

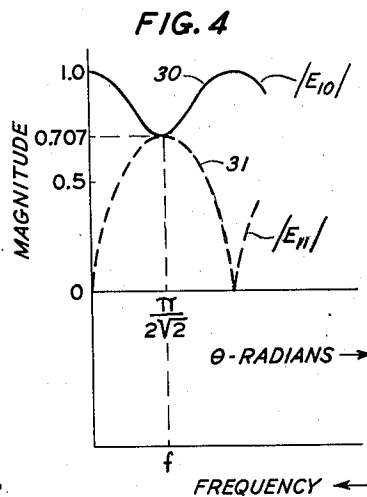
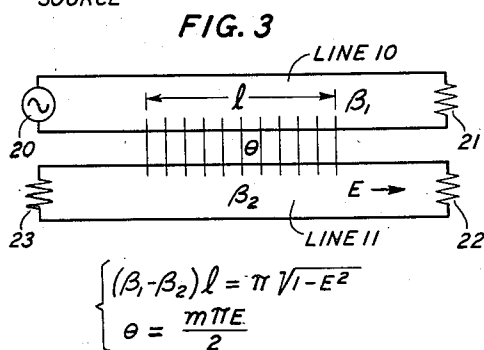
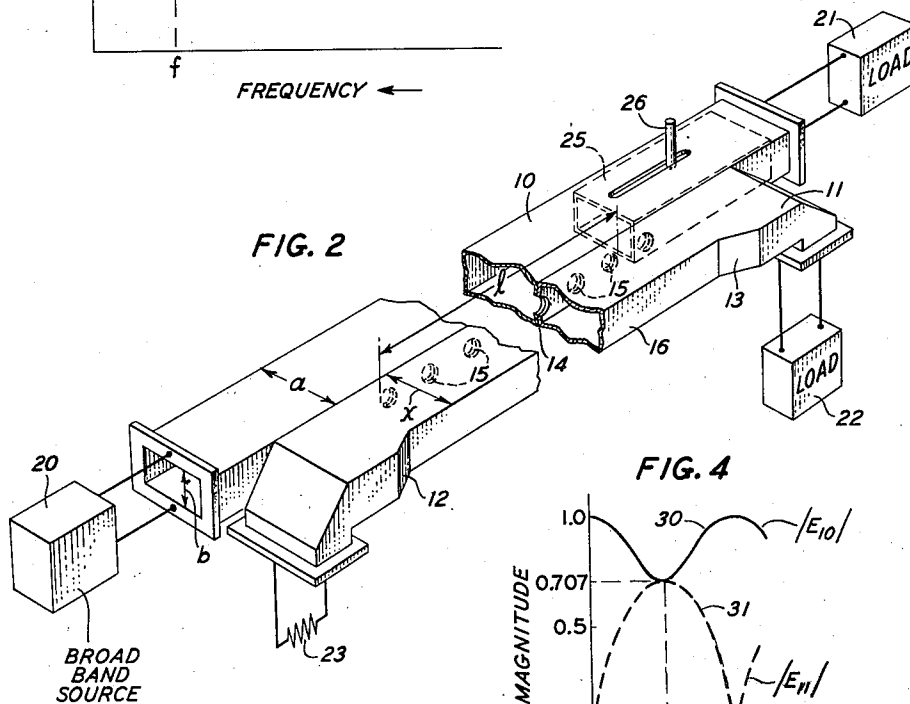
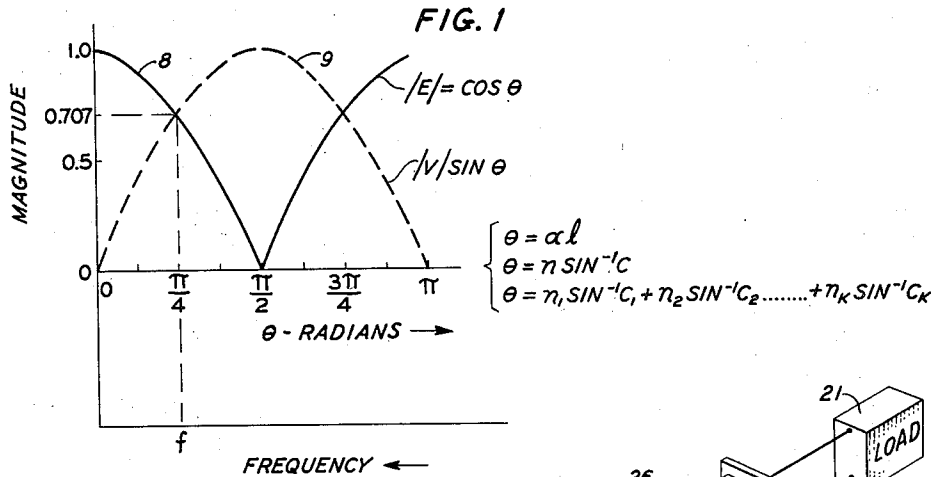
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HIGH FREQUENCY POWER DIVIDING NETWORKS

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HIGH FREQUENCY POWER DIVIDING NETWORKS

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6 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 along the main line induces a principal secondary wave, known as the forward wave, traveling in a single direction 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 traveling in the opposite direction from each forward wave, known as the backward wave. The forward and the backward waves are desirably greatly unequal in strength. Their relative strength is called the directivity of the coupler and is usually expressed as the decibel ratio of the forward wave current to the backward wave current. The strength of the desired induced forward wave in the auxiliary line, hereinafter referred to as the transferred amplitude, to the inducing wave in the main line is called the "coupling loss" and is also expressed as the decibel ratio of the desired or forward induced wave to the inducing wave in the main line. This "coupling loss" is actually the transfer ratio between the two lines as there is no power dissipated in the structure. The performance of a directional coupler may be described in terms of this directivity and coupling.

Heretofore, the interest of the art has been primarily concerned with the directivity of the couplers. It has been shown that the directivity is frequency sensitive and substantial effort has been given to increasing the operating band over which a given value of directivity is maintained.

The forward coupling loss or the transferred amplitude of directional couplers is also a function of frequency to some extent due to the inherent and uncontrollable frequency selectivity of the coupling means itself. This has been found to be the case for every known coupling device.

It is an object of the present invention to transfer a forward traveling induced wave between coupled transmission lines which bears a constant ratio to the inducing wave over an extended frequency band.

It is a further object of the invention to minimize the inherent frequency selectivity of the coupling means in directional coupling structures.

When the parameters of a coupled line circuit are proportioned so that one-half of the wave power in the main line is transferred to and launched directionally in the

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auxiliary line, i. e., a 3 decibel coupling loss, a structure which has electrical properties similar to the microwave hybrid junction or magic-T structure is obtained. The resulting structure has been specifically designated as a coupled line hybrid and is simpler and more economical to manufacture than several of the hybrid structures heretofore employed.

It is, therefore, a specific object of the invention to increase the operating band width of coupled line hybrid structures.

In accordance with the invention, the phase velocity constants of the main and auxiliary lines of the usual directional coupler or coupled line hybrid structures are modified in accordance with a particular optimum relationship of these constants to the ratio of energy transferred from one line into the other by a specific coupling device and to the manner in which this coupling is apportioned along a specific longitudinal length of the lines. The product of the latter two parameters is referred to as the "integrated coupling strength factor" of the coupled lines. Under this optimum condition, the variation of the coupling loss or transferred amplitude versus frequency variation caused by the frequency selectivity of the coupling means is minimized. The relationship applicable for all values of coupling loss will be defined and the specific relationship for the coupled line hybrid will be given.

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

In the drawings:

Fig. 1, given by way of explanation, illustrates the energy transfer versus the integrated coupling strength factor between the coupled lines of the prior art structures and also the energy transfer versus frequency characteristic of these structures;

Fig. 2 shows in pictorial representation a microwave guide coupled line circuit in accordance with the invention;

Fig. 3 is a schematic representation of the structure of Fig. 2 showing the several important parameters in accordance with the invention; and

Fig. 4, given by way of explanation, illustrates the energy transfer versus integrated coupling strength factor between the coupled lines of the structure of Fig. 2 and also the energy transfer versus frequency characteristic of this structure.

In my copending application Serial No. 216,132, filed March 17, 1951, now United States Patent No. 2,701,340, issued February 1, 1955, with respect to directional coupler aspects of coupled lines, and Serial No. 325,488, filed December 11, 1952, with reference to hybrid aspects of coupled lines, it has been demonstrated that when two microwave transmission lines are coupled together over an interval, the power transferred in the forward direction from one line into the other is determined by what has been designated as the integrated coupling strength factor. This factor depends, first, upon the ratio of energy transferred from one line into the other by a specific coupling device, and second, upon the manner in which this coupling is apportioned along a specific longitudinal length of the lines. If the coupling is distributed over this interval or if the coupling involves such a large number of discrete coupling points that the coupling may be considered as substantially distributed, the integrated coupling strength factor in radians is expressed:

$$\theta = \alpha l$$

(1)

in which α represents the distributed coupling per unit length between the lines, and l represents the distance over which this coupling is maintained.

In certain cases, it has been found more convenient to express the integrated coupling strength in terms of the fraction C of the energy in one line coupled by each discrete aperture and the number n of such apertures. In such a case, the integrated coupling strength factor becomes

$$\theta = n \sin^{-1} C \quad (2)$$

or if the coupling strength of each aperture is not equal to that of the other apertures, as

$$\theta = n_1 \sin^{-1} C_1 + n_2 \sin^{-1} C_2 + \dots + n_k \sin^{-1} C_k \quad (3)$$

in which there are n_1 apertures of individual coupling C_1 , n_2 apertures of individual coupling C_2 and n_k apertures of individual coupling C_k .

Whether the integrated coupling strength factor is most conveniently evaluated by equations 1, 2 or 3, it has been shown that the absolute value of the voltage amplitude $|E|$ in the main driven line decreases cosinoidally as θ is increased, and the absolute value of the voltage amplitude $|V|$ in the auxiliary undriven line increases sinusoidally as the integrated coupling factor increases. These functions are plotted on Fig. 1 as curves 8 and 9, respectively. As shown in the above-mentioned coupling applications, all power in the driven line will be transferred into the undriven line when the integrated coupling strength factor θ is equal to odd multiples of

$$\frac{\pi}{2}$$

Smaller fractions of power are transferred for smaller values of θ . For example, when θ is equal to

$$\frac{\pi}{4}$$

the amplitude in each line is 0.707 of the initial amplitude. This represents the equal division of power between the two lines for a 3 decibel coupling loss in a coupled line hybrid structure.

Every known coupling means between the two coupled lines, whether probes, apertures or elongated slots, has a certain degree of inherent frequency sensitivity. In the particular case of coupling through an aperture located in the narrower wall as shown on Fig. 2, the factor α or C above has a coupling amplitude versus frequency characteristic that decreases with increase of frequency. This means that the integrated coupling strength factor is also a function of frequency, and curves 8 and 9 of Fig. 1 may equally well be plotted against an inverse frequency scale as shown. Therefore, when the value of θ is fixed by the structural details of the coupled lines, the power division defined above will be given only within a limited band width. In fact, for equal power division, the ratio of power in each of the lines varies rapidly with changes in frequency as may be seen from Fig. 1 by the sharp intersection made by curves 8 and 9 for the frequency f in the region in which θ is equal to

$$\frac{\pi}{4}$$

The same is true for all power division ratios less than complete power transfer.

Referring now specifically to Fig. 2, a broad band coupled line power dividing circuit is shown by which the effect of the inherent frequency selectivity of the coupling means is minimized to provide directional couplers and coupled line hybrids in which the coupling loss is substantially independent of frequency. This circuit comprises a first section 10 of electrical transmission line for guiding wave energy which may be a rectangular wave guide of the metallic shield type having a wide internal cross-sectional dimension a and a narrow dimension

b . In accordance with usual practice, the wide dimension a is somewhat larger than one-half wavelength of the energy to be conducted by guide 10 and the dimension b is substantially one-half of the dimension a . Located adjacent guide 10 and running for a portion of its length substantially parallel thereto is a second section 11 of transmission line which, except for constricted portion 16, has cross-sectional dimensions similar to those of guide 10. In portion 16 the wider internal dimension of guide 11 is reduced by smooth tapers 12 and 13 to a dimension x . Lines 10 and 11 are coupled in constricted portion 16 over an interval of several wavelengths by one of the several coupling means familiar to the directional coupler art. This coupling means may be, as illustrated, a common wall 14 between lines 10 and 11 having a plurality of apertures 15 therein distributed at intervals of less than one-half wavelength along an interval l of constricted portion 16. The number of apertures 15 may be many approaching the distributed coupling of Equation 1 or it may be few approaching the coupling of Equation 2. Their strength may be equal or they may be unequal according to Equation 3. Lines 10 and 11 are illustrated as being air-filled, but they may, however, be filled or partly filled with material having a different dielectric constant from that of air.

A broad band signal source 20 is connected to the backward terminal of guide 10 to supply an electromagnetic wave signal to guide 10 and loads 21 and 22 are connected to the forward ends of guides 10 and 11, respectively, to receive this signal. The backward end of guide 11 is terminated in a reflectionless impedance 23.

The coupled lines of Fig. 2 are schematically represented in Fig. 3 along with their significant parameters in accordance with the invention. Thus, in Fig. 3, line 10 extends from source 20 to load 21 and is coupled to line 11 which in turn runs between termination 23 and load 22. The coupling between lines 10 and 11 is schematically represented by the integrated coupling strength factor θ for the particular coupling distribution and is maintained over the longitudinal length l of the lines. Since lines 10 and 11 in the region of coupling have different cross-sectional dimensions, they have different phase velocity constants. In Fig. 3, the phase velocity constant of line 10 is designated β_1 and the phase velocity constant of line 11 in the region of coupling as β_2 . If it is assumed for convenience that the amplitude of the wave delivered from source 20 to line 10 is unity, the amplitude fraction of this wave transferred into line 11 and delivered to load 22 may then be designated as the transferred amplitude E , the remaining energy being delivered to load 21.

The present invention is directed to a specific relationship between the different phase constants β_1 and β_2 , the coupling interval l and the integrated coupling strength factor θ , so that over a broad frequency band the predetermined fraction E is transferred from line 10 into line 11. In accordance with the invention and as indicated in Fig. 3, these relationships are as follows:

$$(\beta_1 - \beta_2)l = \pi \sqrt{1 - E^2} \quad (4)$$

with the integrated coupling strength factor

$$\theta = \frac{m\pi E}{2} \quad (5)$$

where m is any odd integer. β_1 and β_2 are the phase constants in radians per unit length dependent directly upon the cross-sectional dimension of guides 10 and 11, respectively, as follows:

$$\beta_1 = \frac{2\pi \sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2}}{\lambda_0} \quad (6)$$

$$\beta_2 = \frac{2\pi \sqrt{1 - \left(\frac{\lambda_0}{2x}\right)^2}}{\lambda_0} \quad (7)$$

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for the frequency at which the free space wavelength is λ_0 .

The significance of these relationships may be understood when it is realized that the absolute amplitude of the forward traveling wave in guide 10 after an interval l of distributed coupling α per unit length may be expressed:

$$|E_{10}| = \cos \left[\frac{1}{2} \sqrt{(\beta_1 - \beta_2)^2 + 4\alpha^2} l \right] - \frac{(\beta_1 - \beta_2)}{\sqrt{(\beta_1 - \beta_2)^2 + 4\alpha^2}} i \sin \left[\frac{1}{2} \sqrt{(\beta_1 - \beta_2)^2 + 4\alpha^2} l \right] \quad (8)$$

and the forward traveling wave in guide 11 may be expressed:

$$|E_{11}| = \frac{1}{\sqrt{\frac{(\beta_1 - \beta_2)^2}{4\alpha^2} + 1}} i \sin \left[\frac{1}{2} \sqrt{(\beta_1 - \beta_2)^2 + 4\alpha^2} l \right] \quad (9)$$

It is seen from the first factor of Equation 9 that the transferred wave in guide 11 goes through a maximum which is equal to:

$$E = \frac{1}{\sqrt{\frac{(\beta_1 - \beta_2)^2}{4\alpha^2} + 1}} \quad (10)$$

in the region in which the second factor of Equation 9:

$$\frac{1}{2} \sqrt{(\beta_1 - \beta_2)^2 + 4\alpha^2} l = \frac{\pi}{2} \quad (11)$$

Now, in this region, the transferred amplitude E depends not alone upon the coupling α (which in turn depends upon frequency) but upon the ratio of

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

Hence, for a given transfer value, there is an optimum ratio of phase constant difference to coupling strength for which the variation of transferred amplitude versus frequency is minimized. This optimum ratio is the ratio at this maximum and is:

$$\frac{\beta_1 - \beta_2}{\alpha} = \sqrt{\left(\frac{2}{E} \right)^2 - 4} \quad (12)$$

for an integrated coupling strength factor

$$\alpha l = \frac{\pi E}{2} \quad (13)$$

Multiplying Equation 12 by Equation 13 gives the convenient relationship specified above in Equation 4.

Equation 13 gives the necessary value of the integrated coupling strength in terms of a distributed coupling α and the length l over which it is maintained as defined by Equation 1 above. However, if the coupling means is not readily expressed as a distributed coupling, for example, if the coupling comprises only a small number of discrete coupling points, or if the points are of unequal strength, the alternative evaluations of Equation 2 or 3 above may validly be equated with Equation 13. In addition, the effect is periodic and occurs every odd multiple of π , so that with the additional generalization obtained by adding the factor m , Equation 5 above accurately defines the value of the integrated coupling strength factor for all cases in accordance with the invention.

In the usual practical embodiment, the value of either the coupling strength α or C , or the coupling length l , will be already determined by considerations not within the scope of the present disclosure. For example, it is assumed herein that in so far as transmission of energy in the backward direction in guide 11 toward termination 23 is concerned, the structure is inherently a directional coupler, i. e., a minimum transmission of energy in this direction will be found since the collective effect of a large number of discrete coupling elements spaced at less than one-half wavelength apart is of itself directionally

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selective. The factors α or C , however, may be determined by considerations designed to improve this directivity or to increase the band width over which a given directivity is maintained. One the other hand, the principles of the invention may be applied to a system in which one or both of the coupled lines are capable of supporting several modes of wave energy propagation. As disclosed in detail in my copending application for patent for "High Frequency Selective Mode Transducer," Serial No. 245,210, filed September 5, 1951, now United States Patent No. 2,748,350, issued May 29, 1956, the length l of the coupling interval will then be chosen for selective coupling between different modes in the coupled lines. Either the interval length or the coupling strength may, therefore, be apportioned with respect to the other to obtain an integrated coupling factor consistent with Equation 5 above, and the necessary phase constant difference then selected consistent with Equation 4 above by choice of the relative cross-sectional dimensions a and x of the guides.

A convenient manner of variably adjusting the integrated coupling strength of a given structure is illustrated in Fig. 2 by a movable thin walled conducting liner 25 within guide 10 which may be moved inside guide 10 by handle 26 in such a way as to cover up a variable number of coupling holes 15 and simultaneously to shorten the coupling interval l .

Applying the relationships in accordance with the invention by way of specific example to a 3 decibel coupling loss structure or hybrid, assume that it is desired to divide the power from source 20 into two equal parts for delivery to loads 21 and 22. This means that the amplitude fraction E to be abstracted by line 11 from line 10 will be 0.707 or

$$\frac{1}{\sqrt{2}}$$

of the available amplitude of the signal from source 20. Substituting this value in Equations 4 and 5, the product $(\beta_1 - \beta_2)l$ must be equal to $\pi/\sqrt{2}$ with an integrated coupling strength θ of

$$\frac{\pi}{2\sqrt{2}}$$

To make the example more explicit, assume that the coupling interval is selected for other reasons to be two times the guide wavelength in guide 10. A difference in the phase constants β_1 and β_2 of substantially 18 percent is then required which is easily obtained from cross-sectional dimensions according to Equations 6 and 7. If distributed coupling is employed the coupling factor α should then be

$$\frac{\pi}{4\sqrt{2}}$$

per guide wavelength in guide 10.

The characteristics of a hybrid designed according to these relationships are shown in Fig. 4. Referring, therefore, to Fig. 4, the curve 30 represents the voltage amplitude of the wave in line 10 and the curve 31, the transferred voltage amplitude in line 11. The amplitude in each line is equal to 0.707 of the available amplitude for the frequency f with an integrated coupling strength factor θ of

$$\frac{\pi}{2\sqrt{2}}$$

A comparison of Fig. 4 with the characteristics of an ordinary coupled line hybrid illustrated in Fig. 1 will show the increased band width over which this coupling ratio is maintained. As noted above with respect to Fig. 1, at the frequency f the lines have equal power but the frequency band about f at which this ratio substantially obtains is very narrow. However, in Fig. 3 the range about the frequency f is considerably extended by the

principles of the invention. A similar improvement will be obtained for all other coupling ratios.

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 line, including open wire lines, for which the relative phase velocities may be controlled. In particular, they may be applied to the all-dielectric wave couplers as disclosed in the copending application of A. G. Fox, Serial No. 274,313 filed March 1, 1952. As there disclosed, electromagnetic wave energy, when properly launched upon a strip or rod of all-dielectric material, i. e., a rod without a conductive shield, will be guided by the strip or rod with a portion of the energy conducted in a field surrounding the strip. These strips or rods may be of any material having a dielectric constant substantially different from that of air or that of free space, and, therefore, having a phase velocity for wave energy substantially different from the phase velocity of energy in free space. For example, these strips may be made of polystyrene, polyethylene or Teflon, to mention only several specific materials. The relative phase velocities in accordance with Equation 4 are controlled by the relative cross-sectional areas of the all-dielectric guides and the dielectric constants of the materials of which the guides are made.

It should be noted also that the principles of the invention may be applied to shielded transmission lines of identical cross-sectional dimensions since the required difference in the phase velocity constants in accordance with Equation 4 may be obtained by filling, or partly filling, one or both of the guides in the region of coupling with material having different dielectric constants or with different amounts of material having the same dielectric constants.

In all cases, it is 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. Apparatus for abstracting an amplitude fraction E of electromagnetic wave energy traversing a main transmission line, said main transmission line having a phase velocity constant β_1 radians per unit length, said fraction being substantially independent of frequency over a broad frequency band, said apparatus comprising an auxiliary transmission line, and means directionally coupling said main and auxiliary lines over an interval of their lengths, said interval being equal to

$$\frac{\pi\sqrt{1-E^2}}{\beta_1-\beta_2}$$

unit lengths, wherein β_2 is the phase velocity constant of said auxiliary line along said interval of coupling, β_2 being substantially different from β_1 along said interval, whereby any inherent frequency selectivity of said coupling means is minimized.

2. The apparatus of claim 1, wherein said coupling means is a substantially distributed coupling per unit length along said length equal to the quantity

$$\frac{m\pi E}{2}$$

divided by said length, wherein m is any odd integer.

3. The apparatus of claim 1, wherein said coupling means comprises

$$\frac{m\pi E}{2 \sin^{-1} C}$$

discrete coupling elements, each coupling a fraction C

of the energy in one line into the other, and where m is any odd integer.

4. A network for abstracting an amplitude fraction E of available wave energy in an electromagnetic wave transmission system, said fraction being substantially independent of frequency over a broad frequency band, said network comprising a first electromagnetic wave transmission line interposed in said system, said first line having a phase velocity constant β_1 radians per unit length, a second electromagnetic wave transmission line interposed in said system, means directionally coupling said first and second lines over an interval along the lengths of said lines, said interval being equal to

$$\frac{\pi\sqrt{1-E^2}}{\beta_1-\beta_2}$$

unit lengths, wherein β_2 is the phase velocity constant of said second line along said coupling interval, β_2 being substantially different from β_1 along said interval, whereby any inherent frequency selectivity of said coupling means is minimized.

5. In combination, a first section of transmission line for electromagnetic wave energy, a second section of transmission line, and coupling means for coupling an amplitude fraction E of energy in said first line into said second line, said means being inherently directional and coupling said lines over a longitudinal length l of said lines, said means having an integrated coupling strength factor which is the product of the coupling strength per unit length of said means and said length when said coupling means is a distributed coupling along said length, and which is the product of the number of coupling points and the summations of the angle whose sine is the coupling strength at each of said points when said coupling means is a plurality of discrete couplings located at said points along said length, said integrated coupling strength factor being substantially equal to

$$\frac{m\pi E}{2}$$

radians wherein m is any odd integer, said lines having different phase velocity constants along said coupling interval, the difference between said constants being substantially equal to

$$\frac{\pi\sqrt{1-E^2}}{l}$$

radians per unit length.

6. A broad band electromagnetic wave-guide hybrid structure comprising a pair of wave-guide sections, said sections being coupled along an interval l of their lengths by a coupling having an integrated coupling strength factor equal to

$$\frac{\pi}{2\sqrt{2}}$$

radians, said sections having phase velocity constants which differ from each other by

$$\frac{\pi}{\sqrt{2}l}$$

radians per unit length in the region of said coupling.

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