

Feb. 16, 1960

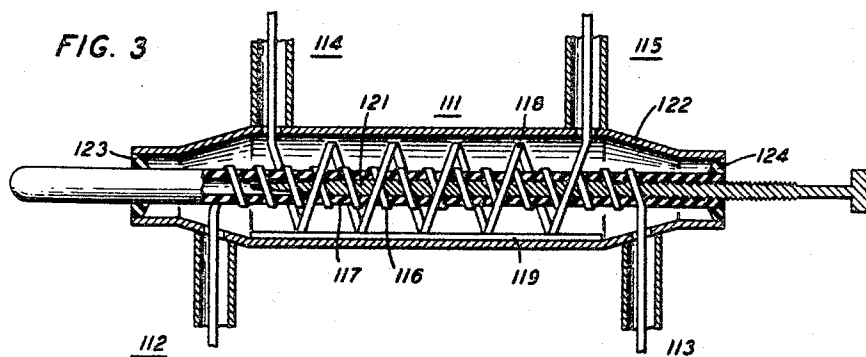
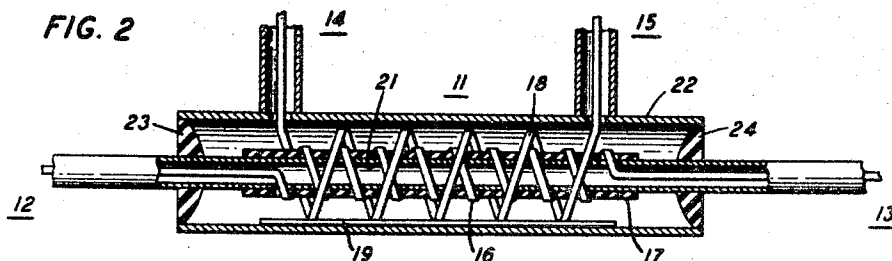
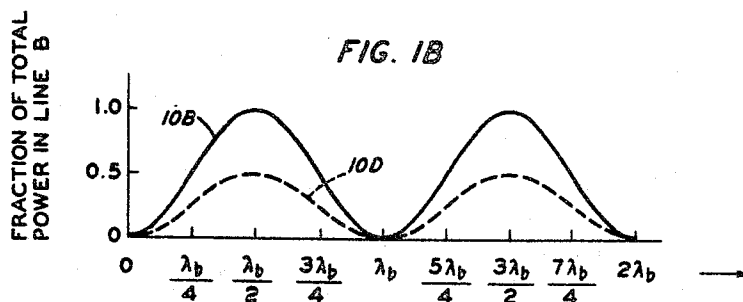
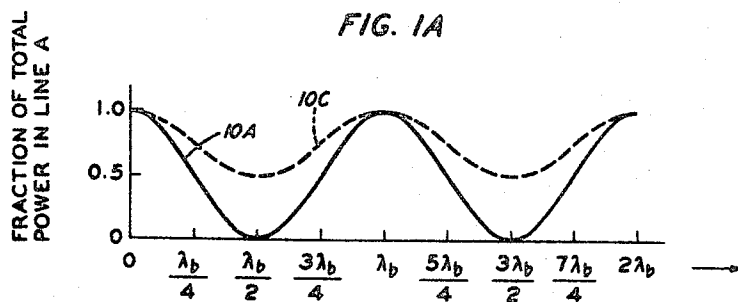
J. S. COOK ET AL

2,925,565

COAXIAL COUPLERS

Filed May 12, 1955

3 Sheets-Sheet 1



INVENTORS: J. S. COOK
R. KOMPNER
BY
Arthur J. Torrington
ATTORNEY

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FIG. 4A

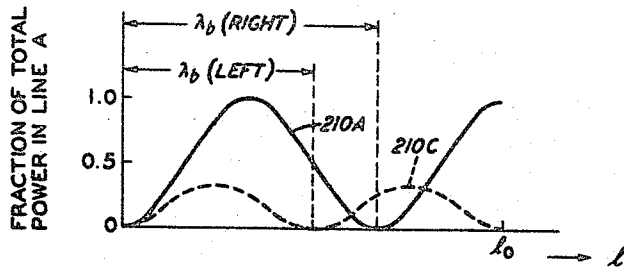


FIG. 4B

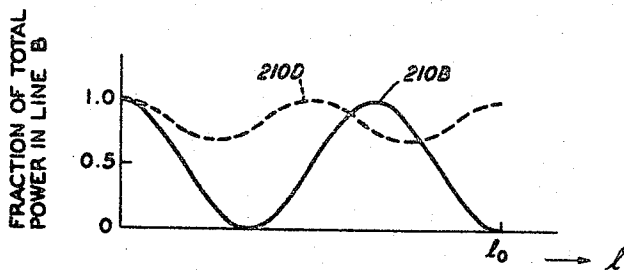


FIG. 5A

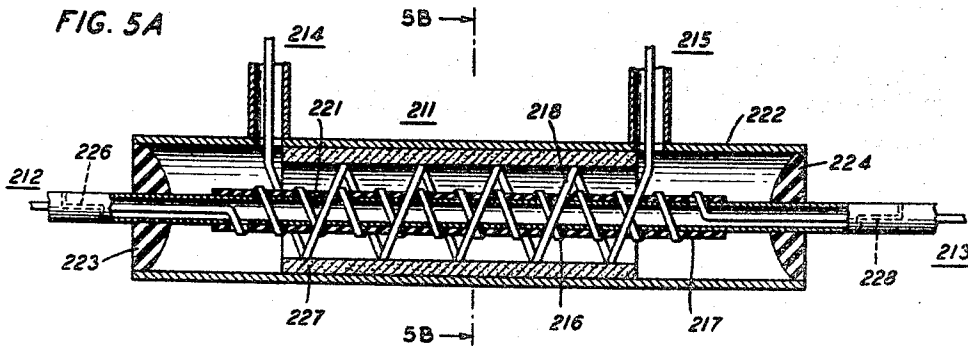


FIG. 5B

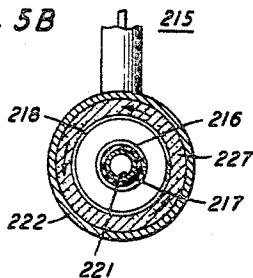
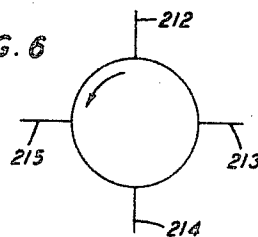


FIG. 6



INVENTORS: J. S. COOK
R. KOMPNER
BY
Arthur J. Tonzigian
ATTORNEY

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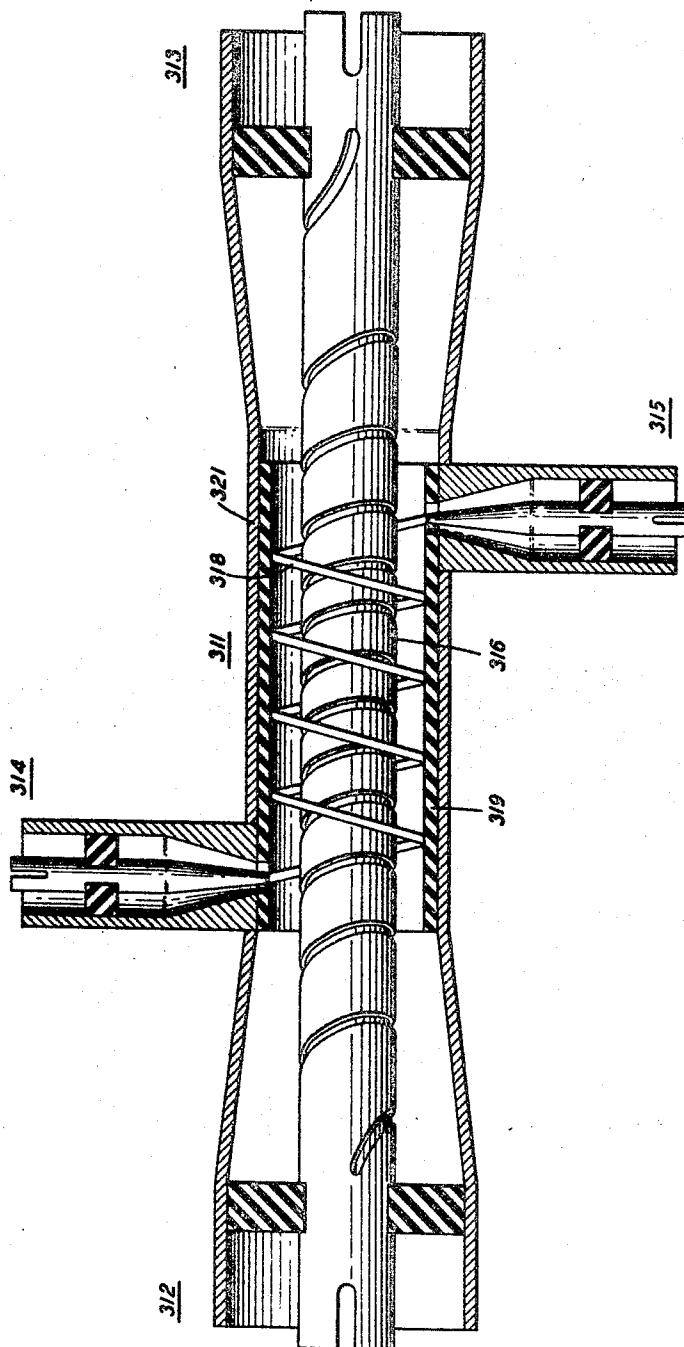
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FIG. 7



INVENTORS: J. S. COOK
R. KOMPNER
BY
Arthur J. Tossiglieri
ATTORNEY

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2,925,565

COAXIAL COUPLERS

John S. Cook, New Providence, and Rudolf Kompfner, Far Hills, N.J., assignors to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Application May 12, 1955, Serial No. 507,766

15 Claims. (Cl. 333-6)

The present invention relates to a broad band power dividing coupler for use in coupling wave energy between coaxial transmission lines.

It is important in many communication applications to couple selectively high frequency wave energy between separate wave paths. Various devices for accomplishing such selective coupling have been proposed for use in coupling hollow conductive wave guides, some of which are characterized by broad band operation. No entirely suitable coupler, however, is available for conveniently coupling energy between coaxial transmission line wave paths over broad frequency bands.

A principal object of the present invention, therefore, is to transfer conveniently high frequency wave energy selectively between coaxial lines over an extremely broad frequency band.

A feature of the present invention is a pair of concentrically arranged helical conductors, each helical conductor being connected between two coaxial transmission lines for selectively coupling wave energy between the coaxial lines over a broad frequency band, in the manner to be described.

A problem in connecting the coupler formed by the concentrically arranged helical conductors to coaxial transmission lines is the attainment of an impedance match between the concentric helical conductors and the coaxial lines over a broad frequency band. This difficulty arises because the characteristic impedance of the concentrically arranged helical conductors varies sharply with changes in frequency whereas the characteristic impedance of the coaxial line is substantially constant with frequency changes. Accordingly, although the coupler may be adjusted to have a characteristic impedance equal to the characteristic impedance of the coaxial lines at the center frequency of the operating band, the impedance match will no longer obtain for components of the wave whose frequency is significantly above or below the selected center frequency, and therefore reflections of these wave components will result. Such reflections result in a deterioration of the transmitted signal and limit the effective operating bandwidth of the coupler.

Another object of the present invention therefore is to increase the frequency range over which reflectionless coupling can be achieved between coaxial lines and a pair of coupled helices.

To this end, a feature of the present invention is a pair of concentrically disposed shielding members in combination with the concentrically arranged helical conductors, one of the shielding members being positioned to extend axially within the helical conductors, and the second shielding member being positioned to surround coaxially the helical conductors. Such an arrangement advantageously exhibits a characteristic impedance which is substantially constant over a wide frequency range and may be made equal to the characteristic impedance of the coaxial lines being coupled, thereby insuring reflectionless broad band operation.

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A related feature of the present invention is a tapered shielding member located axially within the helical conductors in combination with means for axially moving this tapered shielding member, whereby the degree of coupling between the helical conductors can advantageously be varied.

In accordance with the broad principles of the present invention, four coaxial transmission lines are coupled by a pair of helical conductors such that wave energy propagating along a predetermined one of the coaxial lines is selectively coupled to and divided among the other coaxial lines. The characteristic phase velocity of each of the two helical conductors and the length of coupling between the helical conductors are adjusted to effect the desired division of wave energy between the coaxial lines. The term "characteristic phase velocity" is used herein to denote the phase velocity of a wave propagating circuit, such as a helical conductor, independent of coupling to a second wave propagating circuit. For example, it denotes the phase velocity of a single helical conductor measured apart from a second coupling helical conductor.

A more complete understanding of the nature of the invention, together with a better appreciation of its features and advantages, will be obtained by a study of the following detailed description when read in connection with the accompanying drawings, in which:

Figs. 1A and 1B are graphs useful in explaining the principles of operation of the couplers of the present invention;

Fig. 2 is a longitudinal sectional view of one embodiment of the present invention to form a coupling arrangement;

Fig. 3 is a longitudinal sectional view of a modification of the coupling arrangement of Fig. 2;

Fig. 4 is a graph useful in explaining the principles of the coupling arrangement of Figs. 5A and 5B;

Fig. 5A is a longitudinal sectional view of a second embodiment of the present invention to form a coupling arrangement which may be used advantageously as a circulator;

Fig. 5B is a cross sectional view of the coupler of Fig. 5A taken through line 5B-5B of that figure;

Fig. 6 is a schematic representation of the circulator action of the coupling arrangement of Figs. 5A and 5B; and

Fig. 7 is a longitudinal sectional view of a third embodiment of the present invention.

Before describing the illustrated embodiments of the present invention it will be helpful to consider briefly the theory of operation of two coupled transmission lines. It has been found that when two transmission lines are placed in coupling proximity over a substantial portion of their length a periodic interchange of energy takes place between the two lines along their lengths. A portion of the energy initially in the first line will be transferred to the second line and, at a point further along the two coupled lines, will be transferred back to the first line; the interchange of energy between the lines occurring periodically along the length of the coupled lines and the distance required for a transfer from one line to the other and back to the first being referred to as λ_b , the "beat wavelength" of the coupled lines.

The exact nature of the energy interchange between two coupled transmission lines, which shall be designated lines A and B, can best be seen by referring to Figs. 1A and 1B of the drawing. In these figures, the fraction of the total propagating power, as the ordinate, is plotted against measures of the beat wavelength λ_b , as the abscissa. Curves 10A and 10B represent the fraction of the propagating energy which is in lines A and B. respec-

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tively, where lines A and B are effectively synchronous (i.e., have the same characteristic phase velocity). It will be seen that when two transmission lines having substantially equal characteristic phase velocities are coupled a complete energy transfer will be effected between the lines. Following curves 10A and 10B along their length it will be seen that the fraction of the energy contained in each of the two lines varies periodically. Initially, as shown by curve 10A, all of the energy is present in line A and, as shown by curve 10B, no energy is present in line B. At point

$$\frac{\lambda_b}{2}$$

along the abscissa, all of the energy has been transferred to line B, no energy remaining in line A. Further along the curves, at point λ_b on the abscissa, all of the energy is transferred back to line A. This is in accordance with the original definition of a beat wavelength as the distance along the coupling region required for a transfer of energy from one line to the other and back to the first. It will be noted that all of the wave energy will be back in line A at each point along the abscissa corresponding to a multiple of λ_b .

Of particular interest are the points along the curves 10A and 10B corresponding to abscissa values of

$$\frac{n\lambda_b}{4}$$

where n is a positive odd integer. At each of these points half of the wave energy is in each of the transmission lines. By maintaining the length of coupling between the two transmission lines at a length which corresponds to any one of these points there is provided a half-power transfer between the two transmission lines.

It is a characteristic of the two helical conductor transmission lines, when coupled together, that the beat wavelength λ_b can be maintained essentially constant over a certain range of frequencies. In such a coupling arrangement, however, changes in frequency beyond this range will tend to vary the beat wavelength. As a result a coupling length chosen to equal

$$\frac{\lambda_b}{4}$$

for a given frequency range will be equal to an appreciably different fraction of a beat wavelength for frequency components outside of the frequency range for which λ_b remains constant. In such a case a half-power transfer will no longer obtain for these components. For this reason an alternate method of obtaining a half-power transfer, which is less dependent upon changes in λ_b , is explained by reference to broken lines 10C and 10D of Figs. 1A and 1B, respectively.

Curves 10C and 10D represent the fraction of the propagating energy which is in coupled lines A and B, respectively, where lines A and B are not synchronous (i.e., do not have the same characteristic phase velocities). It is characteristic of coupled transmission lines that when the characteristic phase velocities of the two lines are uniform and unequal a total transfer of energy from one line to the other will never be realized. In such a case, where the coupled transmission lines have unequal uniform characteristic phase velocities, the maximum energy transfer is related to the ratio of the characteristic phase velocities of the two coupled lines. In the coupled lines represented by curves 10C and 10D, the ratio of the phase velocities of the two transmission lines is chosen so that the maximum power ever transferred between the lines is only half of the propagating power. In such a case, referring to curves 10C and 10D, it will be seen that initially all of the energy is present in line A. At point

$$\frac{\lambda_b}{2}$$

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along the abscissa, the point of maximum power transfer, half of the energy has been transferred to line B and, as in curves 10A and 10B, at point λ_b , along the abscissa the energy is transferred back to line A.

Of particular interest along curves 10C and 10D are points

$$\frac{n\lambda_b}{2}$$

where n is a positive odd integer. Each of these points is a point of half-power transfer and by maintaining the length of coupling between the two transmission lines, represented by these curves, at lengths which correspond to any one of these points there is effected a half-power coupler between the lines. For a coupling length approximately equal to

$$\frac{\lambda_b}{2}$$

or an odd multiple thereof, it will be observed from curves 10C and 10D, that because of the flatness of these curves in these regions, the amount of energy transferred between the coupled lines does not change appreciably with changes in the length of coupling. For this reason, greater tolerance is afforded in constructing the coupling arrangement. Moreover, because of the flatness of the curves in these regions, changes in λ_b , occasioned by substantial changes in frequency will have little effect on the amount of power which is transferred between two lines. Such a coupler will provide very nearly a half-power transfer even for substantial changes in λ_b .

Referring now more particularly to the embodiments of the present invention which have been illustrated for purposes of explanation, Fig. 2 shows a coupler 11, according to the present invention, which may be used as a broad band half-power hybrid coupler. In this figure four coaxial transmission lines 12, 13, 14 and 15 form the terminals of coupler 11. An inner helical conductor 16 which is supported on the dielectric cylinder 17, is connected at its opposite ends to the free ends of the inner conductors of coaxial lines 12 and 13, and an outer helical conductor 18 is connected at its opposite ends to the center conductor of coaxial lines 14 and 15. The outer helical conductor 18 is supported by three dielectric rods 19 symmetrically disposed around its periphery, only one of which can be seen in Fig. 2. The inner and outer helical conductors are positioned coaxially, and preferably wound in opposite senses for obtaining maximum effective coupling therebetween, and the ratio of the diameter of the outer conductor to the diameter of the inner conductor is advantageously approximately 3 to 2, for the reasons set forth in United States Patent 2,811,673, issued October 29, 1957, of R. Kompfner. For such a ratio the beat wavelength of the coupled conductors remains substantially constant over a broad frequency range. As explained in the cited Kompfner Patent, a maximum coupling can be obtained between the two helical conductors when they are properly wound in opposite senses. Although it is not necessary to have maximum coupling between the coupled helical conductors in the present coupling arrangement, nevertheless the conductors are wound in opposite senses to avoid the possibility of having zero coupling between the conductors, a situation which can prevail in the case of two coaxially positioned helical conductors which are wound in the same sense.

A cylindrical metallic shield 21 extending axially within inner helical conductor 16 forms an extension of the outer conductor of each of the coaxial transmission lines 12 and 13. A second cylindrical metallic shield 22 coaxially surrounds the outer helical conductor and is connected to the outer conductors of coaxial lines 14 and 15. The presence of metallic shields 21 and 22 advantageously makes the characteristic impedance curve of the arrangement of coupled helical conductors substantially constant with frequency. This makes possi-

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ble a broad band impedance match between the concentric helices and the coaxial transmission lines, which is essential to broad band operation. The shields further serve to lower the coupling strength between the coupled helices. This has the effect of increasing the beat wavelength of the coupler so that longer helix lengths are necessary, and therefore, the exact length is not so critical. In the absence of the shields a beat wavelength may disadvantageously be only a single helix turn. In such a case an exact quarter beat wavelength coupler will be only a quarter of a helix turn long and will be very difficult to construct accurately. In the presence of shields 21 and 22, however, a beat wavelength can typically be made twenty helix turns so that greater tolerance is allowed in constructing a quarter beat wavelength coupler.

Between the inner and outer cylindrical shields, at the ends of the coupler, are provided advantageously annular sections 23 and 24 which may be of any suitable lossy material. These annular sections serve both to support the inner cylindrical shield and the helix mounted thereon and to absorb any wave energy propagating along the helix which tends to transform into a coaxial transmission line mode and radiate from the ends of the coupler.

As discussed with reference to Figs. 1A and 1B a half-power coupler may be obtained in either of two ways, namely: (1) choosing the transmission paths, that is, the helical conductors, to have equal characteristic phase velocities and making the length of the coupling region equal to

$$\frac{n\lambda_b}{4}$$

where n is a positive odd integer, or (2) choosing their characteristic phase velocities uniform and unequal, such that the maximum power transfer between the helical conductors is one-half, and making the length of coupling equal to

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

where n is a positive odd integer.

To this end, equal characteristic phase velocities may be achieved by making the pitch angle of the two helices equal as shown in Fig. 1. With equal characteristic phase velocities the length of coupling is preferably adjusted to be a single quarter wavelength.

In the coupling arrangement utilizing two helical conductors having different characteristic phase velocities, which is the preferred embodiment of the present invention, the ratio of the characteristic phase velocities is chosen to afford a maximum power transfer of one-half. To determine the ratio of the characteristic phase velocities necessary to obtain a maximum power coupling of one-half reference may be had to equation (4.29) on page 57 of Technical Report No. 75, April 21, 1954, of the Electronics Research Laboratory of Stanford University. Rewriting this equation:

$$R_p = \frac{1}{1 + \frac{1}{\alpha} \left[\frac{1 - \alpha}{2K} \right]^2} \quad (1)$$

where R_p = the ratio of power transferred between the helices to the total power carried by the coupled helix structure, α = the ratio of the helix characteristic phase velocities, and K = coupling coefficient between the helices.

Where a maximum power transfer of one-half is desired the fraction $\frac{1}{2}$ is substituted for R_p in Equation 1 and the value for α obtained. It is found that the solution of Equation 1 requires that α equal

$$1 + 2K^2 \pm 2K\sqrt{1 + K^2}$$

This may be approximated as $1 \pm 2K$ for small values of coupling K , such as is characteristic of the coupler of Fig. 1 because of the presence of the cylindrical shields.

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After adjusting the pitch angle of the concentric helices to secure the proper characteristic phase velocities along the two helices the length of coupling should be set at

$$\frac{\lambda_b}{2}$$

In a half-power coupling arrangement obtained in either of the above two ways, the second of which is the preferred embodiment of the present invention, wave energy introduced into the coupler by coaxial line 14 will be divided in half as it propagates along outer helix 18, half of the energy remaining in the outer helix and passing to coaxial line 15 and half of the wave energy transferring to the inner helix and passing to coaxial line 13. Likewise, wave energy introduced by coaxial line 12 will be divided equally between coaxial lines 13 and 15, and wave energy introduced at either of coaxial lines 13 and 15 will be divided equally between coaxial lines 12 and 14. As such, coupler 11 operates as an extremely broad band hybrid coupler.

It can be appreciated by reference to Figs. 1A and 1B that a half-power coupling arrangement can also be obtained, in accordance with the present invention, by dimensioning the helix pitch angles to effect a ratio of the helix characteristic phase velocities necessary to give a maximum power transfer of more than half but less than unity, and adjusting the coupling length accordingly to be less than

$$\frac{\lambda_b}{2}$$

but more than

$$\frac{\lambda_b}{4}$$

A modification of the coupler described above is shown in Fig. 3. In this figure coaxial lines 112, 113, 114 and 115 are connected by the coupler 111. Inner helix 116 is connected at its opposite ends to the inner conductors of coaxial lines 112 and 113 and outer helix 118 is connected at its opposite ends to the inner conductors of coaxial lines 114 and 115. The outer helix, as in the coupling arrangement of Fig. 2, is supported by three dielectric rods 119 symmetrically disposed around its periphery, only one of which can be seen in Fig. 3. Unlike Fig. 2, however, the inner helix 116 is supported on an axially symmetric metallic rod-like member 121 distinct from the outer conductors of the coaxial lines being coupled. The metallic member is tapered at one end and surrounded by a hollow cylinder of dielectric material 117, which may be closed at one end. The hollow dielectric cylinder is threaded internally at one end to engage with the screw threads provided along the length of metallic rod 121. Moreover, rod 121 is provided with a screw head at its right-hand end for moving the rod axially within the inner helix. As the tapered metallic section of the rod is moved axially the shielding effect of the metallic member on the inner helix, and therefore the coupling between the helices, is varied, thereby varying λ_b . This enables a final adjustment of the coupler to be made in order to ensure exactly a half-power transfer. As in Fig. 2 the outer helix is surrounded by a cylindrical metallic shield 122, which in this case connects to the outer conductors of all four coaxial lines. The shield is tapered at each end and annular lossy members 123 and 124 are provided to inhibit radiation from the ends of the coupler. The annular lossy members also serve to support cylinder 117, being rigidly fixed thereto to prevent any axial movement of the dielectric cylinder as rod 121 is moved. The length of the coupling section and the characteristic phase velocities of the helices of coupler 111 may advantageously be chosen to provide a half-power hybrid coupler, as explained with reference to Fig. 1.

It should be noted that although the above coupling arrangements have been explained for use as half-power hybrid couplers, if desired, other fractions of the total

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propagating power may be transferred between the coupled helices by appropriately dimensioning the pitch angles and coupling lengths of the helices. For example, if a transfer of one-third of the power is desired this can be accomplished, in one manner, by adjusting the length of two synchronous coupled helices to equal the abscissa value of curves 10A and 10B of Figs. 1A and 1B which correspond to a transfer of one-third of the total propagating power. This will be found to be

$$\frac{\lambda_b}{6}$$

A second manner of achieving a one-third power transfer is to determine the ratio of the phase velocities of two coupled helices necessary to give a maximum power transfer of one-third from Equation 1, and, with the characteristic phase velocities so fixed, adjust the coupling length to be

$$\frac{n\lambda_b}{2}$$

where n is a positive odd integer. The ratio of phase velocities necessary to effect this transfer will be found to be $1+6K^2 \pm 2K\sqrt{3(1+3K^2)}$. Similarly, the ratio of phase velocities necessary for transferring any other fraction of the total propagating power can be determined from Equation 1 or by experimentation.

An illustrative embodiment of the present invention which serves as a circulator 211 is shown in Figs. 5A and 5B. This embodiment has been shown as a modification of the coupler of Fig. 2. Component parts corresponding to parts already described in connection with Fig. 2 have been given similar reference numerals, differing in numerical value by two hundred. In the place of the dielectric rods 119 of Fig. 2 which were spaced to support the outer helical conductor, there is positioned surrounding the outer helical conductor a cylinder of ferrite 227, or similar material of the kind which exhibits ferromagnetic resonance. The ferrite cylinder is permanently magnetized in order to produce a magnetic flux passing circumferentially therethrough, as shown by the arrows of Fig. 5B. As is well known in the art, such a ferrite element when magnetically biased as described can be made to provide nonreciprocal propagating characteristics for wave energy passing therethrough. In particular, the present coupling arrangement takes advantage of the nonreciprocal characteristic phase velocity of wave energy passing through the magnetically biased ferrite. In accordance with the present invention, since the ferrite member is closer to the outer helix 213 of the concentric pair, it will affect the characteristic phase velocity along that helix more than that of the inner helix; thus the characteristic phase velocity in one direction along the outer helix will be substantially different than in the other direction, whereas the characteristic phase velocity of the inner helix will be essentially the same in either direction.

In accordance with the present invention, the characteristic phase velocity of the inner helix is made equal to the characteristic phase velocity of the outer helix in one direction. Thus the two helices have equal characteristic phase velocities in one direction and substantially different characteristic phase velocities in the other direction. For such an arrangement both the beat wavelength λ_b and the maximum amount of power transferable back and forth between the lines is a function of the direction of wave propagation through the coupled helices.

The operation of the coupler of Figs. 5A and 5B will be understood more clearly by referring to the curves of Figs. 4A and 4B. Curves 210A and 210B show the transfer of power between the helices in going from left to right along the helices in the coupling region. Since the characteristic phase velocities of the two helices in this direction are equal, a complete energy transfer from one helix to the other and back to the first is effected.

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Passing from right to left along the helices, however, the helix characteristic phase velocities are unequal because of the presence of the magnetically biased ferrite member and both λ_b and the fraction of propagating power transferred between the helices in this direction are considerably reduced, as shown by broken line curves 210C and 210D. By properly selecting the helix dimensions and the characteristics of the nonreciprocal material, curve 210C can be made to have a minimum at a point where curve 210A has a maximum. On the graph of Figs. 4 and 4B this point is labeled l_0 . For such a case, by fixing the coupling length to be l_0 all of the energy passing from left to right along either helix will be transferred to the opposite helix; whereas energy passing from right to left along either helix will first be transferred to the opposite helix but will subsequently all be returned to the helix in which it originated.

In operation, energy introduced into coupler 211 by coaxial line 213 will pass along inner helix 216 from right to left being transferred to outer helix 218 and back, finally all being coupled to coaxial line 212. Likewise, energy introduced at coaxial line 215 will all be coupled to coaxial line 214. Energy introduced at coaxial line 212 in passing along the inner helix from left to right will all be transferred to the outer helix, thereby being coupled to coaxial line 215 and, similarly, energy introduced at coaxial line 214 will be transferred from the outer helix to the inner helix and thereby coupled to coaxial line 213.

This operation is illustrated by the schematic representation of a circulator shown in Fig. 6. In this circulator energy introduced at any of the four terminals will be coupled to the terminal adjacent thereto in the direction of the arrow, but will not, however, be coupled to the terminal adjacent thereto in the direction opposite to the arrow.

In practice it will be advantageous to space the ferrite cylinder 227 of Fig. 5A slightly away from the outer helical conductor 218 for reducing the attenuation which the ferrite introduces. This spacing may be provided by a thin cylinder of dielectric material. The spacing provided by the dielectric should be chosen experimentally to give the desired nonreciprocal characteristic phase velocity to the outer helical conductor with a minimum amount of added attenuation therealong.

An alternative arrangement for providing broadband reflectionless operation is the embodiment shown in Fig. 7. In this figure four coaxial lines 312, 313, 314, and 315 form the terminals of coupler 311. An inner helical conductor 316 is connected at its opposite ends to the inner conductors of coaxial lines 312 and 313. This helical conductor is advantageously formed by grooving helically a conductive cylinder which is connected at its opposite ends to the inner conductors of coaxial lines 312 and 313. The pitch of the helical grooving is tapered along the end sections of the grooving and maintained constant intermediate said end sections for forming tapered end sections of the helical conductor 316 and a uniform section intermediate the tapered end sections. These tapered sections serve as impedance transforming sections for matching the characteristic impedance of the coupler to the characteristic impedance of the coaxial lines. By utilizing such impedance matching sections having sufficient length the inner helical conductor of coupler 311 will remain matched to coaxial lines 312 and 313 even for substantial changes in impedance of the helical conductor. Such impedance matching sections therefore obviate the need for a shielding member adjacent the inner helical conductor, as was required in the previously described embodiments for maintaining the impedance of the inner helical conductor constant.

An outer helical conductor 318 surrounds the inner helical conductor over its region of uniform pitch; being connected at its opposite ends to the inner conduc-

tors of coaxial lines 314 and 315. The inner and outer conductors of coaxial lines 314 and 315 are tapered such as to keep constant the ratio of the diameters of the outer-to-inner conductors in order to avoid any impedance discontinuity where the inner conductors of these coaxial lines connect to the smaller dimensioned conductor 318. Helical conductor 318 is supported by a surrounding cylinder of dielectric material 319. This cylinder may be of any suitable dielectric material which exhibits reciprocal propagating properties for effecting coupler action as described with reference to the coupling arrangements of Figs. 2 and 3. Alternatively, the dielectric material of cylinder 319 may be chosen to exhibit ferromagnetic resonance for effecting circulator action as described with reference to Fig. 5A. In the latter case means for producing a circumferential magnetic flux through the dielectric cylinder, as described in Fig. 5A, must be employed.

Metallic cylinder 321 surrounds dielectric cylinder 319. This metallic cylinder serves as a conductive shield for maintaining the impedance of the outer helical conductor substantially constant with frequency for ensuring reflectionless coupling to coaxial lines 314 and 315. Cylinder 321 forms an extension of the outer conductors of coaxial lines 312 and 313; being tapered from the region of the coupled helical conductors to the coaxial lines for avoiding impedance discontinuities in this region. Each of the four coaxial lines is provided with an annular dielectric member for supporting the inner conductor within the outer conductor, as is a known practice in the art.

It is understood that the above described specific embodiments are merely illustrative of the general principles of the invention. Various other arrangements may be devised by one skilled in the art without departing from the spirit and scope of the invention. In particular, various ratios of helix characteristic phase velocities may be provided in the coupling arrangement of Figs. 2 and 3 for effecting the transfer of any fraction of the total propagating power. Furthermore, the length of the coupling region of the nonreciprocal coupling arrangement of Figs. 5A and 5B may be changed to effect different nonreciprocal power transfers. Further, the circumferentially directed flux passing through the ferrite cylinder of the coupling arrangement of Figs. 5A and 5B may be provided by various techniques, other than permanently magnetizing the ferrite. For example, permanent magnetic material in the shape of circular sectors which are magnetically polarized to provide circularly directed magnetic flux may be employed. Also, electromagnetic flux producing means may be employed, such as means for passing a low frequency electric current through the inner conductive shield 221 of Fig. 5A. In such a case the section of the inner conductive shield which passes within the ferrite cylinder can be insulated for the low frequency current flow from the remainder of its length by inserting dielectric material in the region of the dotted lines 226 and 228 of Fig. 5A.

What is claimed is:

1. A high frequency power dividing coupler for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, a first wave propagating helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second wave propagating helical conductor electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, said second helical conductor being positioned to surround the first helical conductor in energy coupling proximity therewith over a predetermined length, each of said coaxial line terminals being adapted for use as a signal input terminal, a cylindrical conductive shield positioned to surround said second helical conductor over a major portion of said predetermined length and means for maintaining a

uniform impedance match between said first helical conductor and the coaxial line terminals connected thereto.

2. A high frequency power dividing coupler for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor having a characteristic phase velocity substantially different from that of the first helical conductor and being electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, the difference in characteristic phase velocity between the first and second helical conductors being substantially constant over substantially the entire operating band for providing a desired maximum power transfer between the helical conductors, said second helical conductor being positioned in energy coupling proximity with said first helical conductor over a length of

$$\frac{n\lambda_b}{2}$$

where n is any positive integer and λ_b is the beat wavelength of the coupled helical conductors, and each of said coaxial line terminals being adapted for use as a signal input terminal.

3. The combination of elements set forth in claim 2 wherein the second helical conductor is positioned to surround the first helical conductor.

4. The combination of elements set forth in claim 2 wherein the ratio of the characteristic phase velocities of the two helical conductors is approximately

$$1+2K^2 \pm \sqrt{1+K^2}$$

where K is the coupling coefficient of the coupled helical conductors.

5. The combination of elements set forth in claim 2 wherein the ratio of the characteristic phase velocities of the two helical conductors is $1+6K^2 \pm \sqrt{3(1+3K^2)}$, where K is the coupling coefficient of the coupled helical conductors.

6. A high frequency power dividing coupler for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, said second helical conductor being positioned to surround the first helical conductor in energy coupling proximity therewith over a predetermined length, each of said coaxial line terminals being adapted for use as a signal input terminal, a cylindrical conductive shield positioned to surround the outer helical conductor over a major portion of said predetermined length, and a conductive shield positioned axially within the inner helical conductor along a major portion of said predetermined length.

7. A high frequency power dividing coupler for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, said second helical conductor being positioned to surround the first helical conductor in energy coupling proximity therewith over a predetermined length, each of said coaxial line terminals being adapted for use as a signal input terminal, a cylindrical conductive shield positioned to surround the outer helical conductor over a major portion of said predetermined length, and a tapered conductive shield positioned axially within the

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inner helical conductor over a major portion of said predetermined length, said tapered shield being movable along the axis of said inner helical conductor whereby the coupling between the inner and outer helical conductors may be altered.

8. A high frequency power dividing coupler for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, each of said terminals being adapted for use as a signal input terminal, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor having a characteristic phase velocity substantially different from that of the first helical conductor and being electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, the difference in characteristic phase velocity between the first and second helical conductors being substantially constant over substantially the entire operating band for providing a desired maximum power transfer between the helical conductors, said second helical conductor being positioned in energy coupling proximity with said first helical conductor over a length of

$$\frac{n\lambda_b}{2}$$

where n is any positive integer and λ_b is the beat wavelength of the coupled helical conductors, the predetermined length of coupling and the difference in characteristic phase velocities of the two helical conductors being chosen for a maximum power transfer of one half between the helical conductors, a cylindrical conductive shield positioned to surround coaxially the outer helical conductor over a major portion of said predetermined length, and a conductive shield positioned axially within the inner helical conductor over a major portion of said predetermined length.

9. A high frequency power dividing coupler for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, each of said terminals being adapted for use as a signal input terminal, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor having a characteristic phase velocity substantially different from that of the first helical conductor and being electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, the difference in characteristic phase velocity between the first and second helical conductors being substantially constant over substantially the entire operating band for providing a desired maximum power transfer between the helical conductors; said second helical conductor being positioned to surround coaxially the first helical conductor in energy coupling proximity over a distance of

$$\frac{n\lambda_b}{2}$$

where λ_b is a beat wavelength of the coupled helical conductors, a cylindrical conductive shield positioned to surround the outer helical conductor over a major portion of said distance, and a conductive shield positioned axially within the inner helical conductor over a major portion of said distance.

10. The combination of elements set forth in claim 9 wherein the ratio of the characteristic phase velocities of the two helical conductors is approximately

$$1+2K^2 \pm 2K\sqrt{1+K^2}$$

where K is the coupling coefficient of the coupled helical conductors.

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11. A high frequency circulator for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, a nonreciprocal ferromagnetic member positioned in energy coupling proximity with said second helical conductor, and means for magnetically biasing said ferromagnetic member for nonreciprocally affecting the characteristic phase velocity of the second helical conductor.

12. A high frequency coupler for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, said second helical conductor being positioned to surround the first helical conductor in energy coupling proximity therewith over a predetermined length, a ferrite member extending over a major portion of said predetermined length in coupling proximity with one of said helical conductors, and means for magnetically biasing said ferrite member in a direction parallel to the circumference of said helical conductor with which it is coupled.

13. A high frequency circulator for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, said second helical conductor being positioned to surround the first helical conductor in energy coupling proximity therewith over a predetermined length, a cylindrical nonreciprocal ferromagnetic member positioned to surround said second helical conductor over a major portion of said predetermined length, and means for magnetically biasing said ferromagnetic member in a direction parallel to the circumference of said second helical conductor.

14. The combination of elements set forth in claim 12 wherein the first and second helical conductors have substantially equal characteristic phase velocities.

15. A high frequency circulator for operation over a broad frequency band comprising first and second pairs of coaxial transmission line terminals, a first helical conductor electrically connected at its opposite ends to the respective inner conductors of said first pair of coaxial line terminals, a second helical conductor electrically connected at its opposite ends to the respective inner conductors of said second pair of coaxial line terminals, said second helical conductor being positioned to surround the first helical conductor in energy coupling proximity therewith over a predetermined length, a nonreciprocal ferromagnetic member positioned in energy coupling proximity with one of said helical conductors over a major portion of said predetermined length, means for magnetically biasing said ferromagnetic member in a direction parallel to the circumference of the helical member with which it is coupled, a cylindrical nonmagnetic conductive shield positioned to surround the outer helical conductor over a major portion of said predetermined length, and an axially symmetric nonmagnetic conductive shield positioned axially within the inner helical conductor over a major portion of said predetermined length.

References Cited in the file of this patent

UNITED STATES PATENTS

2,452,529	Snoek	Oct. 26, 1948
2,509,057	Guanella	May 23, 1950
2,588,832	Hansell	Mar. 11, 1952
2,701,338	Boyer	Feb. 1, 1955
2,707,759	Pierce	May 3, 1955
2,724,806	Tillotson	Nov. 22, 1955

2,725,499

2,726,291

2,755,447

2,773,213

2,811,673

716,257

Field	Nov. 29, 1955
Quate	Dec. 6, 1955
Englemann	July 17, 1956
Dodds	Dec. 4, 1956
Kompfner	Oct. 29, 1957

FOREIGN PATENTS

Great Britain	Sept. 29, 1954
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