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MICROWAVE DEVICES FOR WAVE GUIDES OF CIRCULAR CROSS SECTION

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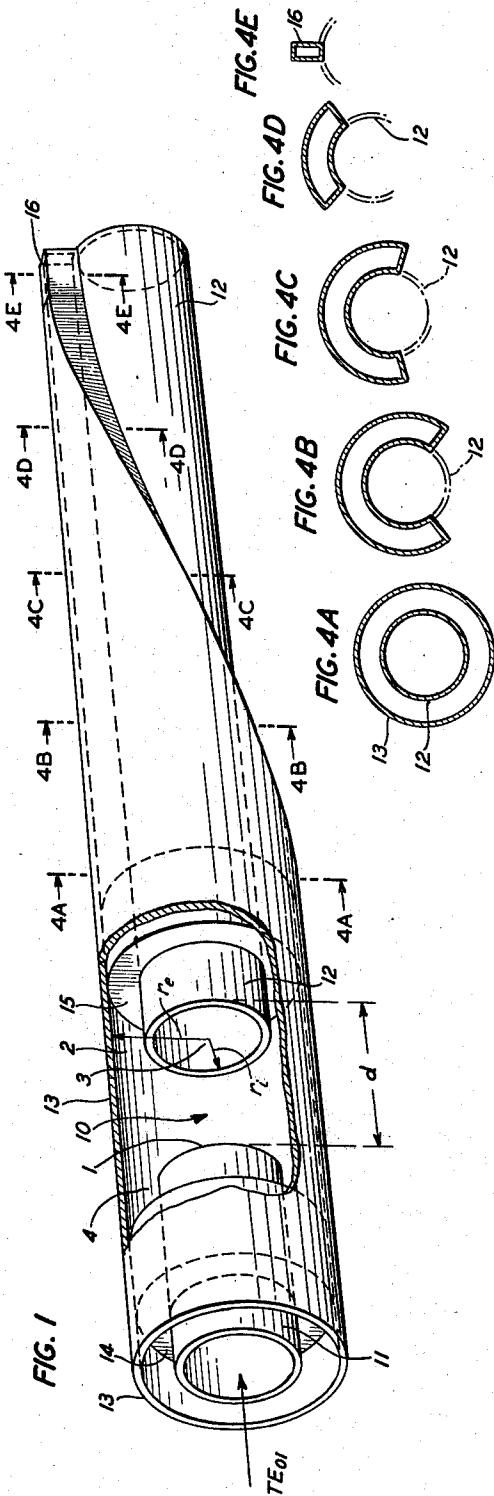


FIG. 4E

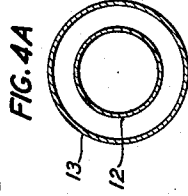
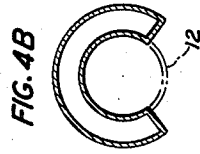
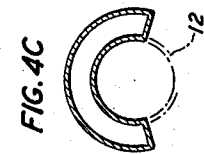
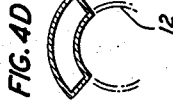


FIG. 3B

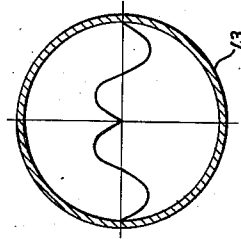


FIG. 3A

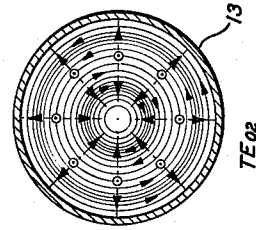


FIG. 2B

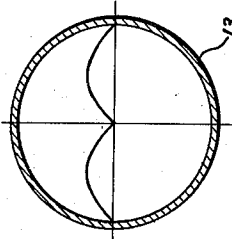
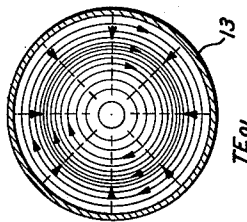


FIG. 2A



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MICROWAVE DEVICES FOR WAVE GUIDES OF CIRCULAR CROSS SECTION

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8 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 components for use in such systems whose geometries are intrinsically compatible with the circular electric mode to provide extraordinarily broad band operation directly in that mode.

The upper limit of the usable portion of the radio frequency spectrum is continually being raised in the effort to provide ever increasing numbers of communication channels. The recognition that the circular electric, TE_{01} , mode propagating in metallic wave guides of circular cross section has a loss characteristic inversely proportional to frequency promises to substantially raise the frequency ceiling. As a consequence, the interest in circular wave guide theory and components has of late flourished considerably. The breakthrough in components development has, however, been quite uneven. Since the transmission means most often used in the propagation of energy through wave guides has been the rectangular wave guide supporting the dominant TE_{10} mode, and the circular wave guide supporting the TE_{11} mode, most of the component devices required in these transmission systems are adapted to these types of modes. The microwave art is replete with directional couplers, hybrids, circulators, isolators, frequency filters and the like, whose structural geometries are peculiarly compatible with the electromagnetic field configuration of these modes of propagation.

This is not the case, however, with the circular electric mode; very few components have been developed which are intrinsically suited to the circular electric mode. As a consequence, in order to perform the various operations upon the circular electric mode required in a transmission system it has been necessary to convert to the TE_{10} mode in rectangular pipe, or the TE_{11} mode in circular pipe. Microwave components have been developed to do this. For example, in United States Patent No. 2,748,350, which was issued May 29, 1956, to S. E. Miller, there is disclosed a directional coupler for dividing wave energy in any desired proportion between the circular electric mode in a round guide and the dominant mode in a rectangular guide, with the two guides disposed parallel to each other and sharing a common wall portion with coupling apertures therein. This directional coupler is excellent for its purposes and has a band width of 20 percent. In my copending application, Serial No. 706,459, filed December 31, 1957, there are disclosed channel dropping filters for extracting given frequency bands from a round guide propagating the TE_{01} mode into a rectangular guide propagating the TE_{10} mode without introducing mode conversion in the process.

It seems clear, however, that at this early point in the development of the circular electric mode wave guide art, the objective should be set for developing microwave components intrinsically suited to this interesting and

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highly useful electromagnetic mode. Ultimately, it is to be hoped that every operation that is required to be performed in a circular electric wave guide system will be performed directly upon the wave energy in the form of a circular electric mode without the necessity for converting to some other mode merely because the microwave component necessary to perform the needed function operates only in the other mode. It is to be expected that because of the very special nature and geometry of the circular electric mode field pattern, the ordinary techniques and structures known in the art and applicable to other modes of propagation will be inadequate for providing guidance in the creation of a class of microwave components peculiarly compatible with the circular electric mode.

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 transmission 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.

It is the primary object of this invention to provide directional coupling between two transmission lines each of which supports energy solely in a circular electric mode.

In accordance with the invention, this object is accomplished by a directional coupler whose geometry is related to the geometry of the circular electric mode field pattern in a manner which is peculiarly consonant and congruent therewith. Specifically, a circular wave guide has a gap interrupting its longitudinally extending conductive boundary. Adjacent ends of the wave guide define the longitudinal extent, d , of the gap. The guide is proportioned to support solely the lowest numbered circular electric mode, namely the TE_{01} . Coaxial with and circumscribing the round guide in the region of the gap is a second round guide proportioned to support both the TE_{01} and the TE_{02} modes, but no other higher numbered circular electric mode. Wave energy propagating through the internal coaxial guide, upon reaching the gap, will excite in the outside coaxial guide in the region of the gap both the TE_{01} and the TE_{02} modes, both of which the external guide is proportioned to support. Since, as is well known in the art, these two modes propagate with different phase velocities, the phase relationship between the two modes will vary with distance. This results in a power division between the internal guide and the external guide at the end of the gap, the ratio of which is dependent upon the length d . Thus, for example, if d is equal to an odd number of one-quarter beat wavelengths there will be an equal division between wave guides; if d is one-half a beat wavelength there will be a complete power transfer from the internal guide to the external guide; while if d is a whole beat wavelength the energy will continue propagating completely within the internal guide on the other side of the gap. It is clear, therefore, that any desired division of power may be obtained by the appropriate choice of the length d relative to the difference between the phase velocities of the two modes. In this way directional coupling is obtained without the inefficient expedient of converting to some other mode incongruent or dissimilar to that of the circular electric type.

At this point in the development of the circular electric mode art, however, it is highly probable that the transferred energy would have to be converted into the dominant mode in a rectangular guide to be effectively utilized, e.g., demodulated, amplified, filtered or the like. This conversion, however, may be done in a manner well

known in the art and will be described in greater detail below.

Nevertheless, the fact that directional coupling is performed, in accordance with the invention, exclusively in the circular electric mode has very important consequences. Firstly, this is a contribution to an emerging development of an entire class of microwave components intrinsically and efficiently operative in the circular electric mode. Secondly, by proportioning the external wave guide so that it is just below cut-off for the TE_{03} mode in the operating frequency range and by proportioning the internal guide so that its conductive boundary coincides with the electric field null of the TE_{02} mode supported by the external guide, the directional coupler will be operating at frequencies considerably removed from cut-off. Since a directional coupler becomes less frequency sensitive with removal of the operating range from cut-off, it is clear that this device is very broad band; indeed frequency bands as great as 40 percent may theoretically be transferred between transmission lines in this way. Whether this theoretical band limit may be achieved in actuality has not been determined since there is no microwave generator known in the art which is sufficiently broad band to test the limits of the device at the mid-band frequencies of interest, i.e., the millimeter wave region.

A feature peculiar to the directional coupler in accordance with the invention, is that no matching elements are needed to eliminate reflections in the region where the energy is divided between the internal and external coaxial guides because the structural geometry of the power divider is intrinsically consonant with the geometry of the electric field patterns of the TE_{01} and TE_{02} modes in round guides.

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 cutaway view of an embodiment of a directional coupler for circular electric modes given by way of example, in accordance with the invention;

Figs. 2a, 2b, 3a, 3b, are representative curves and models, given by way of explanation, of certain mode field patterns helpful for an understanding of the operation of the embodiment of Fig. 1; and

Figs. 4a through 4e are successive transverse cross-sectional views of a mode transducer utilized in the embodiment of Fig. 1.

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 major sections; the first is the directional coupler itself; the second is a 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 first section, namely the directional coupler itself, there are 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 TE_{01} mode to the exclusion of all the higher numbered circular electric modes. Guides 11 and 12 are of the same transverse dimensions and are colinearly disposed in longitudinal succession with adjacent ends spaced from each other by a distance d to form a coupling gap 10. Surrounding guides 11 and 12, and coaxially disposed with respect to each of them is a hollow conductive wave guide 13 of circular cross section providing a conductive boundary around both said guides 11 and 12 and around gap 10. Guide 13 in the region of gap 10 is proportioned to support both the TE_{01} and the TE_{02} circular electric modes, to the exclusion of all higher numbered circular electric modes, and

its radius r_e is related to the radii r_1 of guides 11 and 12 in a special manner to be discussed in greater detail below. Supporting each of guides 11 and 12 in their coaxial positions within guide 13 are hollow dielectric cylinders or washers 14 and 15 circumscribing guides 11 and 12 and otherwise completely filling guide 13, in a manner well known in the coaxial conductor art. Washers 14 and 15 are preferably made of dielectric material having a very low dielectric constant, such as polyfoam, so as to minimize the possibility of reflection of wave energy incident thereon. For ease of reference, the four ports of the directional coupler are designated as follows: Port 1 is guide 11; port 2 is the ring-like region between guide 12 and the internal boundary of guide 13; port 3 is guide 12; and port 4 is the ring-like region between guide 11 and the internal boundary of guide 13. The operation of the directional coupler thus described, and certain other structural relationships in this device, may more readily be understood by considering certain characteristics of the circular electric modes which will now briefly be reviewed, but only to the extent necessary to facilitate a comprehension of the structure of Fig. 1.

The circular electric modes are in general designated TE_{0n} . The TE, representing "transverse electric," indicates that the electric field components are everywhere directed exclusively transverse to the longitudinal axis of the wave guide and the direction of propagation of wave energy therethrough. The 0_n designation represents the order and number respectively, of this family of modes. The order is zero in every case to indicate the number of whole periods of the transverse electric component encountered in passing around the circumference of the cross section of the guide. On the other hand, n represents the number of half periods encountered in passing along the radius of the wave guide cross section. Examples of the field patterns of the TE_{01} and TE_{02} modes in a transverse cross section of a round wave guide will serve to illustrate these designations and also demonstrate the electric field configurations of the two modes of interest in the embodiment of Fig. 1.

Fig. 2a represents the TE_{01} mode. In accordance with the above designation it can be seen that in passing around the circumference of the guide the polarity of the electric field components (the solid concentric circles) is nowhere reversed and thus there is no whole period represented, while in passing from the center of the guide to the circumference along the radius, it can be seen that the polarity remains constant and thus only one-half period is represented. Fig. 2b is another type of representation of the electric field pattern of the TE_{01} mode which is well known in the art. The ordinate represents the intensity of the field pattern, while the abscissa represents distance from the center of the wave guide (this is merely another form representative of the electric field pattern of Fig. 2a). In Fig. 3a the TE_{02} mode is represented; it may be seen that in passing from the center of the guide to the circumference along the radius there is a reversal in the polarity of the electric field components (and thus an electric field null exists), justifying the designation of this field configuration as the second numbered circular electric mode. Fig. 3b is the other type of representation of the electric field pattern of the TE_{02} mode.

As is well known in the art every electromagnetic mode, at a given frequency, requires a wave guide of a certain minimum transverse dimension in order for it to be propagated. Conversely a round wave guide of a given radius will support only those frequencies, in the particular mode of interest, which are above a certain minimum frequency (whose wavelength is known as the cut-off wavelength). Lower frequencies, having larger wavelengths, will not be supported by the wave guide. Parametric expressions relating the cut-off wavelength, the radius of the circular wave guide, and a function of the electromagnetic mode, are well known in the art.

Thus, it is known that the cut-off wavelength for the TE_{03} mode is

$$\lambda_c = \frac{2\pi r}{10.17}$$

for the TE_{02} mode

$$\lambda_c = \frac{2\pi r}{7.02}$$

and for the TE_{01} mode

$$\lambda_c = \frac{2\pi r}{3.83}$$

where λ_c is the cut-off wavelength, r is the radius of the wave guide, and the denominator in each instance is the appropriate Bessel function root for the particular transverse electric mode involved. For a more complete description of this subject, reference may be had to any standard textbook on the subject, such as "Principles and Applications of Waveguide Transmission" by G. C. Southworth, D. Van Nostrand and Co., pages 119 through 129. Keeping the operating frequency range in mind, it is therefore relatively simple with these parametric relationships to design the wave guides 11, 12 and 13 in accordance with the requirements specified above. Thus the radius, r_e , of external guide 13 may be selected such that guide 13 is just below cut-off in the region of gap 10 for the TE_{03} mode at the highest frequency in the operating range. Radii, r_i , of the internal guides 11 and 12 are then readily determined so that the conductive boundaries of guides 11 and 12 coincide with the electric field null of the TE_{02} mode (see Figs. 3a and 3b) supported in the external guide 13 along coupling gap 10, i.e., with r_e determined, r_i is equal to r_e multiplied by the ratio of the Bessel function constants of the TE_{01} and TE_{02} modes; thus

$$r_i = \frac{3.83}{7.02} r_e$$

In this way the directional coupler of Fig. 1 will be operative in a frequency range substantially removed from the cut-off wavelength and will benefit as a result by the relative frequency insensitive characteristic of this type of operation.

The operation of the directional coupler of Fig. 1 may now properly be comprehended with the aid of the field patterns disclosed in Figs. 2a through 3b. Electromagnetic wave energy is exited at the left-hand end of guide 11 exclusively in the TE_{01} mode. This energy propagates to the right along guide 11 until it reaches coupling gap 10. Immediately upon entering gap 10, wherein both the TE_{01} and TE_{02} modes may be supported, the wave energy comprises both these modes. The electric field pattern therefore immediately at the left-hand end of gap 10 may be considered as a superposition of the TE_{01} electric field pattern, as represented in Fig. 2a or 2b, upon the TE_{02} electric field pattern, as shown in Fig. 3a or 3b, respectively. It may be noted that the electric vectors of these modes are in phase within the transverse area corresponding to port 1 but are oppositely phased in the ring-like area corresponding to port 4.

The TE_{01} and TE_{02} modes, as is well known in the art, have different phase constants. They will, therefore, continue propagating along gap 10 in the direction of guide 12 at unequal velocities. Accordingly, the phase relationship of the two modes changes, of necessity, along the distance d of coupling gap 10. If distance d is selected such that the directional coupler is arranged to provide a complete transfer from port 1 to port 2, the electric vectors of the two modes at the end of the gap near guide 12 will be in phase within the ring-like transverse area corresponding to port 2, but will be op-

positely phased in the transverse area corresponding to port 3. Accordingly, port 2 will be excited by the energy which initially entered guide 11. Furthermore, the electric field pattern exciting port 2 and propagating down guide 13 external to guide 12 will be of the TE_{01} type but now, of course, in a coaxial wave guide. In this discussion the phase relationships between the electric field patterns of the TE_{01} and TE_{02} modes in the coupling process have been described. Amplitude relationships are also involved. This latter part of the theory of the device of Fig. 1 does not however lend itself to a simple qualitative description. Computation of the contributions of a multiplicity of modes, many of which are below cut-off, in addition to the TE_{01} and TE_{02} modes must be made in order to present a quantitatively accurate description; i.e. nothing less than a solution of Maxwell's equation for the boundary conditions of the embodiment of Fig. 1 is needed. This theoretical analysis will not be presented since the structure of the invention would not be better understood thereby, and it is a straightforward, albeit laborious, process for one skilled in the art.

It may be noted that in the arrangement of the embodiment of the invention wherein the energy is coupled completely from port 1 to port 2, the phase relationship between the two modes at the right-hand end of gap 10 is exactly 180 degrees out-of-phase from what it was at the beginning of the coupling region, i.e.

$$(\beta_1 - \beta_2)d = (2n - 1)\pi$$

where β_1 is the phase constant of the TE_{01} mode, β_2 the phase constant of the TE_{02} mode, and n is in integer. Were it desired to provide equal power division between ports 2 and 3, the distance d could be changed (to an odd number of one-quarter beat wavelengths rather than an odd integral number of one-half beat wavelengths) so that the phase relationships between the modes at the right-hand end of gap 10 is exactly 90 degrees different from what it was at the beginning of the coupling region, i.e.,

$$(\beta_1 - \beta_2)d = (2n - 1)\frac{\pi}{2}$$

It can be seen, therefore, that any ratio of power transfer desired may be readily accomplished by appropriately fixing the distance d .

It is clear that in the operation of the directional coupler the TE_{02} mode is readily matched to ports 2 and 3 since the conductive boundary of guide 12 is designed, as was explained above, to coincide precisely with the electric field null of this mode. It is not so apparent, however, that the TE_{01} mode is matched since it would appear that the conductive boundary of guide 12 coincides with a region where the electric field of this mode has a finite value. It is the case that in any multi-mode waveguide, the amount of wave energy scattered forward from an impedance discontinuity is far in excess of the amount reflected. Actually, a scattering matrix analysis of the power divider consisting of gap 10 supporting the TE_{01} and TE_{02} modes and ports 2 and 3 demonstrates that the boundary conditions are such that the TE_{01} mode is properly matched to these ports. Accordingly there is negligible reflection from the coupler. The use of scattering matrix representation for analysis of wave guide circuits is well known in the art and a description of this type of representation and analysis is presented in standard works, for example, "Waveguide Handbook," by Marcuvitz, Radiation Laboratory Series, volume 10, 1951, pages 106 through 108, and "The Use of Scattering Matrices in Microwave Circuits," by Mathews, I.R.E. Transactions on Microwave Theory and Techniques, April 1955, page 21. That reflections from the coupler are in fact negligible is well borne out by the data obtained from several successful reductions to prac-

tice of the invention in accordance with Fig. 1. Thus in couplers operating over a frequency range from 50.4 kmc. to 60.6 kmc., wherein guide 13 had an internal diameter of 0.649 inch, guides 11 and 12 had internal diameters of 0.354 inch and the coupling gap length d had values of 0.226, 0.452, and 0.906 inch to provide equal power division between ports 2 and 3, complete power transfer, and no transfer, respectively, the largest reflected signal over the entire frequency band in all three cases was down 23 decibels below the incoming signal. It is of considerable interest to note that there were absolutely no heat losses due to the directional coupler.

Considering the embodiment of Fig. 1 again, we might consider how to make the energy transferred to port 2 available for subsequent use. This is readily accomplished in manner well known in the art and constitutes the second section of the embodiment of Fig. 1 mentioned above. The device to the right of the directional coupler is a transducer for converting the coaxial TE_{01} mode propagating from port 2 between guides 12 and 13 into the dominant mode in a rectangular wave guide 16. This is in essence a mode converter of the type disclosed in G. C. Southworth's book mentioned above, at page 363. The converter progressively varies the transverse shape of the double pipe coaxial guide such that the boundary between guides 12 and 13 is gradually tapered to a rectangular cross section as indicated by Figs. 4a through 4e of the drawings. In this way the TE_{01} coaxial mode is gradually deformed into the TE_{10} dominant mode 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 from port 3 to port 4 and could thence be taken out by a wave converter of the type represented by Figs. 4a through 4e. 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 port 2 to rectangular guide 16 and thence to a repeater station (not shown) for proper amplification, timing, modulation and the like, and could be re-introduced 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 port 4 to port 3 for continued propagation along long distance guide 12.

In all cases, it is to be understood that the above-described arrangements are simply illustrative of a small number of the many possible specific embodiments which 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 multiple port wave guide coupling apparatus for electromagnetic wave energy in circular electric wave modes comprising first and second similar sections of hollow conductive wave guide extending collinearly in longitudinal succession with adjacent ends of said sections spaced apart a given distance to form a gap in the conductive boundary formed by said sections, said first and second guide sections forming first and third ports of said said coupling apparatus, a third section of hollow conductive wave guide disposed external to and coaxial with at least a portion of each of said first and second guide sections to provide a conductive boundary surrounding said gap, the regions between said first and third guide sections and between said second and third guide sections forming second and fourth ports of said coupling apparatus, and means for applying electromagnetic waves in a hollow pipe wave mode to one of said

ports, said third guide section having a cut-off determining dimension k_e proportioned to support first and second distinct hollow pipe wave modes in the region of said gap at the frequency of the applied waves, said first and second guide sections having cut-off determining dimensions k_1 proportioned to support said first mode to the exclusion of said second mode at said frequency, said cut-off determining dimensions being related by the expression

$$k_1 = \frac{J_n}{J_{n+1}} k_e$$

where J_n and J_{n+1} are the Bessel function constants associated with said first and second modes.

2. A combination as recited in claim 1 wherein said first and second modes have different phase constants.

3. A combination as recited in claim 1 wherein said first, second and third guide sections have circular transverse cross sections, said first mode is the TE_{01} circular electric mode and said second mode is the TE_{02} circular electric mode.

4. A combination as recited in claim 3 wherein said third guide section is proportioned to be slightly below cut-off for the TE_{03} mode for frequencies within said range.

5. Coupling apparatus for electromagnetic wave energy in circular electric modal field configurations comprising first and second sections of hollow pipe wave guide adapted to propagate traveling waves in hollow pipe wave modes therethrough at microwave frequencies, said sections having substantially identical circular transverse cross sections with inside radii r_1 and being spaced apart on a common longitudinal axis to form a gap between adjacent end portions thereof, the nonadjacent end portions of said sections forming first and third terminals of said apparatus, a third section of hollow pipe wave guide of circular transverse cross section with inside radius r_e surrounding said gap and at least a portion of each of said first and said second guide sections, the regions between said first and third guides and between said second and third guides forming transmission paths for waves coupled from said gap and also forming second and fourth terminals of said apparatus, said radii r_1 and r_e being related by

$$r_1 = \frac{J_{TE_{0n}}}{J_{TE_{0(n+1)}}} r_e$$

so that said third guide supports first and second distinct hollow pipe wave modes at frequencies within the operating range and said first and second guide sections support said first mode to the exclusion of said second mode in said frequency range, where $J_{TE_{0n}}$ and $J_{TE_{0(n+1)}}$ are the Bessel function constants for said first and second modes respectively.

6. Coupling apparatus according to claim 5 in which said first mode is the TE_{01} circular electric mode and said second mode is the TE_{02} circular electric mode.

7. Apparatus according to claim 5 in which said third wave guide is proportioned to be slightly below cut-off for the $TE_{0(n+2)}$ mode in said frequency range.

8. In combination, a section of hollow pipe wave guide having first and second ends and having a circular transverse cross section with a radius r_1 greater than 0.3 free space wavelength of the lowest frequency waves to be transmitted but proportioned to be below cut-off for all circular electric wave modes except the TE_{01} mode for frequencies within the operating range, a second section of hollow pipe wave guide similar to said first guide section longitudinally adjacent said first section with adjacent ends of said first and second section spaced away to form a gap, and a third guide section having a circular transverse cross section with a radius r_e equal to $1.83r_1$

coaxially disposed about said second section and extending at least to the end of said first section which defines said gap, means for exciting said first section in the TE_{01} wave mode at the end distant from said gap, and means for receiving energy coupled at said gap at the end of said second section distant from said gap and at the end of said third section distant from said gap. 5

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