

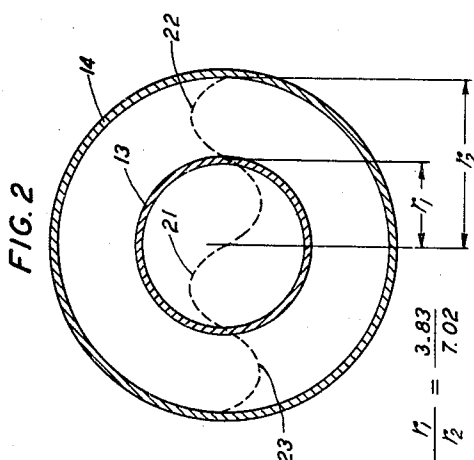
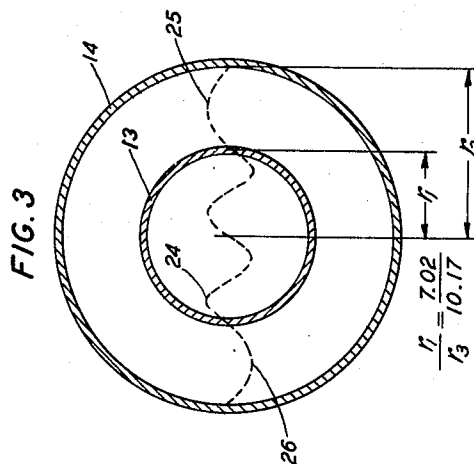
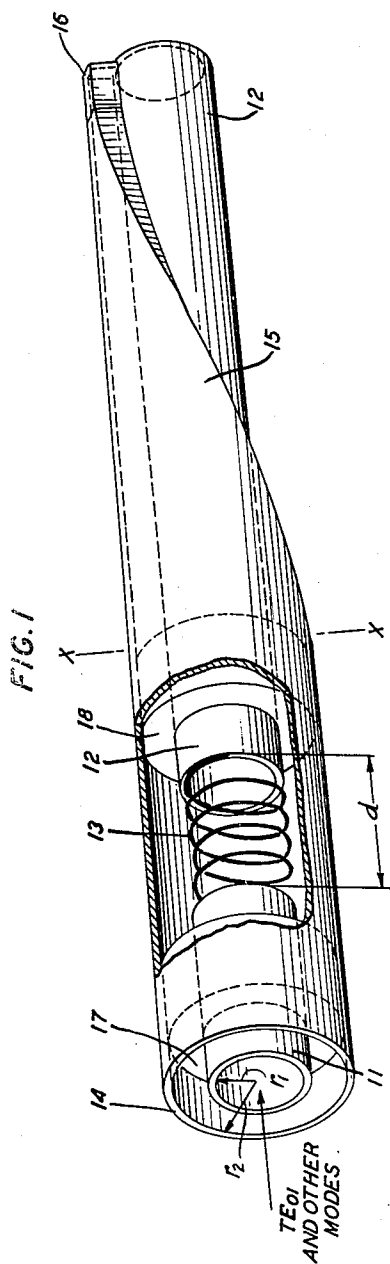
Aug. 30, 1960

E. A. J. MARCATILI
MODE SELECTIVE DEVICES FOR CIRCULAR
ELECTRIC WAVE TRANSMISSIONS

2,951,219

Filed Dec. 29, 1958

2 Sheets-Sheet 1



INVENTOR
E. A. J. MARCATILI
BY *Ray M. Porter, Jr.*

ATTORNEY

Aug. 30, 1960

Filed Dec. 29, 1958

E. A. J. MARCATILI
MODE SELECTIVE DEVICES FOR CIRCULAR
ELECTRIC WAVE TRANSMISSIONS

2,951,219

2 Sheets-Sheet 2

FIG. 4

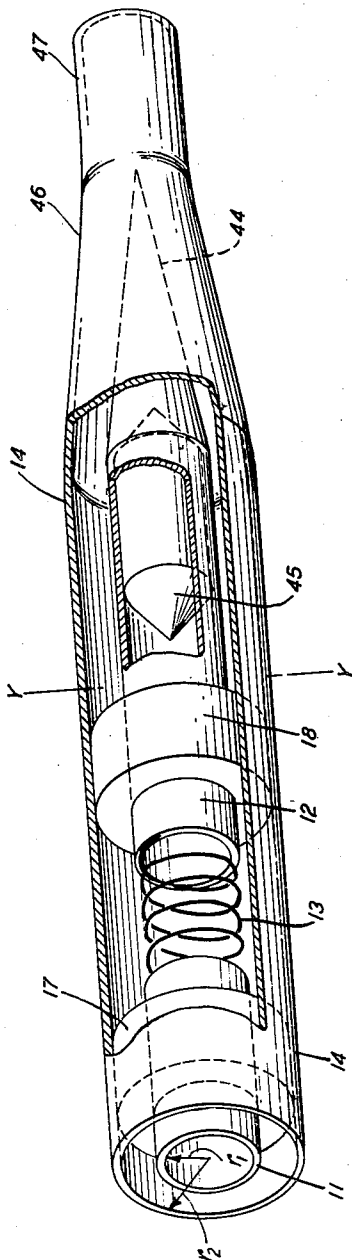
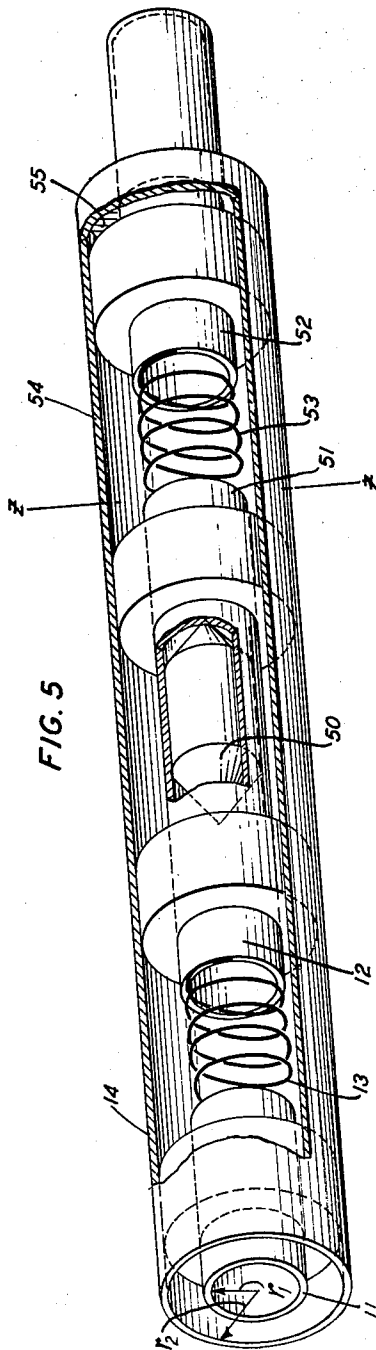


FIG. 5



INVENTOR
E. A. J. MARCATILI
BY *Ray M. Porter Jr.*

ATTORNEY

1

2,951,219

MODE SELECTIVE DEVICES FOR CIRCULAR ELECTRIC WAVE TRANSMISSIONS

Enrique A. J. Marcantili, Fair Haven, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

Filed Dec. 29, 1958, Ser. No. 783,224

7 Claims. (Cl. 333—10)

This invention relates to electromagnetic wave transmission systems whose primary mode of propagation is the circular electric mode, and more particularly to wave guide couplers and/or mode filters for use in such systems whose geometries are intrinsically compatible with the circular electric mode to provide efficient coupling and complete filtering.

One very important operation in any microwave transmission system is that of transferring energy from one transmission line to another, either completely, or in various desired ratios, for the purpose, for example, of sampling energy from the main transmissions path, or introducing wave energy into the main transmission path from a repeater station or for abstracting energy from the main transmission path into the repeater.

In my copending application, Serial No. 724,724, filed March 28, 1958, there is disclosed a directional coupler which accomplishes this purpose wherein the coupling is provided between two transmission lines each of which supports energy in the circular electric mode. One of the substantial advantages of this directional coupler is its unusually broad bandwidth.

One of the problems in circular electric mode energy transmission is that of mode conversion. This directional coupler has the particular advantage of refraining from generating spurious modes. However, it in no way is capable of rectifying the situation once the spurious modes have been developed in the system.

It is accordingly one of the main objects of this invention to directionally couple two transmission lines on a highly mode selective basis such that one and only one mode, circular symmetric in nature, may be transferred between the two lines in any proportion desired.

In accordance with the invention, this object is accomplished by a directional coupler whose geometry is related to that of the circular symmetric mode field patterns in a manner which is particularly congruent therewith, and whose phase constants are arranged so that energy in one and only one circular symmetric mode will be transferred between the transmission lines. Specifically, a circular wave guide is provided having a gap interrupting its longitudinally extending conductive boundary. Adjacent ends of the wave guide define the longitudinal extent of the gap. Connecting these two ends, and therefore extending the length of the gap, is a helical metallic member. Coaxial with and circumscribing the round guide in the region of the helix is a second round guide. The radial dimensions of the coaxially related guides are proportioned such that the phase constant of the internal guide, including the helix, for a particular circular symmetric TE_{0n} mode for a given frequency band of interest is precisely the same as that of the external guide for that same mode in coaxial pipe at that same frequency band of interest. Accordingly, wave energy propagating through the internal guide upon reaching the helix will excite in the outside coaxial guide in the region of the helix solely the TE_{0n} mode for which the guides have equal phase

2

constants. No other mode capable of being supported in the external guide will be excited since the phase constants of all other modes will be unequal in the two guides. The amount of energy coupled from the internal to the external guide is directly dependent upon the length of the helix and the pitch thereof. If the helix has a zero pitch, no energy is coupled; the larger the pitch the greater the amount of TE_{0n} mode energy that is transferred per unit length. For any given pitch, providing a given magnitude of coupling per unit length of a helix, a fixed helix length will of course provide a specified total magnitude of energy transfer between the lines. Power division may in this way be obtained in any amount desired from zero to complete transfer. Coupling of this type is, of course completely reciprocal and energy commencing its trip in the external coaxial guides will be transferred to the internal guide by precisely the same mechanism just described.

It is well known that various types of modes, spuriously generated in a circular electric mode system may be eliminated by mode attenuating filters. However, none of the mode filters known in the prior art is capable of eliminating all the modes other than the one desired to be left undisturbed. For example, in a system operative in the TE_{01} mode, it has been necessary to develop a separate filter to eliminate higher order circular symmetric modes. The mode selective feature of the directional coupler in accordance with the invention may be utilized to provide mode filtering action which overcomes the above-discussed difficulties.

It is therefore an additional object of this invention to filter on a mode selective basis all modes except the TE_{01} circular electric mode in a circular wave guide.

This is readily accomplished in accordance with the invention through the utilization of the directional coupler discussed above. Since the directional coupler is capable of spatially separating any desired TE_{0n} mode from any and all other modes including different order TE_{0n} modes, the undesired modes may then be attenuated by resistive material to the exclusion of the desired TE_{01} mode.

Other objects and certain features and advantages of the invention will become apparent during the course of the following detailed description of the specific illustrative embodiments of the invention shown in the accompanying drawings.

In the drawings:

Fig. 1 is a perspective view of a directional coupler embodiment in accordance with the invention which is mode selective for the TE_{01} mode;

Fig. 2 and Fig. 3 are graphic presentations for purposes of illustrating the relationship between electric field intensity in circular wave guide and the radii of the guides;

Fig. 4 is a mode filter utilizing the mode selective features of the directional coupler in accordance with the invention and operative to isolate the TE_{01} mode from all other modes; and

Fig. 5 is another mode filter used for isolating the TE_{01} mode wherein two of the directional couplers are utilized in tandem separated by mode attenuating material.

In more detail, Fig. 1 is a perspective view of a directional coupler in accordance with the invention whose structural geometry is compatible with that of the field pattern of the circular electric mode. Fig. 1 may be conveniently considered as comprising two sections; the first, which is indicated as being to the left of cross section X—X, is the directional coupler itself; the second to the right of X—X is a standard transducer for abstracting wave energy from one port of the directional coupler and

for converting it into dominant mode wave energy in rectangular guide.

Considering now the directional coupler itself, there is disclosed two lengths 11 and 12 of hollow conductive wave guide having a circular transverse cross section, each of which is proportioned to support the circular electric TE₀₁ mode over the entire operating frequency range. Guides 11 and 12 are of the same transverse dimensions having, as indicated, the same radius r_1 , and are colinearly disposed in longitudinal succession with adjacent ends spaced from each other by a given distance d . Guides 11 and 12 are electrically coupled to each other over this distance by a helix 13 having a pitch to be defined hereinafter and formed of similar conductive material as guides 11 and 12 themselves. Surrounding guides 11, 12 and helix 13, and coaxially disposed with respect to each of them, is a hollow conductive wave guide 14 of circular transverse cross section providing a conductive boundary thereabout. As indicated, guide 14 in the region of the helix 13 has a radius indicated as r_2 . The radii r_1 and r_2 have certain special values which will be discussed in greater detail below in connection with Figs. 2 and 3.

Guides 11 and 12 may be supported within guide 14 in any of several methods well known in the art, for example, hollow dielectric cylinders or washers 17 and 18 may be used as coaxial spacers; alternatively thin metallic rods may extend radially from the external surface of guides 11 and 12 to the internal surface of guide 14 to support the internal guides in coaxial relation to the external guide. In this latter arrangement the TE₀₁ mode remains undisturbed by the supporting metallic rods since the circular electric mode has electric lines of force in the form of concentric circles which would everywhere be perpendicular to the metallic rods so that the rods do not act as impedance discontinuities for any of the TE_{0n} modes.

For ease of reference, the terms coaxial guides 11—14, 12—14 or 13—14 will designate the wave guiding path comprising the annular region between guide 11, guide 12 or helix 13, respectively and the internal boundary of guide 14.

In the operation of the directional coupler of Fig. 1, wave energy in the form of the TE₀₁ mode plus any number of spuriously generated higher order circular symmetric modes, may propagate from the left to the right in guide 11 until helix 13 is reached. As is well known in the art, a helix wave guide can support the propagation of TE_{0n} modes since the wall currents of these modes are circular and transverse to the direction of propagation of wave energy in the guide and consequently find conductive paths in the helix. If any non-circular electric modes are also present, their longitudinally extending wall currents cannot be supported in the helix and these modes will be presented with an infinite impedance due to the interruptions between adjacent portions of the helix. As a consequence, multimode energy reaching helix 13 will behave as follows: Most of the noncircular symmetric mode energy will be reflected back from helix 13 with only a negligible amount leaking past or through the helix into guide 12 or into guide 13—14. In the case of TE_{0n} mode energy, however, it will all continue propagating into helix 13. If the pitch of the helix or the space between the adjacent portions in the helix is at least several times larger than the diameter of the helical conductor, TE_{0n} mode energy may leak from the helix into guide 13—14. Thus, in order to provide a given amount of TE_{0n} mode transfer from guide 11 to guide 13—14, the length of helix 13 and the pitch of the helix must be proportioned relative to each other. The greater the pitch the greater the magnitude of coupling per unit length of the helix, and thus the shorter the total length of the helix need be to provide complete transfer.

Radii r_1 and r_2 of guides 11 and 14, respectively, are

proportioned in a manner now to be described to select which one of the several TE_{0n} modes, and only that mode, is coupled from the helix 13 to guide 13—14, and to insure that a complete transfer of power may be made therebetween in this mode. For this purpose it is necessary that the phase constant of the wave inner transmission path represented by helix 13 be equal to the phase constant of the coaxial wave transmission path represented by the region between helix 13 and guide 14 for the selected mode, exclusively, over the operating range of the coupler. This results in selective coupling of the one mode since it is well known in the art that only with equal phase constants in two transmission paths is complete coupling therebetween possible, and the greater the differential between the phase constants of the two paths the greater the isolation therebetween. For a more detailed discussion of this subject see S. E. Miller's "Coupled Wave Theory and Wave Guide Applications," Bell System Technical Journal, May 1954, pages 661 through 719.

For example, in order to couple the TE₀₁ mode from the inner path 13 into a TE₀₁ coaxial mode in the coaxial path 13—14, radii r_1 and r_2 are proportioned as shown in Fig. 2 which represents a transverse cross-sectional view of helix 13 and guide 14 along with a representative tangential electric field intensity distribution. Curve 21 represents the distribution of the TE₀₁ mode that can be supported within helix 13. Curves 22 and 23 taken together represent the mode which is referred to herein as the TE₀₁ coaxial mode. Projecting curves 22 and 23 into the helix region along the line of curve 21, a distribution similar to the TE₀₂ mode in circular guide 14 is obtained. However, it should be noted that these characteristics cannot be taken to represent the total electric field at a given time for, in fact, the field represented by 21 is 90 degrees out of phase with the field represented by 22 and 23 and the relative amplitudes depend upon the interval over which coupling has been maintained. They do, however, serve to represent the conditions under which the TE₀₁ and TE₀₁ coaxial distributions will have the same phase velocities and equal guide wavelengths. As is well known, the guide wavelength of a particular mode of wave energy propagation in any guide depends upon the cutoff wavelength of that guide and if the cutoff wavelength for any mode in each of two guides is made equal, the guide wavelength of the two modes will be equal regardless of frequency. In circular wave guides, the cutoff wavelength λ_c for a particular mode is determined by the radius r according to

$$\lambda_c = \frac{2\pi r}{k_{mn}}$$

in which k_{mn} is the Bessel function constant for the particular mode. For the modes of interest here, characteristic values of k_{mn} which are the first three roots of the first order Bessel function are:

$$\begin{aligned} \text{TE}_{01} \quad k_{01} &= 3.83 \\ \text{TE}_{02} \quad k_{02} &= 7.02 \\ \text{TE}_{03} \quad k_{03} &= 10.17 \end{aligned}$$

The TE₀₁ mode represented by characteristic 21 in inner path 13 has a cutoff and phase velocity determined by radius r_1 . Since the mode referred to here as the TE₀₁ coaxial mode represented by characteristic 22—23 is the same as the outer one-half part of a TE₀₂ mode, it has a cutoff and phase velocity determined by radius r_2 for the theoretical TE₀₂ mode represented by characteristic 22—21—23. Actually this TE₀₂ mode does not exist but since helix 13 falls at a null in its theoretical distribution, the presence of the helix has no effect upon the phase velocity of the portion of the mode that does exist. Thus, TE₀₁ mode 21 and TE₀₁ coaxial mode

5

22—23 have equal cutoffs and equal phase velocities if the ratio of r_1 to r_2 is

$$\frac{7.02}{3.83}$$

Under this condition the TE_{01} mode in guide 11 will be coupled into the TE_{01} coaxial mode in guide 13—14. All other modes have unequal phase velocities and will not be coupled. It is understood, of course, that unloaded guides are contemplated and if either guide is loaded, the radius ratios must be adjusted accordingly. Alternatively, the energy coupled into guide 13—14 could be in the form of the TE_{02} coaxial mode. This may be achieved by enlarging guide 14 so that its radius bears a ratio to the radius of helix 13 of

$$\frac{10.17}{3.83}$$

If, instead, it is desired to couple the TE_{02} mode from guide 11 into the TE_{01} coaxial mode in guide 13—14, the respective radii are proportioned as shown in Fig. 3 so that the cutoff for the TE_{01} mode in guide 11, represented by characteristic 24, is equal to the cutoff of the theoretical TE_{03} mode represented by characteristic 25—24—26, of which the TE_{01} coaxial mode 25—26 is the outer one-third part. Thus, the ratio of the radius r_1 of helix 13 to radius r_3 of guide 14 is

$$\frac{7.02}{10.17}$$

The coaxial mode energy in guide 13—14 is readily transferred to guide 12—14.

With the TE_{01} coaxial mode in guide 12—14 at cross section X—X, it is now appropriate to consider how this transferred wave energy may be utilized, or abstracted from the wave guide system. This is readily accomplished in a manner well known in the art by the mode transducer constituting the section to the right of line X—X in Fig. 1. The device to the right of the directional coupler is a transducer for converting the coaxial TE_{01} mode propagating in guide 12—14 into the dominant mode in a rectangular wave guide 16. This is in essence a mode converter of the type disclosed in "Principles and Applications of Wave Guide Transmission" by G. C. Southworth, D. Van Nostrand and Co., at page 363. The converter portion 15 progressively varies the transverse shape of the double pipe coaxial guide such that the boundary between guides 12 and 14 is gradually tapered to a rectangular cross section. In this way the TE_{01} coaxial mode is gradually deformed into the TE_{10} dominant mode in rectangular guide to continue propagating along the rectangular guide 16 to the right, to be utilized as desired with standard techniques.

Such a mode converter may also be utilized at the other end of the directional coupler so that energy entering guide 12 from the right would be transferred to guide 11—14 and could thence be taken out by the wave converter. An arrangement such as this would also be useful in a long distance wave guide system. Wave energy from the long distance circular wave guide 11 could be transferred through guide 12—14 to rectangular guide 16 and thence to a repeater station (not shown) for proper amplification, timing, modulation and the like, and could be reintroduced into the wave guide system by means of the wave converter to the left of the directional coupler discussed above (not shown) and thence from guide 11—14 for continued propagation along guide 12.

It should be noted that the helix 13 may be replaced by a series of spaced thin metallic rings of conductive material which may be supported in the external guide by dielectric spacers or the thin radial rods. The use of the spaced rings has the advantage over the helix that there is absolutely no longitudinal conductive material

6

to support wall currents. On the other hand, the helix coupling arrangement is considerably easier to fabricate than that of the spaced rings.

The embodiments of Figs. 4 and 5 now to be described, utilize the mode selective features of the directional couplers described thus far to provide unique mode filtering arrangements. In each case the directional coupler, proportioned to provide complete power transfer between transmission lines, is utilized to spatially isolate solely the desired mode of propagation, namely the TE_{01} circular electric mode, from all other spuriously generated modes in the system. The spurious modes are then passed through an attenuator comprising resistive material filling a wave guide portion, while the TE_{01} mode is shunted around this section.

Considering Fig. 4 in greater detail, it may be noted that to the left of the cross section Y—Y there is represented a directional coupler for transferring the TE_{01} mode from an inner guide 11 to an outer coaxial portion. In brief, this directional coupler is identical to the directional coupler represented to the left of the cross section X—X in Fig. 1. To the right of line Y—Y, however, there is disclosed a mode attenuating structure. More specifically the internal guide 12 continues on to the right from Y—Y and gradually tapers into a conically shaped section 44 such that the guide 12 is terminated thereby. Within guide 12 adjacent the tapered section 44 is a cylindrical block 45 of resistive material which completely fills the guide 12 in a transverse direction. The ends of block 45 are conically tapered so that wave energy propagating toward the block will see a gradual impedance change and will not be reflected thereby. Furthermore, it may be noted that the external guide 14, to the right of Y—Y, tapers in conical fashion at section 46 into a narrower diameter wave guide 47 whose radius is r_1 , the same as the radius of internal guide 11. It may be noted that the tapered transition section 46 between guides 14 and 47 conforms to the shape of the tapered section 44 of internal guide 12 such that the annular spacing between sections 44 and 46 is relatively constant to preclude any abrupt impedance changes therein.

Considering now the operation of the embodiment of Fig. 4, it may be recalled that in the directional coupler portion to the left of Y—Y all the TE_{01} mode energy will be concentrated in coaxial guide 12—14 while all the spuriously generated higher order TE_{0n} mode energy, and any other spurious mode energy that might have gotten past the helix 13, is concentrated in internal wave guide 12. Consider this wave energy propagating to the right of Y—Y. The TE_{01} coaxial mode in guide 12—14 will continue propagating to the right to the region between transition sections 44 and 46. At that point the coaxial structure gradually becomes non-coaxial, i.e., gradually tapers into a single wave guide structure 47. At that point, of course, the TE_{01} coaxial mode has been gradually deformed into the TE_{01} circular guide mode. Thus the TE_{01} circular electric mode which is unaltered by any other TE_{0n} modes continues propagating to the right along guide 47 to be advantageously utilized farther along the wave guide system.

On the other hand, all of the energy in the form of the spuriously generated modes in guide 12 continues to the right until it encounters the attenuating block 45 of resistive material. Since attenuator 45 completely fills wave guide 12, it is clear that irrespective of the mode configurations involved, all of the energy reaching the attenuator 45 is completely dissipated therein.

The embodiment of Fig. 5 comprises two directional couplers, the first comprising internal guides 11 and 12, helix 13 and coaxial guide 14 identical to the coupler of Fig. 1; the second comprising internal guides 51 and 52, helix 53 and coaxial guide 54 also identical to the couplers of Fig. 1. Between internal guides 12 and 51

there is located an attenuating block 50 identical to attenuator 45 of Fig. 4.

In the operation of the mode filler of Fig. 5, the spurious undesired mode energy in guide 12 will be dissipated by attenuator 45 in precisely the same manner as in Fig. 4. The effect on the TE_{01} coaxial mode energy in its propagation to the right of Z—Z, is quite different however from its treatment in the tapered transition portions of Fig. 4. The TE_{01} coaxial mode will propagate to the right until it reaches helix 53. The directional coupler to which it is thus presented is in all respects the same as that which was responsible for the wave energy being transferred from the inner guide 11 to the coaxial guides 12—14. Since these structures are, of necessity, completely reciprocal in their operation, the TE_{01} mode will be transferred completely along the helix into internal guide 52 in the form of TE_{01} circular electric mode energy in a round guide. As a consequence the internal guide 52 continues on to the right to form the rest of the wave guide system, while external guide 14 may be ended abruptly by end plate 55 since it is no longer needed to support wave energy at that point.

It may be noted that the directional coupler to the right of Z—Z merely performs the function of reconvert- ing the TE_{01} coaxial mode back into the TE_{01} mode in circular guides to be utilized elsewhere in the wave guide system. All of the spuriously generated mode energy was eliminated from the system by the attenuator 50 in guide 12. Since it is the case that the directional coupler to the right of Z—Z need not necessarily have mode selective properties, since in that region the mode is pure, the helix directional coupler may be replaced by the non-mode selective directional coupler disclosed in my above-mentioned copending application, Serial No. 724,724.

In all cases it is to be understood that the above-described arrangements are illustrative of a smaller 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. In combination, two hollow conductive wave guides of circular cross section coaxially disposed and individually adapted to support a TE_{on} mode, a multiplicity of interruptions in the conductive boundary of the internal one of said coaxially disposed guides for communication between said two guides, the ratio of the radii of said two guides being proportioned to preclude the coupling of all but one of said TE_{on} modes between said internal and external guides, said ratio of said radii being concomitantly proportioned to induce the coupling between said guides of said one TE_{on} mode.

2. A combination as recited in claim 1 wherein said ratio of radii is equal to the ratio of different roots of the Bessel function of said TE_{on} mode.

3. A combination as recited in claim 1 wherein said interrupted conductive boundary comprises a metallic helix.

4. A combination as recited in claim 1 including resistive attenuating material disposed within one of said two waveguides exclusively for attenuating all of said TE_{on} modes other than said one coupled mode.

5. A combination as recited in claim 4 including means for coupling wave energy propagating in said single TE_{on} mode in a region external to said internal guide into wave energy propagating in said same mode in a circular waveguide of the same radius as said internal waveguide.

6. A combination as recited in claim 5 wherein said last-named means comprises a second of said directional couplers wherein the interrupted conductive boundary comprises a helix and said internal and said external wave guides have said same ratio of radii.

7. A combination as recited in claim 5 wherein said last-named means comprises a section wherein said internal guide is tapered into a conical termination and said external guide in the same region has a similar conical taper to a round wave guide having the same radius as said internal wave guide.

References Cited in the file of this patent

UNITED STATES PATENTS

2,869,085 Pritchard Jan. 13, 1959