

May 13, 1958

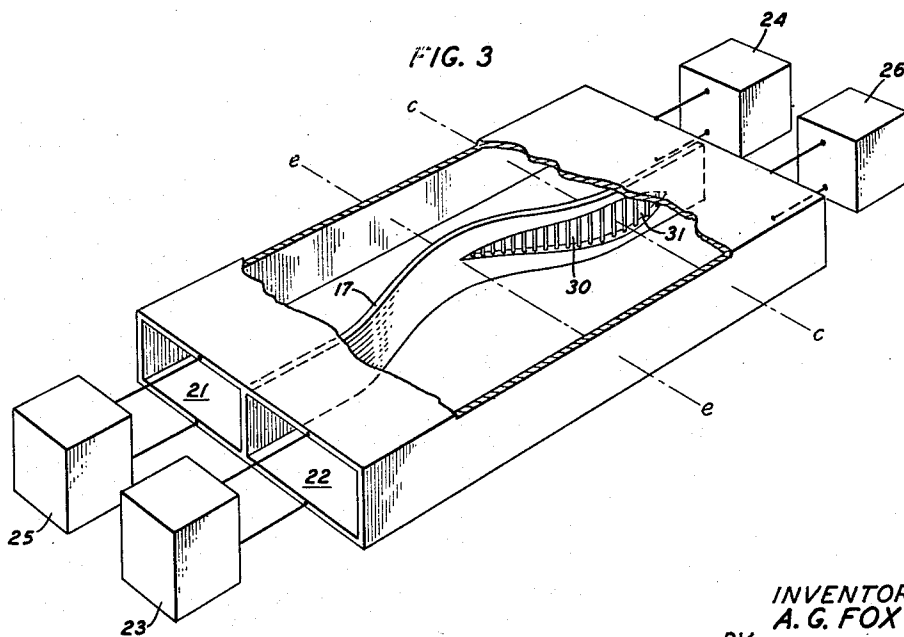
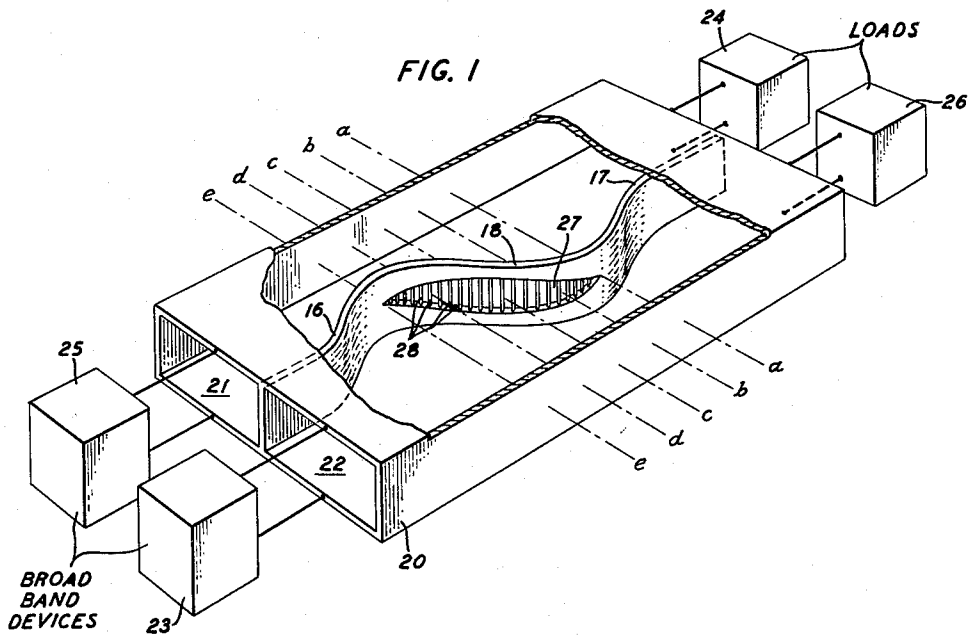
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2,834,944

BROAD BAND DIRECTIONAL COUPLERS

Filed Oct. 29, 1954

5 Sheets-Sheet 1



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FIG. 2A

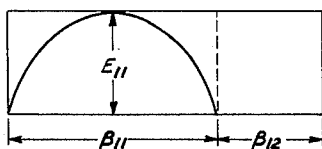


FIG. 2B

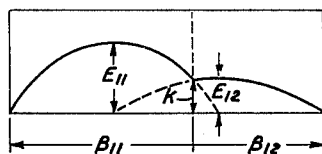


FIG. 2C

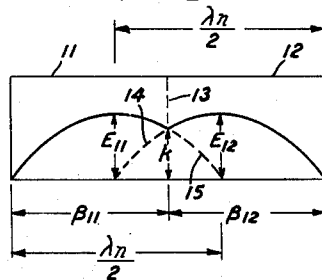


FIG. 2D

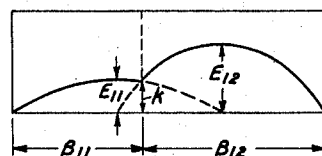


FIG. 2E

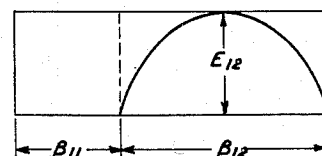


FIG. 4

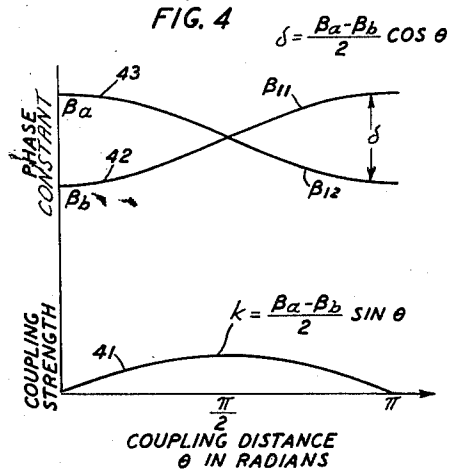
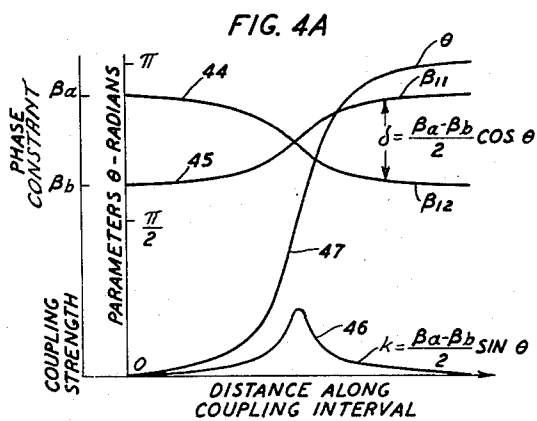


FIG. 4A



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FIG. 5

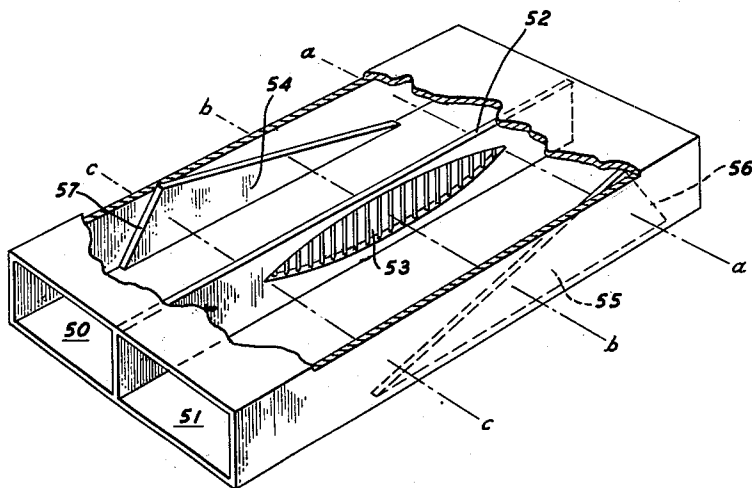
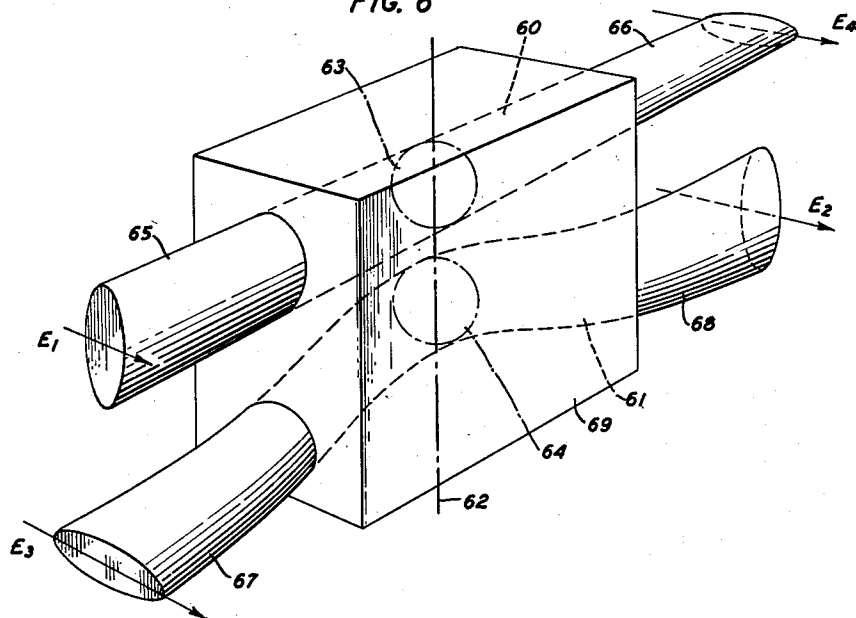


FIG. 6



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FIG. 7

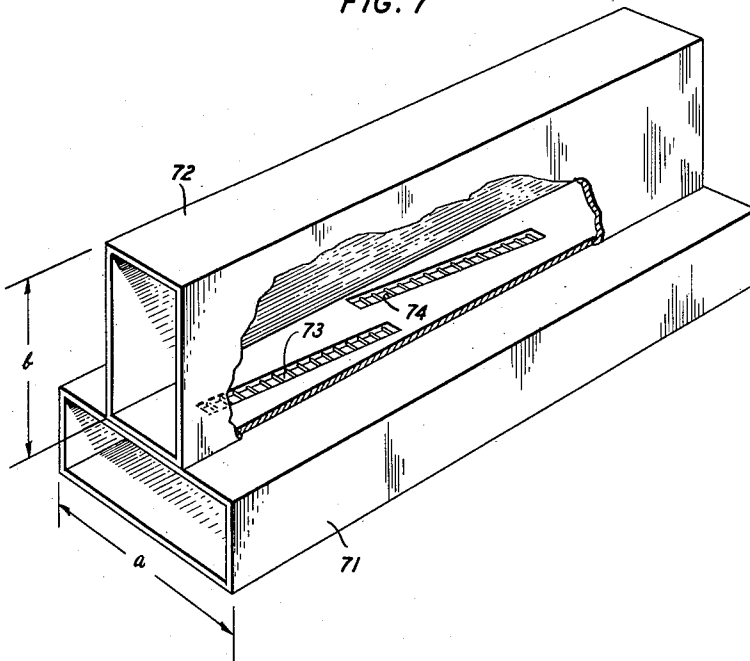
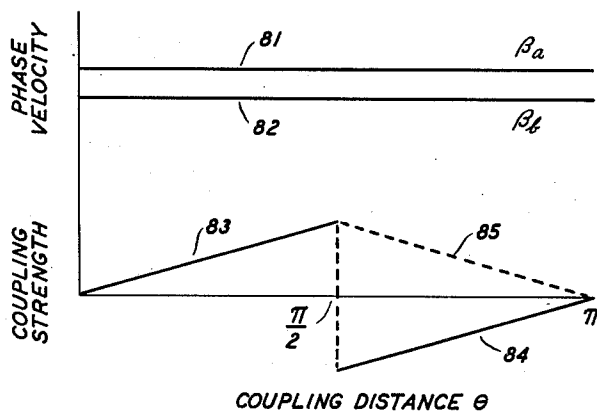


FIG. 8



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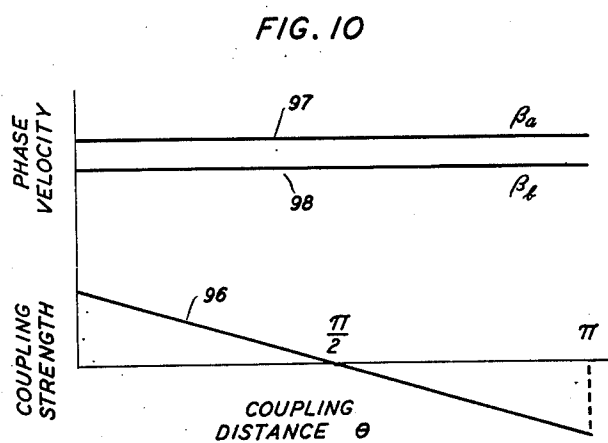
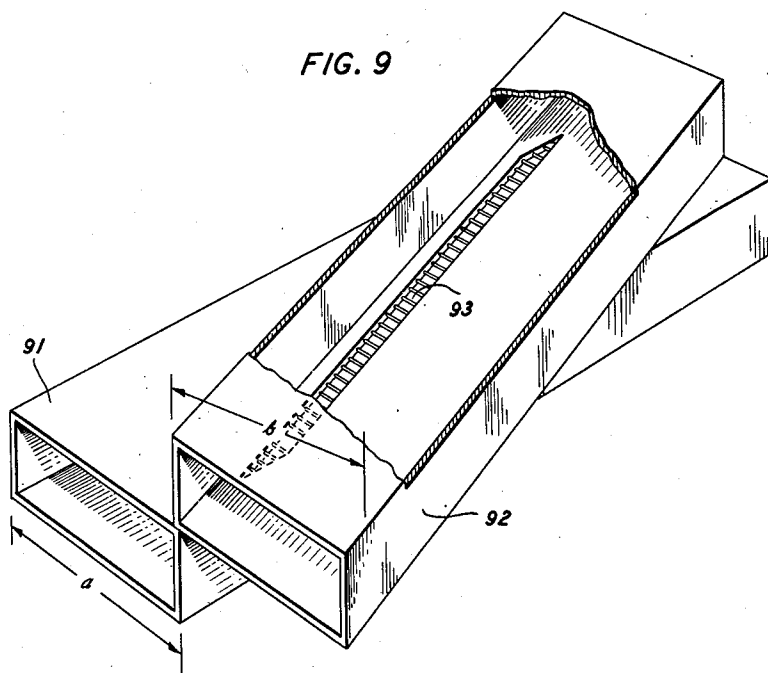
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BROAD BAND DIRECTIONAL COUPLERS

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5 Sheets-Sheet 5



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2,834,944

BROAD BAND DIRECTIONAL COUPLERS

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Application October 29, 1954, Serial No. 465,579

23 Claims. (Cl. 333—10)

This invention relates to very high frequency or microwave electrical transmission systems and, more particularly, to broad band coupled line systems for dividing electromagnetic wave energy, such as directional couplers and coupled line hybrids.

The directional coupler is a familiar component in high frequency and microwave transmission systems for which countless uses and applications have been described in the published art. In general, all presently known directional couplers are formed by a section of main transmission line coupled to a section of auxiliary line. The coupling between the two sections is arranged so that an electromagnetic wave traveling in a single direction in a given mode of propagation along the main line induces a principal secondary wave, known as the forward wave, traveling in a single direction in a given mode of propagation along the auxiliary line. Conversely, a wave traveling in the opposite direction in the main transmission line induces a principal secondary wave traveling in the opposite direction in the auxiliary line.

In most practical directional couplers there is also an induced or secondary wave, known as the backward wave, even when the terminals are match terminated, traveling in the opposite direction from the forward wave. The forward and the backward waves are desirably greatly unequal in strength. Their relative strength is called the directivity of the coupler. The relative strength of the desired induced forward wave in the auxiliary line to the inducing wave in the main line is hereinafter referred to as the transfer ratio. The performance of the directional coupler may be described in terms of this directivity and transfer ratio.

The art is now familiar with a very large number of couplers of different forms each of which was developed in an effort to decrease the frequency sensitivity of the coupler and to increase the operating bandwidth over which a given value of directivity and a given transfer ratio are maintained. With the possible exception of certain very specialized ones of these couplers, a limiting value of frequency selectivity is inherent in all of these couplers because they depend for their operation upon periodic reinforcement and cancellation of components from the main line in the auxiliary line.

It is therefore an object of the present invention to transfer substantially only a forward traveling wave from one transmission line into another, which transferred wave bears a constant ratio to the original wave over an extended frequency band.

It is a further object to increase the operating bandwidth of coupled line structures, such as directional couplers and hybrids.

In accordance with the present invention wave energy is launched and supported in the coupled transmission line system in a distribution which will be termed a "normal mode" of propagation and is transferred from

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one line into another by what is termed "normal mode tapering."

Before proceeding further with a detailed consideration of the present invention, the new concept involving normal modes of coupled transmission line propagation must be understood. This concept will not only make it clear why directional couplers of the prior art types are frequency selective but also why the couplers of the present invention are independent of frequency. In a coupled wave guide system a "normal mode" is defined as 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. Detailed consideration will be given hereinafter to the nature of each. For the moment it should be noted that one of these modes is designated the "in phase" mode, or the low phase velocity mode, since the two portions of the field intensity of the mode in each of the two coupled guides are in phase and propagate 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 phase velocity mode, since the two portions of its intensity are out of phase and propagate at a higher velocity than would a wave in either guide alone.

Applying this concept to a directional coupler of the prior art types, it may be shown that when wave energy is delivered to one of the wave guide terminals, both modes are equally excited. Since the two modes travel at unequal phase velocities along the length of the coupling interval, there will be subsequent regions in which the fields will be in phase in one guide and out of phase in the other and further regions in which this phase relation is reversed. This characteristic is the one exploited in the prior art couplers to obtain transfer of power from one guide into the other although the explanation given usually is taken from a different point of view. Since the distance between the regions of periodic interference and reinforcement is a function of the difference in phase velocities or the guide wavelengths of the energy, it is apparent why the prior art couplers are frequency sensitive.

In accordance with the present invention energy is excited in one normal mode only in a coupled system in which the parameters are chosen to support and propagate this single normal mode. The parameters are varied along the coupler, however, so that the portion of the energy of the normal mode carried in each guide is shifted from one guide into the other. In preferred embodiments of the invention the parameter representing a phase constant difference between the two coupled lines and the parameter representing the coupling coefficient therebetween are both tapered along the coupled system at inverse rates to each other. This results in a shift of energy traveling in the forward direction in one guide into energy traveling in the forward direction in the other guide that is theoretically unlimited in bandwidth. Since this shift is made over a length of several wavelengths, there is little tendency for any backward waves to be generated. Therefore the directivity of the coupler is high.

In other embodiments only the coupling coefficient is varied in a way that produces a reversal in sign of the coupling. This also results in a normal mode tapered

directional coupler of substantially increased bandwidth over the couplers of the prior art.

In the copending application of J. S. Cook, Serial No. 465,578, filed October 29, 1954, there is disclosed and claimed a normal mode coupler of which only the phase velocity difference is varied.

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

In the drawings:

Fig. 1 is a perspective view of a first principal embodiment of the invention showing a pair of wave guiding channels coupled with normal mode tapering produced by varying the relative phase constants and the coupling coefficients of the guides in accordance with the invention;

Figs. 2A through 2E, given by way of illustration, show the electric field distribution in several pairs of coupled wave guides and also represent the normal mode distribution in certain cross sections of the embodiment of Fig. 1;

Fig. 3 is a perspective view of a modification of the embodiment of Fig. 1;

Figs. 4 and 4A show the relative phase constants and the coupling coefficients along an interval of coupling in accordance with preferred adjustments of the embodiment of Fig. 1;

Fig. 5 is a perspective view of a second modification of the embodiment of Fig. 1;

Fig. 6 is a perspective view of an embodiment in which the principles of normal mode tapering are applied to a coupled system of all-dielectric wave guides;

Fig. 7 is a perspective view of a normal mode directional coupler in which only the coupling coefficient is varied along the coupling interval;

Fig. 8 shows the relative phase constants and the coupling coefficient along the interval of coupling in accordance with a preferred adjustment of the embodiment of Fig. 7;

Fig. 9 is a perspective view of a modification of the embodiment of Fig. 7; and

Fig. 10 shows the relative phase constants and the coupling coefficient along the interval of coupling in accordance with a preferred adjustment of the embodiment of Fig. 9.

Referring more specifically to Fig. 1, an illustrative embodiment of a normal mode coupler is shown which produces a shift in energy distribution of the normal mode by tapering the wider cross sectional dimensions of coupled, conductively bounded wave guides. As illustrated, this coupler comprises a section 20 of rectangular wave guide of the metallic shielded type having a wide internal cross sectional dimension which is substantially twice that of a conventional wave guide designed for wave energy in a similar frequency band, being therefore slightly larger than one free space wavelength of the energy to be conducted. The narrow cross sectional dimension is substantially one quarter of the wide dimension being equal to the narrow dimension of a conventional guide.

Extending longitudinally along the length of section 20 is a conductive divider 16—17—18 which divides guide 20 into two wave guiding channels 21 and 22. Divider 16—17—18 is serpentine in form with the portion 17 starting in substantially the center of the far end of guide 20 and tapering to the right so that in the cross section *a—*a** the wide dimension of channel 21 is substantially greater than the wide dimension of channel 22. Portion 18 tapers then toward the left until in section *c—*c** the wide cross sectional dimensions of channels 21 and 22 are equal. The taper then continues toward the left until in section *e—*e** channel 21 has a dimension substantially equal to the dimension of channel 22 in section *a—*a**. A longitudinal distance of several wavelengths is

included between sections *a—*a** and *e—*e**. Portion 16 tapers from its position in section *e—*e** to substantially the center of guide 20 at the near end.

Channels 21 and 22 are coupled between the sections *a—*a** and *e—*e** by a divided aperture 27 in portion 18 of divider 16—17—18. Divided aperture 27 has a transverse dimension which is zero in section *a—*a**, tapers to a maximum in section *c—*c**, and decreases again to zero in section *e—*e**. It is divided by a plurality of parallel wires 28 in accordance with the teachings of applicant's copending application, Serial No. 236,556, filed July 15, 1951. Suitable coupling may also be provided by a plurality of discrete apertures of tapered sizes spaced relatively close together in portion 18. The near ends of channels 21 and 22 are adapted to be connected by conventional wave guide circuits to broad band devices 25 and 23, respectively, while the other ends thereof are connected to loads 24 and 26, respectively.

The operation of the coupler employing normal mode tapering thus far described from a structural standpoint will more clearly be understood from the consideration of Figs. 2A through 2E which follows. It will first be assumed that these figures represent separate pairs of coupled wave guides having relatively different wide cross sectional dimensions. After the normal mode field patterns in such guides have been considered it will be shown that these figures may represent the field distribution in the several cross sections *a—*a** through *e—*e** of Fig. 1.

Referring to Figs. 2A through 2E, the electric field pattern of the "in phase" normal mode referred to above is shown as it would be supported in the cross section of several conductively bounded transmission paths each comprising two rectangular guides 11 and 12. In each figure suitable coupling means is represented schematically by 13 in the conductive boundary between the contiguous narrow walls of guides 11 and 12. Referring more specifically to Fig. 2C, the normal mode is shown in the two guides 11 and 12 when the guides have equal wide dimensions and therefore equal phase constants β_{11} and β_{12} (these parameters being proportional to the wider dimension of the guides, for example). The total field pattern of the mode comprises two portions of electric intensity on opposite sides of the conductive boundary 13 that are maximum at the same instant of time and are in the same direction. Note that each portion of the electric intensity forms a sine curve distribution of less than a full half wave pattern since the two portions are merged by the strong coupling to form the complete pattern defined as the normal mode. At the position of merger, i. e., at the coupling means 13, both sine curves have equal amplitudes that are greater than zero and in the same sense. Therefore the strength of the coupling means 13 is represented by the distance *k*. The dotted projections 14 and 15 of each sine curve are shown to illustrate the effective transverse wavelength of the mode designated on Fig. 2C as

$$\frac{\lambda n}{2}$$

This mode is the low phase velocity one of the two normal modes since its transverse wavelength is greater than the transverse wavelength of a wave that would normally be supported in an uncoupled guide of cross sectional dimensions equal to those of either guide 11 or guide 12. Such a wave would propagate jointly along guides 11 and 12 without change in the field distribution so long as the coupling and phase constants of the guides remained constant.

Now, in Fig. 2B guides 11 and 12 are modified so that β_{11} is greater than β_{12} and the coupling factor *k* is less than the factor *k* of Fig. 2C. The two portions of the normal mode will no longer have equal amplitudes. Rather the distribution will be similar to that shown in Fig. 2B with the amplitude of E_{11} in guide 11 substantially greater than the amplitude E_{12} in guide 12. Obviously,

there is a unique relationship between the difference $\beta_{11}-\beta_{12}$ and the coupling coefficient k that will support a given voltage distribution since the transverse wavelength of the two portions of the normal mode must always be equal in a given cross section. Conversely, for a given phase constant difference between the guides and a given coupling coefficient there is a given distribution of the normal mode energy between the two guides.

In accordance with the present invention, therefore, energy is excited in a coupled system in one normal mode only. While maintaining a given relationship to be defined hereinafter between the phase constant difference between the guides and the coupling coefficient therebetween so that the energy remains only in the original normal mode, these parameters are varied smoothly and gradually to shift the energy of the normal mode carried by one guide into the other.

A typical shift of this type may be seen by means of the sequence of Figs. 2A through 2E. Starting with Fig. 2C, assume that wave energy in the distribution discussed above has been excited by some means with equal amplitudes E_{11} and E_{12} in the two guides. Now, the parameters of the two guides are varied smoothly until the cross section becomes that represented by Fig. 2D, for which β_{11} is much smaller than β_{12} and k has also been decreased. The pattern of the normal mode will therefore shift with the amplitude E_{11} becoming smaller than the amplitude E_{12} . If the difference between the phase constants β_{11} and β_{12} is further increased and k is decreased to zero, as shown in Fig. 2E, all energy will be shifted into the right hand portion of the field pattern and the amplitude in the left hand portion will be zero. A similar shift can be produced into the left hand portion of the field pattern by decreasing β_{12} and increasing β_{11} as shown in the cross section sequence of Figs. 2B and 2A.

Since the shift action described above is reciprocal, Figs. 2A through 2E may now be used to describe the operation of the coupler of Fig. 1 by allowing Fig. 2A to represent the cross section of guides 21 and 22 at the section designated $a-a$ on Fig. 1 and Figs. 2B through 2E to represent the subsequent sections designated $b-b$ through $e-e$, respectively, with the cross sections of guides 21 and 22 tapering smoothly between these positions. Therefore, as wave energy is applied from broad band device 23, serving as a source, to the forward terminal of guide 22, the field pattern of the wave in guide 22 will spread as the wave passes taper portion 16 until at the section $e-e$ it will have the distribution of Fig. 2E. At the section $c-c$ it will be divided equally between guides 21 and 22 as shown by Fig. 2C. At section $a-a$ it will be completely transferred into guide 21 as shown by Fig. 2A to be delivered at load 24. This transition is independent of frequency since it is made with the energy always in only one normal mode, in this case the low velocity mode, and does not depend upon a periodic interference and reinforcement between several components. Also, except for possible reflections due to impedance discontinuities, no energy will be directed in the backward direction toward load 25 thereby producing in the coupler a high degree of directivity.

When broad band device 25 serves as a source of signals, a similar shift of energy will transfer all power from guide 21 into guide 22 for delivery to load 26. Transmission in this direction, however, is made in the "out of phase" normal mode or the high phase velocity mode noted above. A typical field pattern for this mode would look similar to those shown in Figs. 2A through 2E except that the two portions of electrical intensity on opposite sides of the conductive boundary would be out of phase and the transverse wavelength of the mode would be the same as the transverse wavelength of a wave that would be supported in an uncoupled guide. As a result the two portions of a wave in the cross section $c-c$ that result from energy being applied to guide

21 are equal in amplitude but out of phase, and such energy will be delivered to load 26 out of phase with respect to energy launched originally in guide 22 and delivered to load 24.

The structure thus described constitutes a directional coupler capable of complete power transfer and high directivity over an extremely broad band. When energy is initially excited in the branch having the larger phase constant, it will be delivered in an in phase normal mode at the other end in the branch having the larger phase constant. When energy is initially excited in the branch having the smaller phase constant, it will be delivered in an out of phase normal mode at the other end in the branch having the smaller phase constant.

The coupler, however, is not limited to complete power transfers. If the coupling of aperture 27 was gradually closed starting from section $a-a$, any desired division of power could be made between loads 24 and 26. A structure producing the particular division of equal power, which is the typical characteristic of a hybrid type structure, is illustrated by the modification of Fig. 3 in which aperture 30 between the sections $c-c$ and $e-e$ is substantially one half of aperture 27, i. e., an aperture ending with its point of maximum coupling at the section of equal cross sectional dimensions of guides 21 and 22. An additional aperture section 31 beyond the section $c-c$ is provided in the straight portion of divider 17 to avoid a sharp impedance discontinuity at section $c-c$. Wave energy from device 23 will therefore be divided equally and in phase between loads 24 and 26 with none appearing at 25. Wave energy from device 25 will be divided equally and out of phase between loads 24 and 26 with none appearing at 23. Aperture section 31 actually plays no part in the coupling, other than to match the impedance as noted above since beyond the section $c-c$ energy is already equally divided in the normal mode distribution.

Referring again to Figs. 2A through 2E, it should be apparent in view of what is taught above that there are an unlimited number of sequences of intermediate field distributions through which the energy may be shifted in transition between the distributions of Fig. 2A and Fig. 2C or between Fig. 2C and Fig. 2E. It may be shown that the distance required to shift a given portion of the energy from one guide into the other is inversely proportional to the quantity

$$\sqrt{\delta^2 + k^2} \quad (1)$$

in which δ is equal to one half the difference in the phase constants β_{11} and β_{12} of the guides and in which k is the coupling coefficient. In order to keep the coupler short, it is desirable then that this quantity be as large as possible. The limiting values are determined in the cross sections of Figs. 2A and 2E on one hand when δ is maximum and k is zero, and in the cross section of Fig. 2C on the other, when δ is zero and k is maximum.

Between these extremes the quantities δ and k are varied smoothly at substantially inverse rates to each other. As used herein and in the appended claims the term "inverse" means only that as one quantity is increasing with distance along the coupling interval, the other is decreasing with distance and not necessarily that they are reciprocal or vary at equal absolute rates. More particularly, according to a preferred form of the invention, δ in the sections of Figs. 2A and 2E should be substantially equal to k in the section of Fig. 2C so that the quantity $\sqrt{\delta^2 + k^2}$ in the three limiting cross sections is equal. Furthermore both δ and k are varied between these sections so that $\sqrt{\delta^2 + k^2}$ as calculated for each finite intermediate cross section is substantially constant from one section to the next. These proportions appear to give optimum performance of the coupler for the shortest coupling interval. This action may be explained on the theory that when the quantity $\sqrt{\delta^2 + k^2}$ is constant

along the interval the characteristic impedance presented to the normal mode along the interval is also constant so that no impedance discontinuity is present to distort and reflect components of the shifting wave.

A simple distribution meeting all these qualifications is illustrated in Fig. 4. The coupling coefficient k as represented by the characteristic 41 is varied in accordance with a sine function and the phase constants β_{11} and β_{12} of the guides as represented by the characteristics 42 and 43 are varied inversely to each other according to the corresponding cosine function along the coupled interval. For such a distribution the phase constant difference

$$\delta = \frac{\beta a - \beta b}{2} \cos \theta \quad (2)$$

in which βa and βb are the phase constants of guides 11 and 12 at their greatest difference and θ is proportional to the distance along the coupling interval and is expressed in radians. The coupling coefficient k is then varied according to

$$k = \frac{\beta a - \beta b}{2} \sin \theta \quad (3)$$

which makes the quantity $\sqrt{\delta^2 + k^2}$ calculated at each point along the coupling interval a constant.

Other distributions will also be satisfactory. It is desirable in some cases, for example, that the parameter θ in Equations 2 and 3 be varied non-linearly with distance along the coupling interval, and more specifically, to vary more rapidly in the center portion of the coupling interval and more slowly at the ends of the interval. Such a characteristic is shown in Fig. 4A by curve 47 which forms an S shape when θ is plotted against distance along the coupling interval and having the region of rapid variation at the center of the interval. Curves 44 and 45 represent the resulting phase constant characteristics and curve 46 the resulting coupling strength characteristic for a condition of complete power transfer. These characteristics exhibit maximum changes of rate in the center of the coupling interval and vary at rates approaching zero at the ends of the interval. If such a distribution is foreshortened as in the structure of Fig. 3 to produce a transfer that is less than complete, maximum variation of θ must still occur in the center of the coupling interval. The corresponding phase and coupling characteristics will still vary at maximum rate in the center of the coupling interval but will not necessarily approach zero at the ends of the interval. In either case it should be noted that the desirable relation maintaining Equation 1 equal to a constant along the coupling interval is preserved.

In the case of either complete power transfer or less than complete transfer, the S-shaped distribution of θ produces a coupler in which a shorter coupling interval is required for a given bandwidth, or conversely, a wider bandwidth for a given coupling interval.

It should be noted that in the preceding discussion, reference to the phase constant or phase velocity refers to properties of a wave in one of the guides as perturbed by the presence of the coupling slot and other wave guide. However, if the coupling is small these quantities are very nearly the same as those for an uncoupled wave guide and may be calculated from its cross sectional dimensions, and its dielectric and permeability constants.

In the embodiment of Fig. 1 the phase constants of the guides are tapered by tapering the wider cross sectional dimensions of the guiding channel. The phase constants of the guides may also be tapered by tapering their dielectric and/or permeability constants. Referring to Fig. 5, an illustrative embodiment of the invention is shown in which the guides are loaded by tapered members of high dielectric constant. Guides 50 and 51 are rectangular wave guides of uniform cross sectional dimensions which

are located side by side to provide a contiguous or common wall 52. A divided aperture 53 several wavelengths long is located in common wall 52 to provide a tapered coupling of the type described above between cross sections $a-a$ and $c-c$. Located in guides 50 and 51 are identical taper members 54 and 55, the cross sections of which, and therefore the masses, increase from zero to a maximum and then decrease to zero. Members 54 and 55 are so oriented that at the cross section $a-a$ member 54 has a minimum mass and member 55 has a maximum mass; at cross section $b-b$, members 54 and 55 have equal masses; and at cross section $c-c$, member 54 has a maximum mass and member 55 has a minimum mass. Taper portion 56 of member 55 and portion 57 of member 54 provide a reflectionless transition between the unloaded portions of the guides and the maximum dimensions of members 55 and 54, respectively. Numerous and varied other physical arrangements of dielectric or permeability material will occur to those skilled in the art which would provide similarly tapered phase constants for guides 50 and 51.

The principles of the present invention are by no means limited to shielded transmission lines, either wave guide or coaxial, but may likewise be applied to other forms of electrical transmission lines such as the lines employed in the all-dielectric wave couplers disclosed in my copending application, Serial No. 274,413, filed March 1, 1952. As there disclosed, electromagnetic wave energy, when properly launched upon a strip or rod of all-dielectric material without a conductive shield, will be guided by the rod with a portion of the energy conducted in a field surrounding the rod. These strips may be made of polystyrene, polyethylene or Teflon, for example, to mention only several specific materials.

Referring to Fig. 6, an all-dielectric directional coupler employing normal mode tapering is shown. This coupler comprises a straight strip 60 of all-dielectric wave guide of the type hereinbefore described and a smoothly curved portion of a strip 61 of similar material which arches into proximate relation to a portion of guide 60. The transverse cross sections of both guides 60 and 61 at the position of center line 62 are symmetrical and, more particularly, circular, as represented by the cross sectional showings 63 and 64. On either side of center line 62, guides 60 and 61 are squashed or deformed into avoid transverse cross sections having different perpendicular transverse cross sectional dimensions. More particularly, the left hand end 65 of guide 60 is deformed into an elliptical cross section having its longer major axis in a vertical position. The right hand end 66 of guide 60 is deformed into an elliptical cross section having its longer major axis horizontal. The left hand end 67 of guide 61 is deformed into an ellipse having its longer major axis horizontal while the right hand end 68 of guide 61 has its longer major axis vertical. Guides 60 and 61 may be held in this relative position in numerous ways such as the one illustrated in the above mentioned copending application comprising a block 69 of material having a low loss and a low dielectric constant and which is provided with suitable slots into which guides 61 and 60 may be pressed. Also, the several alternative physical orientations for the two guides as disclosed in said copending application may be used.

Since a substantial amount of wave power is carried in the space surrounding each guide, when the guides are brought into proximate physical relationship the fields carried by the guides interact to produce electromagnetic coupling between the two dielectric paths. The amplitude of this coupling is inversely proportional to the distance between the guides. Therefore the spacing between guides 60 and 61 is suitably chosen to produce a distributed and tapered coupling which gradually decreases from maximum coupling at center line 62 to an infinitesimal coupling at points where the guides are separated by a larger

amount. This coupling is tapered in accordance with the desired coupling characteristic which may be the sine curve 41 as illustrated in Fig. 4.

Since the phase velocity of wave energy conducted by guides 60 and 61 is inversely proportional to the thickness of the rod measured parallel to the polarization of the electric vector of the energy, it is apparent that guide 60 will have a maximum phase velocity for wave energy polarized horizontally in portion 65 and will decrease to a minimum phase velocity for wave energy polarized horizontally in portion 66. The rate of deformation of guide 60 between portions 65 and 66 may therefore be selected to produce any desired taper of the phase constant including the cosine curve 42 illustrated hereinbefore with reference to Fig. 4. Similarly, guide 61 provides a minimum phase velocity for the wave energy polarized horizontally in the portion 67 and a maximum phase velocity for wave energy polarized horizontally in the portion 68. Thus a maximum difference in the phase velocities between guides 60 and 61 is provided at the points of minimum coupling removed from center line 62 while equal phase velocities in the two guides are provided at the point of maximum coupling at center line 62. This then is the desired phase velocity and coupling characteristic represented by Fig. 4. In all respects a shift of wave energy of the normal mode carried either horizontally or vertically by guides 60 and 61 will be exhibited which is similar to the shift demonstrated hereinbefore with reference to Figs. 2A and 2E. Therefore wave energy applied in a horizontal polarization represented by the vector E_1 to guide 60 will appear at the end of guide 61 in the polarization represented by vector E_2 and wave energy of the polarization represented by E_4 applied to guide 60 will appear on guide 61 in the polarization represented by the vector E_3 . Similar directional coupling action exists for vertically polarized waves.

The embodiments thus far described illustrate how both the phase constants and the coupling coefficients may be varied to obtain normal mode tapering in a directional coupler structure. When tapered according to the optimum relationships given, the bandwidth of the directivity and transfer ratio of the coupler are limited substantially only by the inherent bandwidth of the wave guide components. In some applications it may be inconvenient or impossible to vary both of these parameters freely and also a bandwidth somewhat less than the maximum will be satisfactory. In these cases normal mode tapering may still be employed if the single parameter of coupling or phase constant is varied in a particular way. Variation of the phase constant alone is the subject matter of the above copending application of J. S. Cook.

In Fig. 7 is shown an embodiment of a normal mode directional coupler in which only the coupling coefficient is varied, and more specifically, varied along the coupling interval from zero to a positive maximum, reversing in sign to a negative maximum, and decreasing again to zero. As shown in Fig. 7, the coupler comprises a first section 71 and a second section 72 of rectangular wave guide. One narrow wall of guide 72 is placed contiguous to and centered upon a wide wall of guide 71. The wide dimension a of guide 71 is somewhat larger than the wide dimension b of guide 72 giving to guide 72 a larger phase constant than guide 71 as shown by the characteristics 81 and 82 of Fig. 8.

Guides 71 and 72 are electromagnetically coupled over two intervals, each extending several wavelengths along the longitudinal length of the line by divided apertures 73 and 74, respectively. The near end of aperture 73 commences on the longitudinal center line of guide 71 at which point the longitudinal magnetic field components in guide 71 are zero. Aperture 73 is a fraction of a wavelength in width so that it is unresponsive to transverse magnetic field components in guide 71. Thus the coupling coefficient at this point is zero. Aperture 73 extends toward one wide wall of guide 72 and so extends

toward increasingly larger values of longitudinal field in guide 71. Therefore the coupling coefficient of aperture 73 is represented by characteristic 83 of Fig. 8. Aperture 74 commences at a point on the opposite side of the longitudinal center line of guide 71 that corresponds to the termination point of aperture 73, and extends to the center line of guide 71. Since aperture 74 couples to longitudinal field components in guide 71 having opposite signs from those coupled by aperture 73, aperture 74 produces a coupling coefficient that is represented by the characteristic 84 of Fig. 8.

A non-mathematical explanation of why the structure thus described will produce a normal mode transfer of energy from one guide into the other may be given by analogy to the transfer illustrated in Figs. 2A through 2E described above. If wave energy is applied to the near end of guide 71, the initial conditions are the same as those existing in Fig. 2E, i. e., energy is applied to the guide of larger phase constant at a point of zero and subsequently increasing coupling factor. Therefore, one of the pairs of normal modes will be initially excited in the coupled system, being the "in phase" or "out of phase" mode depending upon what relative polarizations in the two guides are defined as being in phase. An initial difference in the phase constants βa and βb prevents initial excitation of the other normal mode in the region of small coupling. As the coupling of aperture 73 increases, an increasingly larger portion of the normal mode energy will shift into guide 72 until at the end of aperture 73 in the center cross section of the guide substantially equal portions of the normal mode will be found in guides 71 and 72, which is analogous to the distribution of Fig. 2C.

Now, assume for the purposes of explanation that the coupling between guides 71 and 72 is decreased in the second coupling region to zero along the broken line characteristic 85 of Fig. 8. In such an assumed structure all the energy would return to guide 71, that is, the process performed in the first coupling region would be reversed in the second coupling region. The operation of the assumed structure therefore fails to follow the complete transfer sequence of Figs. 2C through 2A because there is no "crossover" in the phase constants of the guides as was provided by the characteristics of β_{11} and β_{12} of Fig. 4. However, the coupler of Fig. 7 actually provides an equivalent "crossover" by reversing the sense of the coupling coefficients produced by aperture 74 relative to aperture 73 as shown by the characteristics 84 and 83 of Fig. 8, respectively. The transfer sequence is completed and all energy in the normal mode will appear at the far end of guide 72.

Further demonstration that this is true may be made as follows. If wave energy applied at the near end of guide 71 produces normal mode components in the center cross section of the coupler that are defined as in phase in guides 71 and 72, then energy applied to the far end of guide 71 produces out of phase components. Similarly, wave energy applied to the near end of guide 72 produces out of phase components at the center while energy applied to the far end of guide 72 produces in phase components. These relative phases are obvious from an examination of the field patterns of the waves taking into account the reversal of the coupling coefficient in the two portions. Since all sections of the coupler are reciprocal, the energy distribution produced by exciting the near end of guide 71 and the far end of guide 72 match, and coupling is established therebetween. Likewise the energy distribution produced by exciting the near end of guide 72 and the far end of guide 71 match, and coupling is established therebetween.

In the embodiment of Fig. 9 the coupling regions are transposed relative to their positions in the embodiment of Fig. 7 with an interesting result. Thus in Fig. 9 guides 91 and 92 are located with their wider walls contiguous and their longitudinal axes skew so that an elongated di-

vided aperture 93 runs diagonally in the wide wall of guide 91 from a point near one narrow wall to a point near the other narrow wall, but runs in the wide wall of guide 92 near and parallel to one narrow wall. This produces the coupling coefficient represented by the characteristic 96 of Fig. 9 that runs from a positive maximum at one end of the coupling region, through zero, and to a negative maximum at the other end of the coupling region. The wider cross sectional dimension a of guide 91 is larger than the wide dimension b of guide 92 giving to the guides phase constants βa and βb , respectively, as represented by the characteristics 97 and 98 of Fig. 10.

Note that the phase and coupling characteristics at the ends of the embodiment of Fig. 9 correspond to these characteristics at the center of the embodiment of Fig. 7. Conversely, the phase and coupling characteristics at the ends of the embodiment of Fig. 7 correspond to these characteristics at the center of the embodiment of Fig. 9. Therefore the energy distribution at the several corresponding cross sections will also correspond. From this the interesting characteristic of the embodiment of Fig. 9 may be understood. If equal portions of wave energy are applied in phase to the near ends of guides 91 and 92, equal out of phase portions will be produced at the far ends of the guides. This structure is therefore useful in any one of the many applications in which it is necessary to produce a phase inversion in a one-half portion of energy relative to the other half portion. The inserted 180 degree phase shift is, however, independent of frequency since it has all the broad band characteristics of the normal mode coupling structure.

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 transmission lines, means for coupling said lines along a given longitudinal section of said lines, said coupling varying smoothly between substantially different maximum and minimum coupling amplitudes at different points along said section, said lines having phase constants, the difference between said phase constants varying smoothly along said section with a maximum difference at substantially the point of minimum coupling and a minimum difference at substantially the point of maximum coupling.

2. A coupling device comprising a pair of electromagnetic wave transmission lines, means for coupling said lines with a variation in the coupling coefficient along a given longitudinal section of said lines, said coupling coefficient being a function of the rate of voltage change with distance along said section in each of said lines, said lines each having phase constants that vary inversely to each other along said section with the difference between said constants varying inversely to said coupling coefficient along said section.

3. The combination according to claim 2 wherein the maximum value of said coupling coefficient along said section is substantially equal to one half of the maximum difference between said phase constants along said interval.

4. The combination according to claim 2 wherein the quantity

$$\sqrt{\delta^2 + k^2}$$

as calculated at each point along said section is constant, in which δ is one half of the difference between said phase constants at each point and k is the coupling coefficient at said point.

5. The combination according to claim 2 wherein the difference between said phase constants varies proportionally as the cosine of the distance along said section and wherein said coupling coefficient varies proportionally as the sine of the distance along said section.

6. Directional coupling apparatus for electromagnetic wave energy comprising a pair of conductively bounded wave guides, means for coupling said guides with a tapered variation in coupling strength along a longitudinal interval of said guides, a pair of members of high dielectric constant material located one in each of said guides, the mass of each of said members being tapered with distance along said interval at substantially different rates to each other, the mass of one of said members being tapered with distance along said interval at substantially an inverse rate to the strength of said tapered coupling.

7. Microwave coupling apparatus comprising first and second dielectric members, said members each being substantially symmetrical in transverse cross section in a center portion thereof and being ovoid in cross section on either side of said center portion, each of said members being unsheathed whereby a portion of electromagnetic wave power conveyed therealong is conveyed in a field surrounding said members, said members being in proximate physical relationship in said center portion to provide interaction between the fields surrounding said strips.

8. Apparatus according to claim 7 wherein the longest dimension of said ovoid cross section of one member on one side of said center portion is substantially parallel to the longest dimension of said ovoid cross section of the other member on the other side of said center portion.

9. Apparatus according to claim 7 wherein at least one of said members has a smoothly curved portion of its length that arches into proximate relationship to said center portion of the other of said members.

10. A coupling device comprising a pair of electromagnetic wave transmission lines, said lines having different phase constants, means for coupling said lines with a coupling coefficient that varies with distance over two intervals each several wavelengths long, the sign of said coefficient being opposite in said two intervals.

11. The coupling device of claim 10 wherein said coupling coefficient increases from zero with distance along one of said intervals to a positive maximum, reverses abruptly in sign to a negative maximum, and decreases with distance along the other of said intervals to zero.

12. The coupling device of claim 10 wherein said coupling coefficient is zero at a point between said coupling intervals, increases with distance from said point to a positive maximum in one interval and increases with distance from said point to a negative maximum in the other of said intervals.

13. A coupling device comprising a pair of partially contiguous conductive wave guides of rectangular cross section, means for coupling said guides comprising a common wall in said contiguous portion having elongated aperture means therein, said wall being the wider wall in at least one of said guides, said aperture means extending at different longitudinal positions along said wide wall through points that include a point on the center line of said wide wall and points displaced on both sides of said center line.

14. A coupling device comprising a pair of electromagnetic wave transmission lines, means for coupling said lines with a coupling strength that varies with distance along a longitudinal interval of said lines, said lines each having phase constants that are different from each other along a substantial portion of said interval, said difference varying with distance along said interval inversely to said coupling strength variation.

15. A coupling device in accordance with claim 14 in which said difference and said coupling strength vary at substantially larger rates in the vicinity of a center

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portion of said interval than in portions of said interval on either side of said center portion.

16. A coupling device in accordance with claim 15 in which said difference varies as a function of $\cos \theta$ and said coupling strength varies as a function of $\sin \theta$, wherein θ is a parameter that increases with distance along said interval in said center portion at a substantially larger rate than in said portion on either side of said center portion.

17. Directional coupling apparatus for electromagnetic wave energy comprising, a conductively bounded wave-guiding channel having a pair of wide and a pair of narrow walls, a conductive divider extending longitudinally along said channel and perpendicularly to said wide walls of said channel, said conductive divider being spaced nearer to a first narrow wall of said channel than to the second narrow wall in at least a first transverse cross section perpendicular to said wide walls and being equidistant between said first and second narrow walls in a second transverse cross section perpendicular to said wide walls, said conductive divider having a coupling aperture extending therethrough to include in at least said first transverse cross section a portion of the conductive boundary of said coupling aperture, whereby electromagnetic coupling is provided between the portions of said channel on either side of said divider, said aperture having a dimension in the direction parallel to said narrow walls which varies along a longitudinally extending portion of said channel.

18. Apparatus according to claim 17 wherein said second transverse cross section also includes a portion of the conductive boundary of said coupling aperture.

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19. Apparatus according to claim 18 wherein the dimension of said aperture in the direction parallel to said narrow walls in said first cross section is smaller than in said second cross section.

20. Apparatus according to claim 19 wherein the dimension of said aperture in the direction parallel to said narrow walls in said second cross section is a maximum.

21. Apparatus according to claim 20 wherein the dimension of said aperture in the direction parallel to said narrow walls in a third cross section of said divider is zero, said divider being spaced nearer to said first narrow wall than to said second narrow wall in said third cross section, and wherein said first cross section lies between said second and third cross section.

22. Apparatus according to claim 18 wherein said divider is spaced closer to said second narrow wall than to said first narrow wall in another cross section, and wherein said second cross section is disposed between said first cross section and said other cross section, said other cross section including portions of the conductive boundary of said coupling aperture.

23. Apparatus according to claim 22 wherein the largest dimension of said aperture in a direction parallel to said first and second narrow walls and perpendicular to said wide walls exists in said second cross section.

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