig. 4, there is therein represented a directional coupler in many ways similar to that of Fig. 1; however, the coupling interval L is somewhat longer and the difference between the phase constants of the two lines is reversed at three separate points corresponding to

$$\frac{L}{4}, \frac{L}{2} \text{ and } \frac{3L}{4}$$

Similarly the directional coupler of Fig. 4 provides for complete transfer from the driven wave guide 41 to the undriven periodically constructed guide 42. Fig. 4A graphically demonstrates the phase constant relationship of these two guides. In this arrangement, however,

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 4.82$$

and because of the additional reversals in the phase constant difference provides even greater broad-banding than did the coupler of Fig. 1. Phase constant reversals occur at equally spaced points along the coupling interval such that one-quarter of the power is transferred to the driven line by the time the first reversal is reached, one-half is transferred by the time the second reversal is reached, three-quarters is transferred by the time the third reversal is reached, and all the power is transferred at the end of the coupling interval.

How this arrangement broad-bands the coupler may be visualized from Fig. 5. In Fig. 5 curve 21 is the same as curve 21 of Fig. 2 showing the energy transfer characteristic for equal phase constants without reversals in order to achieve complete power transfer. Curve 52 demonstrates the transfer characteristic of a directional coupler which can provide a maximum of one-quarter transfer of wave energy to the undriven line, i.e.,

$$\frac{\beta_1 - \beta_2}{c} = 4.82$$

with no reversals in phase constant. The coupler of Fig. 4 utilizes this characteristic in providing the broad-banding effect. Thus the first reversal in the coupler of Fig. 4 occurs at the point of the first maximum of curve 52. The second reversal in the coupler occurs at the end of the first cyclical period of curve 52 and the third reversal occurs at the second maximum of curve 52. As a consequence, the transfer characteristic of the coupler is represented by curve 53. It may be noted that the slope of this transfer characteristic is much more gradual than that of curve 21, the case of no reversals, and indeed is more gradual than the transfer characteristic of the directional coupler which utilizes solely one reversal as represented by curve 23 of Fig. 2. As a consequence, this arrangement is less frequency sensitive than the prior art device and also the coupler utilizing a single reversal. One may in general extrapolate this information and formulate the general proposition that the more reversals provided the more gradual will be the slope of the transfer characteristic and thus the

broadband the device. From Equations 1 through 3 expressions may readily be determined for the optimum values of

$$\frac{\beta_1 - \beta_2}{c}$$

and the coupling distance

$$\frac{L}{n}$$

between reversals, for couplers using any number of reversals. These values are:

$$\frac{\beta_1 - \beta_2}{c} = 2 \left[\frac{\left(\sin \frac{90^\circ}{n} \right)^2 - 1}{\left(\sin \frac{90^\circ}{n} \right)^2} \right]^{\frac{1}{2}} \quad (4)$$

where n is the number of sections into which the coupling region L is divided, while $(n-1)$ is the number of reversals in phase constant difference along the coupler (or reversals in sign of coupling coefficient as will be seen hereinafter); and

$$c \left(\frac{L}{n} \right) = \frac{\pi}{2} \sin \frac{90^\circ}{n} \quad (5)$$

Concomitant with the broadbanding produced, it may be demonstrated from Equation 5 (and visualized from Figs. 2 and 5) that for the same value of c an optimum complete power transfer coupler with $(n-1)=1$ would be 40 percent longer than a coupler having no reversals at all, while the arrangement for $(n-1)=3$ would be 53 percent longer than the arrangement of no reversals and 8 percent longer than for $(n-1)=1$.

Although we have thus far explicitly described directional couplers wherein complete transfer of power is provided, it is apparent that any division of power may be readily accomplished in accordance with the invention. Thus, if a 3 db coupler were desired, the coupler of Fig. 4 would serve the purpose by modifying it such that the coupling interval would be only one-half the length indicated therein. In this way the transfer characteristic of the 3 db coupler would be as represented in Fig. 5 along the interval from 0 to $.383\pi$. This results in a normalized voltage of .707 or a power division of 3 db. That this would also provide broadbanding for a 3 db directional coupler may be readily seen by comparing that portion of curve 53 with the portion of curve 22 of Fig. 2 from 0 to 3.54π which also provides for a 3 db division. In this way a directional coupler of any desired ratio of power division can be broadbanded.

Fig. 6 represents a directional coupler in accordance with the invention which is also a mode transducer. Wave guide 61 is a hollow metallic wave guide having a circular cross section. Rectangular wave guide 62 is disposed parallel to guide 61 with one of the narrow sides contiguous with a portion of the side of hollow guide 61. The contiguous faces of the guides are perforated by coupling apertures 63 extending in a longitudinal series along the contiguous portion. Guides 61 and 62 are proportioned so as to exclusively support the dominant mode wave energy in circular and rectangular guides, respectively. As is well known in the art, the phase constants of these two guides for these modes of propagation are different. Reference may be had to my United States Patent No. 2,748,350, issued May 29, 1956, for a detailed discussion of how to design directional couplers so that a mode of one type in one wave guide may be coupled exclusively to a different type of mode in the second wave guide. Along two portions of the coupling interval, guide 62 is loaded by two series of reactive posts, 64 and 65. Each of the metallic posts in these series is disposed parallel to the narrow dimension of guide 62 and extends from one wide wall thereof to the other with each post being spaced from the next succeeding post in that series by a distance of less than one-half

the guide wavelength at the operating frequency. The first series of posts 64 extends longitudinally along guide 62 over the first quarter of the coupling interval while the second series of posts 65 extends longitudinally over the third quarter of the coupling interval. Effectively, series 64 and 65 of reactive components serve to change the phase constant of guide 62 in the two regions wherein they are located, as is well known in the art. Effectively, therefore, this loading serves the same function of changing the phase constant relationship between the wave guides as did the constrictions in the transverse dimension of guide 42 of Fig. 4. Similarly, the phase constant difference between the two guides including the reversal in sense thereof is the same as represented in the graphical illustration of Fig. 4A. In all essentials then Fig. 6 serves as a directional coupler providing for a complete transfer of wave energy between a driven and undriven line as did the embodiment of Fig. 4 and similarly provides the same broadbanding characteristic to this type of operation.

Various other means for changing the phase constant in a wave guide may be utilized in accordance with the invention rather than the corrugations or post-loading thus far described. It is well known in the art that a slab of dielectric material in a wave guide will have this same effect as will also dielectric posts properly spaced. These and various other phase changing means may be utilized in any of the embodiments of the invention thus far described.

We have discussed embodiments wherein the reversal of the sense of the phase constant difference between the channels has been utilized for broadbanding purposes. The same effect, however, can be achieved by reversing the sense of the coupling coefficient in lieu of the phase constant difference; Figs. 7 through 8B disclose such arrangements.

Considering Fig. 7 in greater detail, there is disclosed two rectangular cross sectioned hollow pipe wave guides 71 and 72 disposed parallel to each other with a narrow wall of guide 71 contiguous to a portion of the wide wall of the other guide 72. Disposed in this common contiguous region are two series of rectangular coupling apertures 73 and 74 for communication between the two guides. The dimensions of guides 71 and 72 and the apertures in series 73 and 74 are proportioned such that

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 2$$

One series of rectangular apertures 73 is displaced on one side of the common center line of the common contiguous wall portion. The second series of apertures 74 commences in a longitudinal direction where series 73 ends, but is displaced from the common center line on the opposite side thereof from series 73. As is well known in the art the dominant mode of wave energy in rectangular wave guides has a magnetic field pattern which may be represented as a plurality of rectangularly shaped loops, the planes of which loops lie parallel to the wide wall of the guide. Thus the polarity of the magnetic lines of force on one side of the center line will be opposite in sense to the polarity of the magnetic lines of force on the other side of the center line. It may be seen, therefore, that relative to guide 72, coupling apertures 73 couple to magnetic lines of force which are of opposite sense to the magnetic lines of force to which the series of apertures 74 will be coupled. The individual coupling apertures, rectangular in shape, have a narrow dimension very small compared to a guide wavelength and thus will not couple to the transverse components of the magnetic loops but solely to the longitudinally extending components. It may be seen, therefore, that over the coupling interval L , which commences at the left hand end of series 73 and terminates at the right hand end of series 74, the sense of the magnetic components that are coupled is reversed midway along the coupling interval, i.e., where series 73 terminates and

series 74 commences. In this manner, therefore, the sense of the coupling coefficient, which may be noted remains constant in magnitude, reverses in sense. This is portrayed graphically in Fig. 7A wherein the coupling coefficient of the guide in the region along series 73 is represented by the curve above the axis while the coupling coefficient for series 74 is represented below the axis. With this directional coupler proportioned to provide complete transfer from the driven line to the undriven line, one-half of the energy is transferred by virtue of the series 73 while the second half is transferred by virtue of the series of apertures 74. The second half of the power is transferred in an analogous way to that of Fig. 1 as represented by curve 23 of Fig. 2. Thus, at the point of 3 db power transfer, the vector relationships in the two guides rather than interfering in the undriven channel reinforce by virtue of the reversal of the coupling sense, while in the coupler of Fig. 1 this was achieved by virtue of the reversal in the sense of the phase constant difference. The broad-banding effect, however, is identical. The frequency response of the directional coupler of Fig. 7 is thus the same as the frequency response represented by curve 32 of Fig. 3 which heretofore was considered to represent the response characteristic of the directional coupler of Fig. 1.

Fig. 8 presents an illustrative embodiment wherein the reversal in sign of the coupling coefficient is also utilized. However, in Figs. 8 through 9 coupling is not provided between two separate physical wave guides but between two different wave modes or components. Fig. 8 is a Faraday rotator arranged in accordance with the invention. Disposed within circular metallic wave guide 81 is a ferrite pencil-like element 82 located along the center line of guide 81. Ferrite element 82 is of the type well known in the art wherein a linearly polarized wave propagated therethrough will have its plane of polarization rotated by an amount dependent upon the dimensions and magnetic saturation of the ferrite element and the strength of the magnetic biasing field applied to the element. Encasing and supporting element 82 in wave guide 81 is a slab 83 of dielectric material oriented horizontally, which is coextensive to element 82 in a longitudinal direction and extends across the diameter of guide 81 in a transverse direction. Ferrite element 82 is magnetically biased such that its magnetic polarity from its midpoint to one end is of opposite sense from its polarity from its midpoint to the other end (as indicated by the arrows labeled H_{dc} which represent a steady state magnetic biasing field). This opposing magnetic bias may be accomplished by cylindrical permanent magnets disposed about wave guide 81 in a manner well known in the art or oppositely wound solenoids (not shown).

The embodiment of Fig. 8 provides 45 degrees rotation of the plane of polarization and as will be demonstrated this constitutes a 3 db coupler. To the left of guide 81 at its input side there are represented two perpendicularly related vectors 86 and 87. Vertical vector 86 represents the plane polarized wave energy entering guide 81 and by analogy to the physical wave guide situation, this vector orientation constitutes the driven channel. Horizontal vector 87 constitutes the undriven channel and is represented as a dotted vector to indicate that no energy is applied in this plane of polarization at the input of the Faraday rotator. It may be seen therefore that channel 87 which is parallel to the dielectric slab 83 has a phase constant which is different from channel 86 oriented perpendicularly to dielectric slab 83. The phase constant difference between the driven and undriven channels is maintained constant along the entire coupling interval, i.e., along the entire length of the ferrite, by virtue of the constant geometry and dielectric constant of slab 83. As is well known in the art, coupling between channels 86 and 87 occurs by virtue of the precession of the electrons in the fer-

rite. Since this is effectively a 3 db coupler, i.e., 45-degree rotator, the relationship

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 4.82$$

obtains with solely one reversal in coupling coefficient occurring. The reversal in coupling coefficient is provided by the reversal in the biasing magnetic field which occurs at the midpoint as represented by the H_{dc} vectors. Thus, after one-quarter of the power in channel 86 has been transferred to channel 87 at the midpoint, the reversal in the sense of the coupling coefficient serves to continue the transfer of wave energy in the same direction until half the power has been transferred from channel 86 to channel 87 at which point the ferrite element and thus the coupling mechanism is terminated. The result of this coupling is demonstrated at the right hand output side of the Faraday rotator. Thus, it may be seen that vertical channel 86 now has one-half the power (.707 of the voltage magnitude) that it had at the input end of the rotator, and the undriven channel 87 now contains the other half of the power. The result of this, of course, is that we have two components of equal amplitude perpendicular to each other providing a resultant wave 88 having a plane of polarization at 45 degrees to each component. Thus, effectively, the transfer of 3 db from the driven channel to the undriven channel has resulted in a rotation of the plane of polarization by an angle of 45 degrees.

Other means may be utilized to provide a phase constant difference between orthogonally oriented channels 86 and 87. Thus, for example, in Fig. 8A a horizontally oriented slab of dielectric material extending from the guide wall partially into the guide along a diametral plane may be utilized in lieu of slab 83. In Fig. 8B the ferrite pencil is located off the center line in a horizontal direction to achieve a phase constant difference. By virtue of the fact that ferrite is a dielectric material, in addition to having gyromagnetic properties, it will effectively load horizontal channel 87 more than channel 86 and thus provide a phase constant difference therebetween. An off-center arrangement of the ferrite may also be used to provide a linear to circular polarization converter which is broad-band in its operation.

Fig. 9 represents a Faraday rotator similar to that of Fig. 8 wherein a reversal in the sense of the phase constant difference is provided rather than a reversal in the sense of the coupling coefficient as was done in Fig. 8. Utilizing the loading of Fig. 8A, a horizontal dielectric slab 91 extends into the guide coextensive with the first half of the ferrite element 92 while a second slab 93 extends into the wave guide in a vertical direction coextensive with the second half of ferrite 92. Thus, the first dielectric slab 91 serves to load channel 87 while the succeeding dielectric slab 93 serves to load channel 86. This loading arrangement is somewhat different from those which have heretofore been described in previous figures. Fig. 9A demonstrates the phase constant relationship of the two channels. It may be noted that unlike the phase constant characteristics represented in Figs. 1A and 4A wherein the phase constant of one guide remains constant and the phase constant of the other guide varies about this value, both the phase constants of the channels in Fig. 9 change abruptly. Nevertheless, the magnitude of the difference between the phase constants remains constant along the entire coupling interval.

In the discussion of all of the preceding embodiments, the optimum values of

$$\left| \frac{\beta_1 - \beta_2}{c} \right|$$

have been selected for the channel couplers (the optimum depending upon the number of reversals utilized and the division of power desired). It must be emphasized,

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however, that the broad-banding result may be considered as a separate function of the reversals in the sense of the phase constant difference or coupling coefficient removed from considerations of the optimum value of

$$\left| \frac{\beta_1 - \beta_2}{c} \right|$$

This may readily be demonstrated by taking an example of a situation wherein a reversal is provided but

$$\left| \frac{\beta_1 - \beta_2}{c} \right|$$

is not at its optimum value. Thus, for example, consider a directional coupler such as the type disclosed in Fig. 1 wherein complete power transfer is provided with one reversal in phase constant difference. As shown in Fig. 2 the optimum value is

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 2$$

However, let us suppose that rather than utilizing this optimum relationship we have

$$\left| \frac{\beta_1 - \beta_2}{c} \right| = 1$$

Curve 33 of Fig. 3 demonstrates the frequency response of such a device. It may be noted that although curve 33 is not as frequency insensitive as curve 32 which also utilizes a single reversal but optimum values, it is nevertheless more frequency insensitive than curve 31 wherein no reversal in coupling sense or phase constant difference is provided at all. We thus find that even with a 50 percent change from the optimum value of

$$\frac{\beta_1 - \beta_2}{c}$$

the frequency response of the coupling mechanism between the driven and undriven channels is measurably improved. Furthermore, with this arrangement a coupling length is required which is only approximately 3 percent longer than the length needed for a coupler having no reversals at all, assuming the same coupling coefficient.

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 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 an electromagnetic wave transmission system, a first communication channel having a phase constant β_1 , a second communication channel having a phase constant β_2 where β_2 is different than β_1 , means for distributively coupling between said first and second channels over a given length of said transmission system with a coupling coefficient c , $(\beta_1 - \beta_2)$ and c thereby being parameters of said system, and means for abruptly reversing the sense of one of said parameters at least once along said given length of distributive coupling with the absolute value of each of said parameters remaining constant over said given length, whereby coupling between said first and second channels is rendered uniform over a broad frequency band.

2. A combination as recited in claim 1 wherein $(\beta_1 - \beta_2)$ and c have finite absolute values along said length of distributive coupling.

3. First and second communication channels supportive of wave energy having unequal phase constants β_1 and β_2 , respectively, a plurality of directional coupling means having a coupling coefficient c arranged in tandem along said channels for communication between said channels,

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each of said coupling means being arranged to transfer a portion of wave energy from one of said channels to the other, the phase constant difference $(\beta_1 - \beta_2)$ of said channels and the coupling coefficient c of said coupling means being parameters effecting the frequency response of said coupling means, and means for making the sign of one of said parameters at each of said coupling means different from the sign of a like parameter at a next adjacent coupling means, with the magnitudes of each of said parameters remaining constant at all said coupling means.

4. In an electromagnetic wave transmission system, first and second wave channels having phase constants β_1 and β_2 , respectively, means for distributively coupling between said channels over a given common length of said channels with β_1 and β_2 having different values from each other along said length, and means for abruptly reversing the sense of the difference between said phase constants at least once along said length while maintaining the magnitude of said difference constant.

5. A combination as recited in claim 4 wherein said wave channels are hollow metallic wave guides sharing a common bounding surface, said coupling means comprises a longitudinally extending series of apertures in said common boundary and said phase constant difference reversing means comprises an abrupt constriction of the width of at least one of said wave guides.

6. A combination as recited in claim 5 wherein one of said wave guides has two said constrictions within the longitudinal interval defined by said series of apertures.

7. A combination as recited in claim 4 wherein said first channel comprises a hollow rectangular metallic wave guide, said second channel comprises a hollow circular metallic wave guide, said guides being disposed to share a common bounding surface along a common length, said coupling means comprising a longitudinally extending series of apertures in said common boundary along said length, and said phase constant difference reversing means comprising a longitudinally extending series of periodically spaced reactive components within one of said wave guides.

8. A combination as recited in claim 4 wherein said wave transmission system comprises a Faraday rotator, said first and second channels comprise first and second modes of electromagnetic wave energy supportable by said Faraday rotator with the electric vectors of said respective modes oriented perpendicularly to each other, said coupling means comprises a magnetically polarized element of gyromagnetic material in the path of both said modes, and said phase constant difference reversing means comprises a first dielectric vane oriented parallel to the electric vectors of said first mode along a distance coextensive with a portion of the length of said element and a second dielectric vane oriented perpendicular to said first vane along a distance coextensive with a different portion of the length of said element.

9. In an electromagnetic wave transmission system, first and second wave channels distributively coupled along a common length with a coupling coefficient c , said coupling coefficient c remaining constant in magnitude along said entire length and reversing in sign at least once along said length.

10. A combination as recited in claim 9, wherein said first and second channels comprise first and second rectangular hollow metallic wave guides oriented parallel to each other with a narrow wall of said first guide contiguous to a wide wall of said second guide, a first longitudinally extending series of coupling apertures through said contiguous walls disposed parallel with and displaced from the centerline of said wide wall, a second such series of apertures commencing its longitudinal extent in a region where said first series terminates its longitudinal extent but displaced from said centerline on the opposite side thereof from said first series, whereby the disposition of said first and second series on opposite

sides of said centerline provides a reversal in the sign of said coupling coefficient.

11. A combination as recited in claim 9 wherein said wave transmission system comprises a Faraday rotator and wherein the gyromagnetic element comprising the Faraday rotator is magnetically polarized in one sense over an interval of its length and is magnetically polarized in an opposite sense over a different interval of its

length whereby the sign of said coupling coefficient is reversed by virtue of the reversal in magnetic polarity.

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