

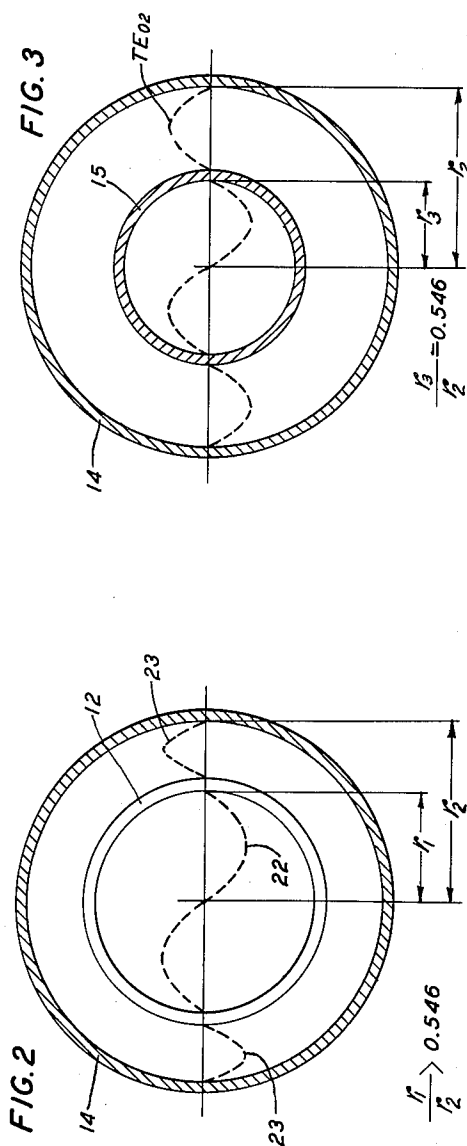
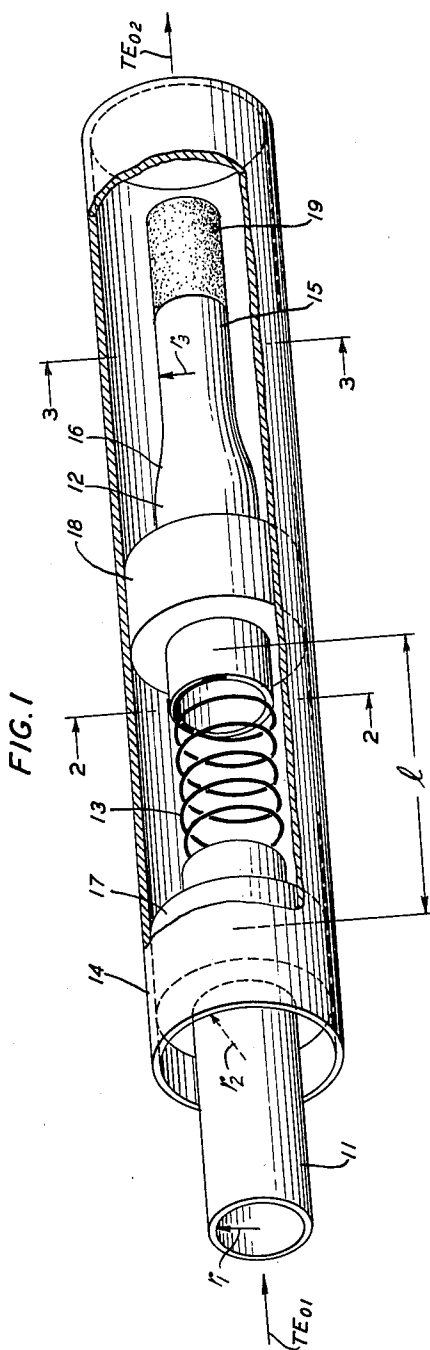
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WAVE MODE CONVERTER

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3,020,495

WAVE MODE CONVERTER

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6 Claims. (Cl. 333-10)

This invention relates to electromagnetic wave transmission systems whose primary modes of propagation are the circular electric modes.

In wave guides of circular cross section, it is well known that if the guide dimensions are large enough, a number of circular electric modes can propagate at a given operating frequency. The lowest order of these modes is the TE_{01} and the next higher order circular electric mode is the TE_{02} . Ordinarily the higher order modes are considered undesirable and much effort has been devoted to eliminating their presence. However, there are many obvious reasons why it is desirable to be able to produce them and particularly to convert between them and the lower order modes. For example, in order to test the efficiency of any device for eliminating a higher order mode, it is necessary to reliably generate this mode.

It is, therefore, an object of the present invention to efficiently convert wave energy between the TE_{01} mode and higher order circular electric modes such as the TE_{02} mode.

In United States Patent 2,762,982 granted September 11, 1956 to S. P. Morgan, Jr., it was pointed out that conversion between the TE_{01} and a higher order circular electric mode such as the TE_{02} could be achieved by appropriately delaying some of the wave energy in a center zone of the TE_{01} mode relative to wave energy in the remaining outer tubular zone to produce the two concentric oppositely phased cophasal zones characteristic of the TE_{02} mode. Conversely, if one of the cophasal zones of the TE_{02} mode is appropriately delayed with respect to the other, at least some of the field pattern is converted into that characteristic of the TE_{01} mode. The present invention makes similar use of the concept of the cophasal zones, but offers substantial improvement in two major respects. First, the inherent frequency sensitivity involved in any "delaying operation" is eliminated and second, the desired conversion is made much more completely. In accordance with the present invention, use is made of a circular electric mode directional coupler similar to that described in the copending application of E. A. J. Marcatili, Serial No. 783,224, filed December 29, 1958, now Patent No. 2,951,219, to couple one-half of the energy in a TE_{01} mode field into a TE_{01} coaxial field with a 180 degree phase difference therebetween. Specifically, a circular wave guide is provided having distributed interruptions in its longitudinally extending conductive boundary. Coaxial with and circumscribing the round guide in the region of the interruptions is a second round guide. The radial dimensions of the coaxially related guides are proportioned with respect to the coupling parameters of the interruptions to produce the desired power division and phase. The inner guide is then tapered so that its conductive boundary coincides with the null of the TE_{02} mode. It is then terminated in a resistive cylinder. The two concentric fields combine to form the desired TE_{02} 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 illustrated embodiment of the invention shown in the accompanying drawings.

In the drawings:

FIG. 1 is a cutaway perspective view of a mode transducer in accordance with the invention; and

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FIGS. 2 and 3 are transverse cross sections of FIG. 1 for the purpose of illustrating the relationship between electric field intensity in the concentric wave guides and the radii of the guides.

Referring more specifically to FIG. 1, an illustrative embodiment in accordance with the invention is shown which may be conveniently considered as comprising two sections: a coupled line hybrid or directional coupler section on the left and a field pattern-conforming section on the right.

Considering now the directional coupler section, there is disclosed two lengths 11 and 12 of hollow conductive wave guide each having a circular transverse cross section that is proportioned to support the circular electric TE_{01} 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 collinearly disposed in longitudinal succession with adjacent ends spaced from each other by a given distance l . 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. 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 FIG. 2.

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 any TE_{0n} mode remains undisturbed by the supporting metallic rods since these circular electric modes have electric lines of force in the form of concentric circles which would everywhere be perpendicular to the metallic rods. Thus the rods present no impedance discontinuity to 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.

As will be discussed in more detail hereinafter, it is necessary to conform the field patterns in guide 12 and in the coaxial guide 12-14 into a field pattern that is exactly coincident with the field pattern of the TE_{02} mode in guide 14 alone. For this purpose a field pattern-conforming section is connected at the right hand end of guide 12. In particular, the right hand end of guide 12 is connected to a guide 15 of smaller radius r_3 by a smooth, relatively short taper 16. The exact value of r_3 will be defined in connection with FIG. 3 hereinafter. Forming a continuation of guide 15 is a thin wall cylinder 19 of electrically dissipative or resistive material such as a suitable plastic of low dielectric constant impregnated with carbon black. Guide 14 continues to the right in coaxial relationship with taper 16, guide 15 and cylinder 19.

In operation of the transducer of FIG. 1, wave energy in the TE_{01} mode from a suitable source for conversion into TE_{02} wave energy is applied to guide 11 to propagate from left to 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 the TE_{01} mode since the wall currents of this mode are circular and transverse to the

direction of propagation of wave energy in the guide and these currents consequently find conductive paths in the helix. If the pitch of the helix, or the space between the adjacent portions of the helix, is at least several times larger than the diameter of the helical conductor, some of the TE_{01} mode energy will leak from the helix into guide 13—14. Thus, a given amount of TE_{01} energy designated by the coupling factor α may be transferred from guide 11 to guide 13—14 per unit length by properly proportioning the pitch of the helix. The greater the pitch of the helix the greater the coupling factor α in radians per unit length.

Radii r_1 and r_2 of guide 11—12 are now selected with respect to the coupling factor α and the coupling interval l along which it is maintained according to the principles developed and defined in detail in my prior Patent 2,820,202 granted January 14, 1958 in order to produce a broad band transfer of one-half of the wave power applied to guide 11 from guide 11 into guide 13—14. In particular, the radius r_1 is proportioned to produce a phase velocity constant for helix guide 13 of β_1 radians per unit length and the radius r_2 is proportioned to produce a phase velocity constant for the coaxial guide 13—14 of β_2 such that for a distributed coupling per unit length α maintained along the interval l

$$\frac{\beta_1 - \beta_2}{2\alpha} = 1 \quad (1)$$

and

$$\alpha l = \frac{\pi}{2\sqrt{2}} \text{ radians} \quad (2)$$

The derivation of these relationships and broadband hybrid-type power transfer that results are fully set forth in the above-mentioned patent. For further information, reference may also be had to my article, "Coupled Wave Theory and Wave Guide Applications," Bell System Technical Journal May 1954, pages 661 through 719.

Under this condition the electric field distribution shown in FIG. 2 exists at the end of the coupling region, i.e., at the left end of guide 12. Thus, FIG. 2 shows a transverse cross section of guides 12 and 14 along with a representative electric field intensity distribution. Curve 22 represents one-half of the power remaining within guide 12. Exactly 180 degrees out of phase therewith is the transferred one-half power represented by curve 23 in coaxial guide 12—14. While the combined distribution of energy represented by curves 22 and 23 bears a phase and an amplitude relationship that is similar to the two cophasal zones of the TE_{02} mode, it is not identical to the TE_{01} mode. This difference will be apparent from FIG. 3 which shows the actual distribution of the TE_{02} mode and indicates that the electric field null between the oppositely phased cophasal zones falls at a radius r_3 that is equal to $0.546r_2$. This is also the radius ratio between r_3 and r_2 for which the coaxial field energy in guide 14—15 will have a phase velocity constant that is equal to the phase velocity constant of the TE_{01} energy within guide 15. Derivation of this condition is set out more fully in the above-mentioned copending application of E. A. J. Marcatili. However, in accordance with the present invention, it is necessary for β_2 in coaxial guide 13—14 to be substantially smaller than β_1 in helix guide 13 along the coupling interval l . In particular, solution of Equations 1 and 2 will indicate that

$$\beta_1 - \beta_2 = \frac{\pi}{\sqrt{2}l} \text{ radians per unit length} \quad (3)$$

This means that radius r_1 must be substantially greater than $0.546r_2$ with the result that the field distribution 23 in the outer cophasal region is restricted to the cylindrical space between guide 14 and helix 13 that is smaller than the similar region of the TE_{02} distribution in guide 14—15 of FIG. 3. Thus, taper 16 is required to enlarge the

outer cophasal region (which at the same time decreases the inner region) to produce a transition from the radius ratio

$$\frac{r_1}{r_2} > 0.546$$

to the radius ratio

$$\frac{r_3}{r_2} = 0.546$$

and to conform the field patterns of different phase velocity in guide 12 and in coaxial guide 12—14, respectively, into the field patterns of equal phase velocity in guide 15 and in coaxial guide 15—14. It should be noted that this change in dimensions theoretically results in a change in phase constant that tends to alter the desired 180 degree phase between the inner and outer cophasal zones. However, in practice, taper 16 may be made sufficiently short without presenting substantial impedance discontinuity that actual relative phase shift is minor and usually no further provision need be included for its correction. Alternatively, methods familiar to the art can be employed to delay the phase of energy in the outer cophasal zone sufficiently to maintain the desired out-of-phase relationship at the end of taper 16. As another alternative, the radius of guide 14 could be enlarged with respect to the radius of guide 12 to achieve the proper ratio between radii at the end of the field-forming section. In either event, the conductive boundary of guide 15 coincides with the null of the TE_{02} distribution and may be discontinued to allow the inner and outer zones to combine to form an actual TE_{02} mode. Resistive cylinder 19 is provided to dissipate any residual TE_{01} mode energy. Since cylinder 19 lies upon a null in the TE_{02} mode, none of the converted energy is dissipated.

It should be noted that helix 13 may be replaced by a series of spaced thin metallic rings of conductive material which may be supported in guide 14 by dielectric spacers or thin radial rods. The use of spaced rings has an advantage over the helix in that it provides a continuous circumferential conducting path for circular electric wall currents. On the other hand, the helix coupling arrangement is considerably easier to fabricate than that of the spaced rings.

The transducer is, of course, reciprocal so that TE_{02} energy applied to the right end of guide 14 will be converted into TE_{01} energy at the left end of guide 11. While the principles of the invention have been illustrated specifically in terms of the TE_{01} and TE_{02} modes, it should be noted that these principles may be extended to convert between or to any TE_{0n} mode.

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. A mode transducer comprising two hollow conductive wave guides of circular cross section coaxially disposed with respect to each other, a multiplicity of interruptions in the conductive boundary of the internal one of said guides to provide energy coupling between said guides, the relative radii of said guides along said coupling region having a first ratio for which the phase velocity constants of said guides for a wave field supported in said internal guide and for a wave field supported between said guides are equal respectively to materially different first and second values, the relative radii of said guides in a region adjacent to said coupling region having a ratio between them that is different from said first ratio and for which the phase velocity constants of said guides for said two wave fields are

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equal to each other and to a third value that falls between said first and second values, said guides being smoothly tapered between said different radii relationship.

2. The transducer according to claim 1 wherein said radii along said coupling interval bear to a ratio to each other of greater than 0.546 and wherein said radii adjacent to said coupling interval bear a ratio to each other equal to 0.546.

3. The transducer according to claim 1 wherein said coupling region extends along a longitudinal interval l with a coupling factor equal to

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

radians per unit length, said guides for said two wave fields 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.

4. The transducer according to claim 1 wherein the internal one of said guides is terminated in said region adjacent to said coupling region in a thin walled cylinder of dissipative material having a radius equal to the radius of said internal guide.

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5. The transducer of claim 1 including means for coupling with TE_{01} circular electric mode energy supported by the internal one of said guides and means for coupling with TE_{02} circular electric mode energy supported by the external one of said guides.

6. In combination, two hollow conductive wave guides of circular cross section coaxially disposed and individually adapted to support a TE_{0n} mode, a multiplicity of interruptions in the conductive boundary of the internal one of said guides to provide energy coupling between said two guides, the radii of the two guides and the length of the coupling region being proportioned to impart an equal power division with a 180 degree phase difference between said guides, said internal guide being gradually reduced in radius beyond the coupling region to coincide with a null of a TE_{0n} mode higher than TE_{01} .

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